We get technical

Configuring four-switch buck-boost μModule regulators for versatile applications

Vicor power modules simplify high-voltage conversion for the shift to 48 V

How to drive SiC MOSFETs and IGBTs with precision, efficiency, and protection

An introduction to thermal management

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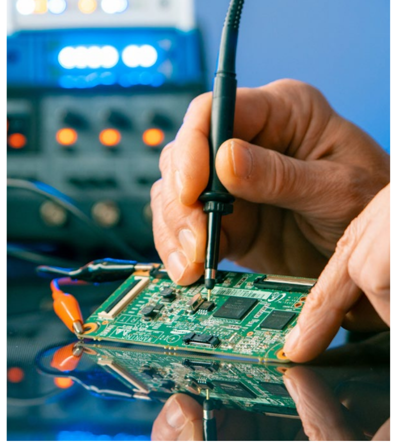


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Editor's note

Welcome to the DigiKey eMagazine Volume 36 – Power.

Power is the foundation upon which modern electronics, industrial systems, communications infrastructure, transportation, and emerging technologies are built. As applications become increasingly sophisticated, designers face growing demands for higher efficiency, greater power density, improved thermal performance, enhanced reliability, and more intelligent power management solutions.

In this edition, we explore the technologies, design strategies, and innovations that are shaping the future of power conversion, distribution, and management across a broad spectrum of industries.

We begin with Renesas and their RRW11011, highlighting advancements that help engineers address the challenges of next-generation power applications. Advanced Energy examines the industry's transition toward higher efficiency standards in *Are You Ready for Level VII Efficiency?*, offering valuable insight into evolving regulatory requirements and their impact on power supply design.

Delta Electronics presents its PJ 2nd Generation Open Frame SMPS Power Supply, showcasing how modern power solutions deliver enhanced performance, reliability, and flexibility for demanding applications. RECOM Power GmbH explores the growing role of IC and discrete power solutions, providing designers with practical approaches to optimizing system performance and integration.

From Analog Devices, Inc., we feature *Configuring Four-Switch Buck-Boost μModule Regulators for Versatile Applications: Step-Up, Step-Down, or Inverting Output*, a comprehensive look at how advanced regulator architectures enable greater design versatility across a wide range of operating conditions. Vicor Corporation contributes an in-depth discussion on efficient high-voltage to 48V conversion, addressing one of the key challenges in today's power delivery networks and high-performance systems.

Complementing these industry perspectives are two insightful technical features. *How to Drive SiC MOSFETs and IGBTs with Precision, Efficiency, and Protection* examines critical considerations for maximizing the performance and reliability of modern power semiconductor technologies. Meanwhile, *An Introduction to Thermal Management* explores one of the most important aspects of power system design, providing a foundation for understanding how effective heat dissipation directly influences efficiency, longevity, and system reliability.

Together, these articles provide valuable knowledge for engineers, designers, and decision-makers seeking to stay ahead in an increasingly power-conscious world. Whether your focus is efficiency, power conversion, thermal optimization, or next-generation semiconductor technologies, this issue offers practical insights and innovative solutions to support your design objectives.

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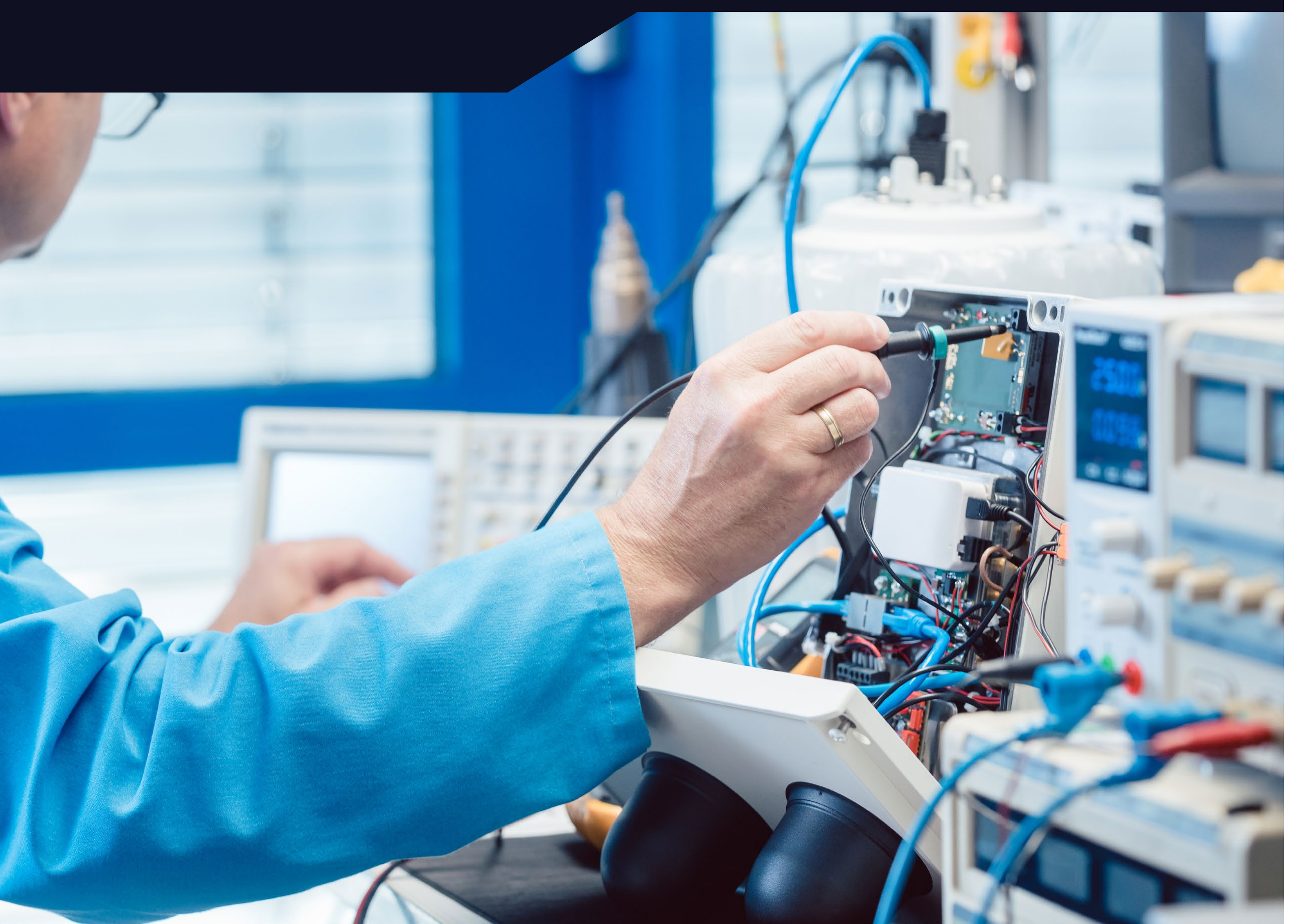
Renesas' RRW11011 shrinks 500 W GaN power designs with one chip for PFC and LLC



Designing a high-power AC/DC supply means balancing requirements that are contradictory. Higher power density is expected, mandating that the same wattage fits into a smaller enclosure. Additionally, efficiency and standby-power rules grow stricter with each revision, and EMI and heat must still be managed within that shrinking volume. The control scheme is also typically split between a separate power-factor-correction controller and a separate resonant-converter controller, which increases component count and board area. Renesas Electronics designed its RRW11011 to solve these challenges by combining its interleaved PFC and half-wave LLC digital control into a single primary-side controller, built for compact GaN-based supplies up to 500 W.

Two control jobs in one device

The RRW11011 (Figure 1) is an AC/DC primary-side digital controller that combines an advanced interleaved boost PFC controller with a half-wave LLC converter controller, all in one 16-lead DFN package. Bringing them both under one device's intelligent digital two-stage control allows coordinating the PFC and resonant stages as a system, rather than as two independently tuned blocks. This coordination helps optimize efficiency while minimizing EMI and audible noise. It also lowers bill of materials (BOM) costs and simplifies the overall layout.

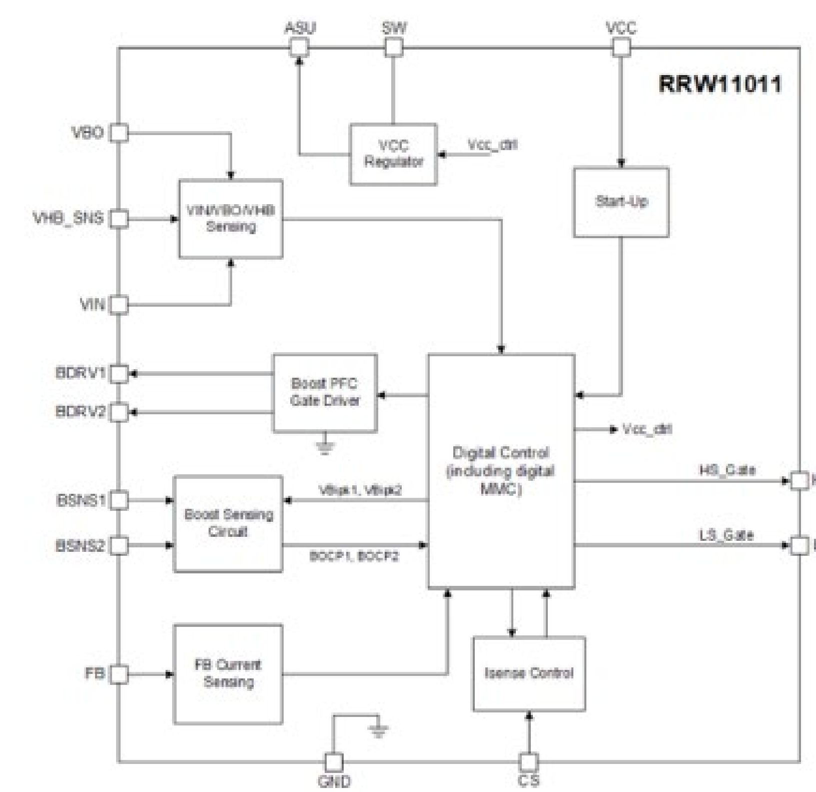
Why interleaved PFC matters here

The PFC stage uses an interleaved architecture, operating in two staggered switching phases, and utilizing phase-shift control with a 2-phase current-sharing technique to maintain balance. Because the two phases alternate in drawing and delivering current, their ripple currents partially cancel each other, lowering both the input ripple at the line and the output ripple at the bulk capacitor. This partial ripple cancellation pays off in several ways. First, the design can use smaller filter components and magnetics while also lowering EMI, increasing the power density and lowering the overall component count. Additionally, the integrated boost PFC stage improves the power factor and reduces the total harmonic distortion, helping high-power supplies meet line-quality requirements.

The benefits of the half-wave LLC stage

Typically, LLC converters are chosen for their soft switching and high efficiency, and they rely on a main transformer with an auxiliary

Figure 1: The RRW11011 functional block diagram. Image source: Renesas



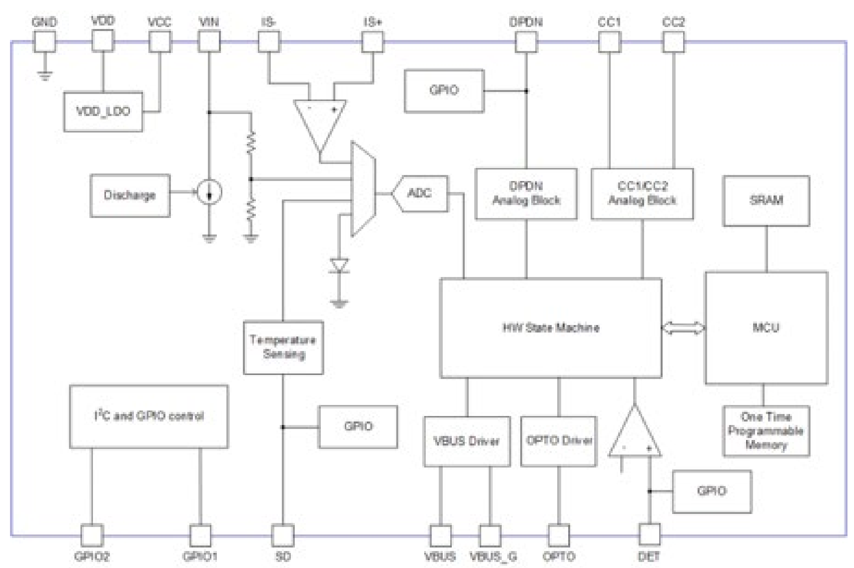


Figure 2: The RRW30120 functional block diagram. Image source: Renesas

winding to generate a low-voltage rail to power their internal circuitry. Alternatively, the half-wave LLC design of the RRW11011 employs a patent-pending, direct VHB voltage-sensing technique that eliminates the transformer auxiliary winding, and it uses adaptive zero-voltage switching control and adaptive multi-mode control to keep efficiency high and EMI low across the load range.

Built for GaN switching

The RRW11011 is designed to drive gallium-nitride (GaN) switching devices, and that pairing is where the architecture reaches its highest density at the top of the power band. GaN switches move charge faster and with lower switching loss than silicon, which lets the converter run at a higher frequency. Higher frequency shrinks the transformer and filter components, while the lower switching loss keeps the thermal budget manageable as power climbs toward 500 W. The half-wave LLC stage preserves the soft-switching behavior that keeps resonant converters efficient. Renesas demonstrated the result in a 240 W USB PD EPR power adapter design built on this platform, which achieved a power density of 3 W/cm³ and a peak efficiency of 96.5% at 230 VAC.

GaN switches move charge faster and with lower switching loss than silicon, which lets the converter run at a higher frequency.

To keep the efficiency high without the wide range working against it, the RRW11011 controller applies adaptive VBULK regulation, adjusting the intermediate bus voltage to current operating conditions rather than holding it fixed, which improves the efficiency and saves energy. On the protection side, the device integrates multiple built-in safeguards, including AC-line brown-out, output short circuit, output overvoltage, and optocoupler failure, among others.

Pairing with the RRW30120 for wide-range output

A high-power primary-side controller still has to deliver a tightly regulated output, and the needs of modern fast charging make that range unusually wide. USB Power Delivery Extended Power Range (EPR) raised the ceiling of USB-C charging to 240 W, or 48 V at 5 A, well beyond the levels older USB-C devices supported. To meet that need, the RRW11011 is optimized to work alongside the RRW30120 (Figure 2), a programmable USB PD controller that manages the Power Delivery protocol and closed-loop output regulation across a 5 to 48 V range.

Regulating on the secondary side lets the system control the output voltage right where it is delivered, which suits the tight, fast-changing targets of USB Power Delivery. The primary and secondary controllers coordinate across the isolation barrier, so the PFC stage, the resonant stage, and output regulation behave as one system (Figure 3).

Scalable across applications and power levels

The combination of a single integrated primary-side controller, GaN-based switching, and a wide regulated output makes the RRW11011 well suited to rapid-charging AC/DC adapters for phones, tablets, and notebooks, as well as television power, power tools, and e-bikes. It scales with the broader half-wave LLC platform from roughly 100 W up to 500 W.

The RRW11011 is also part of a four-IC family designed to be used together. Alongside the RRW30120, it works with the RRW40120 GaN gate driver and the RRW43110 synchronous rectifier controller. That shared architecture carries across products at different wattages, output voltages, and form factors without the need for a clean-sheet redesign.

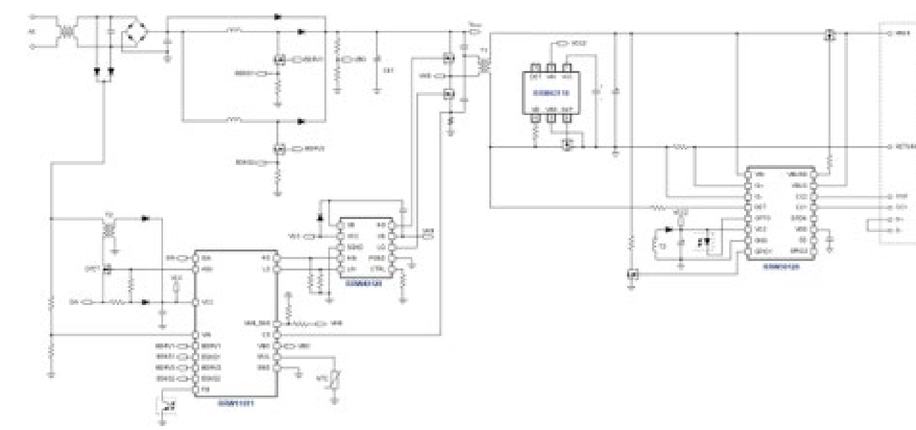


Figure 3: A typical application diagram for a USB PD EPR charger. Image source: Renesas

Conclusion

For engineers trying to build smaller, cooler, more efficient high-power supplies, the RRW11011 consolidates the control function into one device while serving the wide output range that modern fast-charging needs. Full specifications are detailed on the RRW11011 500 W AC/DC primary-side digital controller product highlight.

Are you ready for Level VII efficiency?

Written by Michael Acepcion

The U.S. Department of Energy's (DOE) Level VII efficiency standards will impact numerous applications, from medical and industrial technologies to IT equipment as well as home appliances, lighting, consumer products, and HVAC systems.

Level VII tightens the constraints on energy consumption and addresses concerns about operational costs and greenhouse gas emissions. Increasingly, this is reflected in the need to meet global efficiency standards, including those mandated by the DOE.

The DOE has not yet set a formal enforcement date for Level VII, as it is still in its proposed rulemaking phase. When the proposed Level VII standards are finalized, they will undergo a standard two-year implementation window before taking effect.

Level VII efficiency specification

The current Level VII draft goes beyond existing specifications to further increase demands for efficiency and no-load operation (25% reduction in no-load power draw) as outlined in Table 1.

Nameplate output power (P out)	Minimum average efficiency in active mode (expressed as a decimal)	Maximum power in no-load mode [W]
Single-Voltage External AC-DC Power Supply, Basic-Voltage		
P out ≤ 1 W	≥0.5 × P out + 0.169	≤0.075
1 W < P out ≤ 49 W	≥0.071 × ln(P out) −0.00115 × P out + 0.67	≤0.075
49 W < P out ≤ 250 W	≥0.890	≤0.150
P out > 250 W	≥0.890	≤0.150
Single-Voltage External AC-DC Power Supply, Low-Voltage		
P out ≤ 1 W	≥0.517 × P out + 0.091	≤0.075
1 W < P out ≤ 49 W	≥0.0834 × ln(P out) −0.0011× P out + 0.609	≤0.075
49 W < P out ≤ 250 W	≥0.880	≤0.150
P out > 250 W	≥0.880	≤0.150
Single-Voltage External AC-AC Power Supply, Basic-Voltage		
P out ≤ 1 W	≥0.5 × P out + 0.169	≤0.075
1 W < P out ≤ 49 W	≥0.0582 × ln(P out) −0.00104 × P out + 0.727	≤0.075
49 W < P out ≤ 250 W	≥0.902	≤0.075
P out > 250 W	≥0.902	≤0.200
Single-Voltage External AC-AC Power Supply, Low-Voltage		
P out ≤ 1 W	≥0.517 × P out + 0.091	≤0.072
1 W < P out ≤ 49 W	≥0.0834 × ln(P out) −0.0011 × P out + 0.609	≤0.072
49 W < P out ≤ 250 W	≥0.880	≤0.185
P out > 250 W	≥0.880	≤0.500
Multiple-Voltage External Power Supply		
P out ≤ 1 W	≥0.497 × P out + 0.067	≤0.075
1 W < P out ≤ 49 W	≥0.0782 × ln(P out) −0.0013 × P out + 0.643	≤0.075
49 W < P out ≤ 250 W	≥0.885	≤0.125
P out > 250 W	≥0.885	≤0.125

Table 1: Originally published in the Federal Register

These are still subject to revisions until the specifications are ratified. However, the consensus is that there will be little or no change to these specifications once the standard is in force. As with previous standards, there is likely to be harmonization with other global standards, such as the European CoC Version 5 Tier 2. Therefore, it is important that customers understand the impact of this forthcoming standard on their designs and the power supplies they incorporate today.

Level VII versus Level VI and previous DOE efficiency standards

As early as 1992, the U.S. Environmental Protection Agency started a voluntary program to promote energy efficiency and reduce pollution, which eventually became the Energy Star program. However, it was not until 2004 that the first mandatory regulations dictating average efficiency minimums and no-load power consumption maximums were enacted. Designed to reduce energy consumption and promote sustainability, the DOE standards fall under the authority of multiple legislative acts, including the Energy Policy and Conservation Act (EPCA), and the Energy Independence and Security Act (EISA).

As Table 2 below indicates, these standards have evolved quickly, and the incoming Level VII specification is drafted for higher efficiency and reduced no-load power draw when compared with the current Level VI specification.

1. **Basic Voltage:** Nameplate voltage ≥ 6V.
2. **Low Voltage:** Nameplate output voltage < 6V and nameplate output current ≥550mA.

By establishing minimum efficiency requirements and encouraging the adoption of energy-saving technologies, the DOE standards help consumers save money on energy bills while contributing to a more reliable power grid.

Effect of the Level VII specification on design

While there is no date yet set for the implementation of Level VII, the incoming efficiency specification needs to be considered in light of development timelines. As for many products, Level VII will likely be in place by the time systems are ready for market launch. This is especially true in sectors requiring product certification, such as medical devices.

In many designs, the choice of an internal or external power supply is fundamental to the ability of a system to meet both its performance specifications and the relevant efficiency standards. To this end, power supply manufacturers should already be providing information on how their supplies match the various levels of efficiency.

For example, Advanced Energy (AE) is already offering power supply technologies that meet or exceed the requirements of Level VII as they currently exist. All Advanced Energy products are engineered with a focus on energy efficiency, leveraging advanced power management techniques, low-loss designs, and intelligent control algorithms to ensure compliance with efficiency standards and often surpass the stringent requirements set forth by regulatory bodies.

Most recently, Advanced Energy launched the new SLE33SPD series (Figure 1) of 33 W AC to DC wall mount USB-C power delivery adaptors for medical and industrial applications. These off-the-shelf devices are both ITE rated and medically pre-certified for IEC 60601-1, and are crucially compliant to meet the Level VII efficiency specification.

Conclusion

As the world marches towards a greener future, energy efficiency standards such as Level VII will play an increasingly important role in shaping the landscape of electronic products.

Advanced Energy is leading the charge with innovative power supply solutions designed to meet and exceed the specifications mandated by global standards such as Level VII. As a result, choosing AE technologies for future designs will give OEMs confidence that they are complying with the latest regulations, while addressing customer expectations for energy-efficient electronics that both save money and contribute to a more sustainable environment.

Fig 1: Advanced Energy's new SLE33SPD series that is Level VII efficiency compliant.

Level	Nameplate Output Power (Pno)	Minimum Average Efficiency in Active Mode	Maximum Power in No-Load Mode (W)	Power Factor
I	Used if none of the other criteria are met			
II	<1 watt	≥0.39 x Pno	≤0.75	Not Applicable
	1 to ≤10 watts	≥0.107 x Ln(Pno) + 0.39		
	>10 to 49 watts	≥0.107 x Ln(Pno) + 0.39	≤1.0	
	>49 watts	≥0.82		
III	≤1 watt	≥0.49 x Pno	≤0.5	Not Applicable
	>1 to <10 watts	≥0.09 x Ln(Pno) + 0.49		
	10 to 49 watts	≥0.09 x Ln(Pno) + 0.49	≤0.75	
	>49 to 250 watts	≥0.84		
IV	<1 watt	≥0.5 x Pno	≤0.5	Not Applicable
	1 to 51 watts	≥0.09 x Ln(Pno) + 0.50		
	>51 to 250 watts	≥0.85		
V	≤1 watt	Basic Voltage[1]: ≥0.480 x Pno + 0.140 Low Voltage[2]: ≥0.497 x Pno + 0.067	≤0.3	≥0.9 at 115 Vac/60 Hz for power supply with input power ≥100 W
	>1 to ≤49 watts	Basic Voltage[1]: ≥0.0626 x Ln(Pno) + 0.622 Low Voltage[2]: ≥0.0750 x Ln(P-no) + 0.561		
	≥50 to ≤250 watts	Basic Voltage[1]: ≥0.870 Low Voltage[2]: ≥0.860	≤0.5	
VI	≤1 watt	Basic Voltage[1]: ≥0.5 x Pno + 0.160 Low Voltage[2]: ≥0.517 x Pno + 0.087	≤0.100	≥0.9 at 115 Vac/60 Hz for power supply with input power ≥100 W
	>1 to ≤49 watts	Basic Voltage[1]: ≥0.071 x Ln(Pno) - 0.0014 x Pno + 0.67 Low Voltage[2]: ≥0.0834 x Ln(Pno) - 0.0014 x Pno + 0.609		
	>49 to ≤250 watts	Basic Voltage[1]: ≥0.880 Low Voltage[2]: ≥0.870	≤0.210	
	>250 watts	Basic Voltage[1]: ≥0.875 Low Voltage[2]: ≥0.875	≤0.500	
VII	≤1 watt	Basic Voltage[1]: ≥0.5 × P out + 0.169 Low Voltage[2]: ≥0.517 × P out + 0.091	≤0.075	
	>1 to ≤49 watts	Basic Voltage[1]: ≥0.071 × ln(P out)−0.00115 × P out + 0.67 Low Voltage[2]: ≥0.0834 × ln(P out)−0.0011× P out + 0.609	≤0.075	
	>49 to ≤250 watts	Basic Voltage[1]: ≥0.890 Low Voltage[2]: ≥0.880	≤0.150	
	>250 watts	Basic Voltage[1]: ≥0.890 Low Voltage[2]: ≥0.880	≤0.150	

Table 2: Efficiency level requirements: AC-DC EPS single output.

Delta's PJ Series is built for compact spaces, peak loads, and harsh environments

Industrial and commercial equipment rarely hands the power supply an easy specification. For example, a test bench instrument may need to fit a shallow enclosure yet survive the inrush of an actuator under test; an elevator controller must ride through brief sags on the building feed without faulting, and a refrigerated display case must run efficiently and reliably in environments full of dust and condensation. Specifying a separately optimized supply for each of these jobs can needlessly multiply your qualification work and, ultimately, your inventory.

Delta Electronics designed its second-generation PJ open-frame series (Figure 1) to meet this mix of demands in one family, with 100 and 150 W models offering 12, 24, and 48 V outputs, a universal AC input of 85 to 264 VAC, and a wide DC input range of 120 to 373 VDC. They are offered in both open-frame and enclosed configurations, allowing the same electrical design to serve various installation requirements.

A single part balances durability and efficiency

The concept behind Delta's PJ Series is combining industrial-grade durability with commercial-grade efficiency into one design, suitable for use in either sector. Power supplies are usually chosen for cost, compactness, and often force trade-offs. For example, a unit robust enough for a factory floor tends to be over-built and power-hungry, while a unit tuned for efficiency in a commercial fixture tends to be fragile in the field. By combining peak-handling, ride-through power, environmental robustness, and an efficient front-end into a single family, the PJ supplies serve as strategic building blocks across several product lines, offering savings in qualification, sourcing, and inventory. Standardizing on one family also shortens design cycles, because a board team can reuse the same footprint, hold-up behavior, and protection scheme from one product to the next rather than re-characterizing a new supply each time.

The flexibility of the PJ series also extends to their wide input voltage range. A single part can run from ordinary mains, a rectified or DC-bus distribution scheme, or from a backup source, avoiding the need to specify a different supply for each power architecture. This DC capability is useful where equipment draws from a battery string or an intermediate DC bus, as the same unit that runs on AC during normal operation can keep running on stored DC energy during an outage, without having to qualify a second power stage.

Solving the space vs. peak-power problem

Motors, solenoids, and the mechanisms inside automated test equipment draw far more current at startup than they do in a steady state, sometimes several times their nominal load. To sustain these inrush surges, the PJ series provides a 200% power boost for up to ten seconds, which is usually enough time to let a motor come up to speed or charge a bank of input capacitors before the load settles back to its continuous draw. The PJ supplies maintain a 27 mm low-profile open-frame footprint that drops into space-constrained installations. A built-in remote ON/OFF function makes it easy to sequence and control from a larger system, which is useful when several rails must come up in a defined order or when a controller needs to reduce load and cut standby power.

Safety, compliance, and clean power-up

The PJ series is certified to the IEC/EN/UL 62368-1 safety standard and is fully compliant with Japan's PSE regulation, which confirms its safety pedigree and streamlines entry into Japanese markets, a key advantage when a product has to ship into multiple regions. IEC 62368-1 is the hazard-based standard that has replaced the older 60950-1 for ICT and audio/video equipment, so designing around it positions a product for current approvals rather than a legacy baseline. Additionally, the series low inrush and low leakage current can help minimize the strain on upstream protection when several supplies share a feed. For installers, this means breakers and fuses are less likely to nuisance-trip when a bank of equipment powers up.

Efficiency and protection in commercial and industrial spaces

Figure 1: The PJ 2nd-generation industrial open-frame power supplies.
Image source: Delta Electronics

Another consideration is the link between efficiency and running cost. Commercial fixtures like display cases run continuously, so every percentage point of lost efficiency directly increases operating costs and may also appear as extra waste heat that must be removed. Factory-floor placement can also expose boards to airborne dust, moisture, and chemicals that can degrade unprotected electronics over time.

Delta's PJ supplies address the energy side with active power factor correction and a high-efficiency design that complies with the IEC/EN 61000-3-2 Class A limits for harmonic current emissions, keeping their distortion of the AC line within specified limits while lowering operating costs.

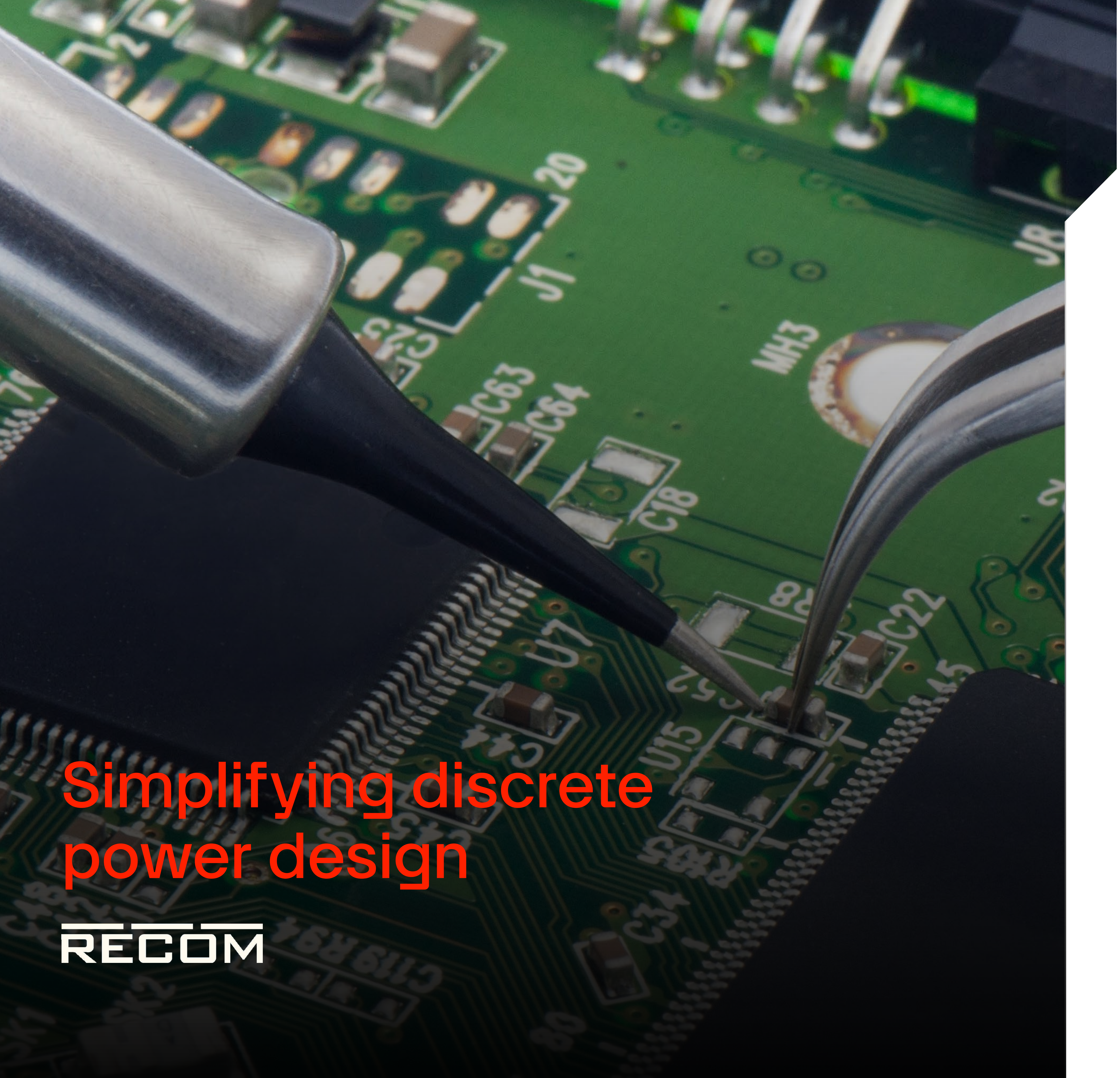
For higher durability, the PJ supplies use conformal-coated printed circuit board assemblies that form a barrier against dust, moisture, and chemical contaminants. The coating matters most on fine-pitch boards, where condensation and ionic contamination can create leakage paths, corrosion, or dendrite growth between closely spaced conductors.

Delta's PJ supplies operate across an ambient temperature range of -40°C to +70 °C. At the top end, they deliver full output up to roughly +50°C, then derate gradually toward their +70°C limit. The low end is handled by a -40°C cold-start capability, removing the uncertainty of startup for equipment that sits unpowered in cold or unconditioned spaces, such as outdoor enclosures or refrigerated fixtures.

Conclusion

All in all, the PJ series' value is in consolidation. Rather than specifying separate supplies to handle peak loads, ride-through, efficiency, and environmental protection, the PJ supplies let you address all of them with one open-frame family, configured to the installation requirements.

For more information on the PJ supplies, please visit Delta's PJ 2nd Generation open-frame power supply product highlight.



Simplifying discrete power design

RECOM

For decades, the fastest way to add an isolated rail to a design has been to drop in a fully packaged DC/DC module, and for a great many projects that remains the right call. A module hides the transformer, the switching controller, and the feedback network behind a single part number, and it ships already certified and characterized. The convenience has a cost, though, in unit price at volume, in fixed board real estate, and in the limited room you have to tune the converter to your exact rail, ripple, and efficiency targets. When any of those constraints become limiting, building the isolated stage from discrete parts becomes attractive, and that is the path that has typically carried the most engineering burden.

RECOM Power is addressing that burden directly by expanding beyond modular supplies into discrete power solutions, pairing its own power ICs with pre-tested, matched SMD transformers, allowing you to assemble a custom isolated converter without starting from scratch.

Transformer matching is the hard part

The main reason designing your own isolated stage is challenging comes down to the transformer. It is the central element of the converter, and getting it right means reconciling a list of interacting parameters. For example, you have the turns ratio that sets your output voltage, magnetizing inductance that governs switching behavior, the leakage inductance that drives voltage spikes and snubber losses, the saturation margin that keeps the core linear under peak current, and creepage, clearance, and insulation that determine whether the part meets your isolation rating.

A driver IC that performs perfectly well with one transformer can misbehave with another whose leakage inductance or saturation point differs, prompting engineers to spend significant time characterizing potential transformers, building prototypes, and validating the pairing across line and load before they trust it. Moreover, if you layer multi-vendor sourcing on top, where the IC comes from one supplier and the magnetics from another, the schedule and risk grows further. This is the dilemma RECOM is removing from your procurement by validating the IC and transformer combination.

A single-source, pre-validated approach

Rather than qualifying a driver against a transformer of unknown fit, you can choose a combination RECOM has already tested, which reduces compatibility risk, simplifies the bill of materials (BOM), and shortens the validation cycle.

The main reason designing your own isolated stage is challenging comes down to the transformer. It is the central element of the converter, and getting it right means reconciling a list of interacting parameters.

RECOM's IC and solutions program is highly flexible. You can purchase an IC or a transformer individually, a pre-matched IC and transformer set, or a fully customized discrete solution for higher-volume production beyond 50,000 units. This allows a prototype or a mature, cost-optimized product to draw from the same familiar building blocks, enabling a design to scale from the bench to the production line without redesign.

The driver and rectifier ICs

RECOM's portfolio is organized around two series of power ICs, split between primary-side transformer drivers and secondary-side rectifiers. On the primary side, the RVP series provides unregulated transformer drivers for push-pull and full-bridge topologies, contained in compact packages with integrated timing and overcurrent-monitoring for a low-component-count design, making them suitable for cost-sensitive open-loop isolated converters. Also on the primary side, the RVPW series handles flyback topologies and is available with an integrated switch or with a gate-drive output for an external MOSFET. They provide a versatile feedback arrangement with three selectable modes: primary-side regulation that monitors the primary waveform and avoids an optocoupler altogether, secondary-side regulation utilizing optocoupler feedback to maintain isolation, and direct DC monitoring for non-isolated use.

Primary side regulation is worth dwelling on, since the optocoupler is a common reliability and accuracy weak point in isolated supplies; its current transfer ratio drifts with temperature and ages over the life of the product, so regulating on the primary side removes a troublesome component.

On the secondary side, the RVS series provides synchronous rectification in three variants. The RVS variant offers basic rectification through a fully integrated full-bridge rectifier in a compact package; the RVSY variant is a high-performance synchronous rectification controller that drives an external MOSFET on either the high side or the low side; and the RVSW variant adds bi-directional control and switching for battery cell charging and discharging, as embodied by the RVSW013 (Figure 2). Synchronous rectification replaces the forward voltage drop of a diode with the low on-resistance of a MOSFET, which allows these stages to recover efficiency that would otherwise be lost as heat in the output rectifier.

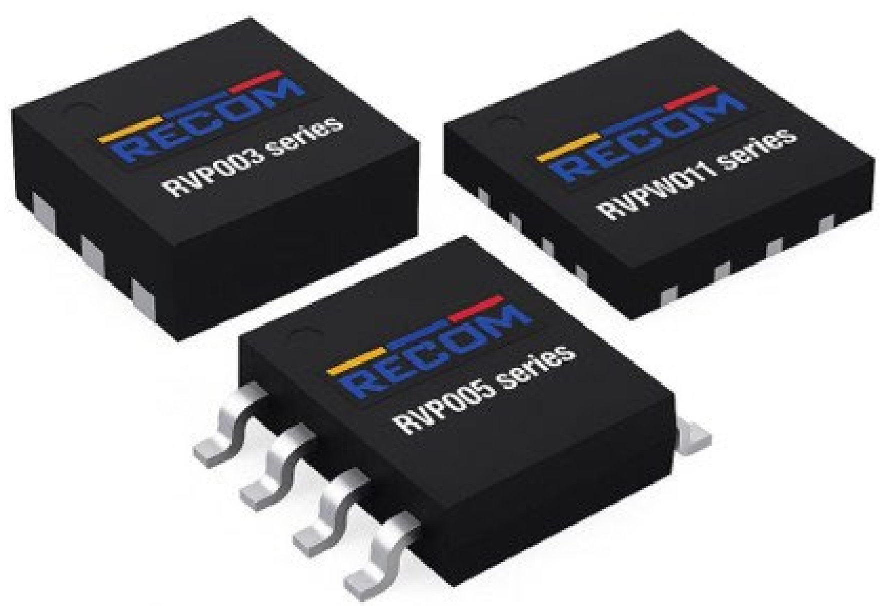


Figure 1: The RVP and RVPW series. Image source: RECOM

Matched SMD transformers

Because transformer choice is so critical, RECOM supplies a standard range of sub-miniature SMD transformers chosen to match these drivers. The RMR family covers sub-miniature 1 W and 2 W toroidal parts for push-pull and full-bridge drivers, with isolation ratings from 1.5 kVDC up to 4.5 kVDC, while the RMR-018, RMR-028, and RMR-031 raise that to an enhanced 5 kVAC rating with wider creepage and clearance for designs that need more separation. For flyback designs, the RBE family offers bobbin-type transformers from 6 W to 30 W matched to the RVPW drivers, with isolation withstand starting at 1.5 kVDC. For applications that require even greater separation, RECOM's RPE-021 extends isolation up to 4.3 kVAC.

Across the range, the transformers support flyback, push-pull, and full-bridge drivers spanning 1 W to 30 W with isolation withstand up to 5000 VAC. They can tolerate a reflow peak up to 250°C for as long as ten seconds and survive two reflow passes. Where a standard part will not suffice, RECOM offers custom transformers subject to a minimum order quantity.

Figure 2: The RVSW013 series. Image source: RECOM

Matching the Solution to the Power Level

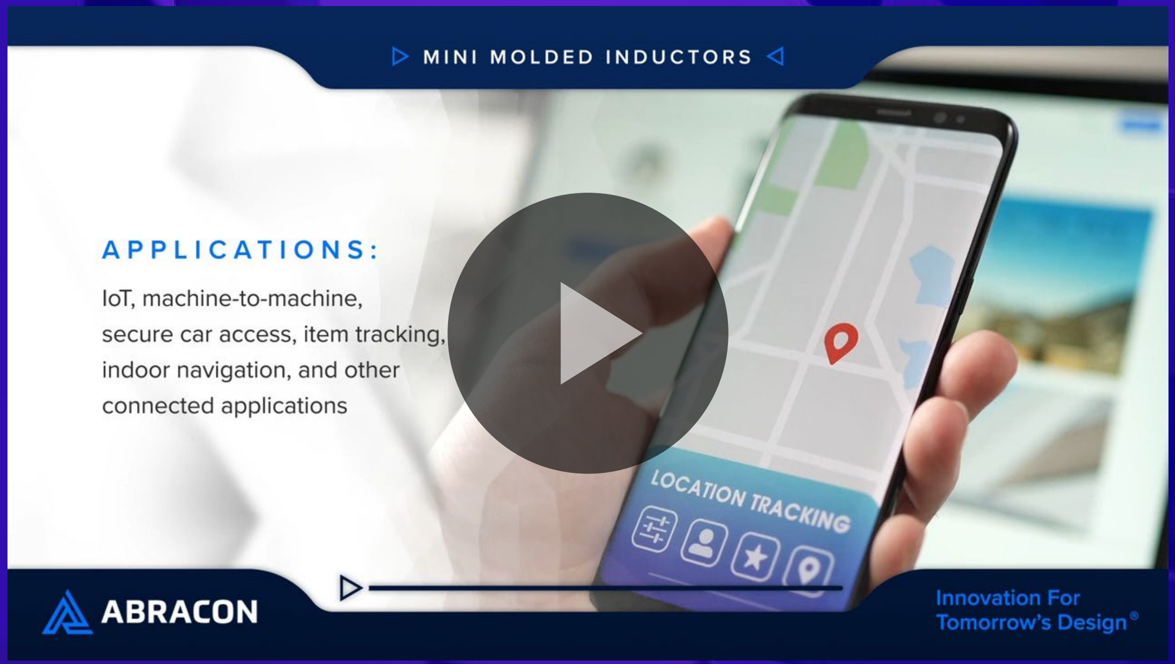
It helps to keep the power tiers straight when you specify a design. An RVP primary-side driver combined with an RVS synchronous rectifier supports isolated DC/DC conversion up to roughly 10 W, which suits compact point-of-load and auxiliary rails, while the broader range built around the RVPW flyback drivers and RBE transformers extends to 30 W for high-power needs. These ICs support isolation grades from functional up to reinforced, so the same building-block design philosophy serves basic functional barriers as well as stricter separation that safety-critical equipment requires. These ICs suit a wide range of applications, from industrial, factory, and building automation to power generation, energy distribution, test/measurement, and telecom infrastructure, all environments where compact, scalable, isolated conversion is in demand.

Conclusion

Discrete power supply design no longer requires assembling and validating an isolated stage entirely on your own. By pairing characterized power ICs with matched transformers, and by offering them individually, as sets, or as custom assemblies, RECOM lets you choose the level of integration that fits your project and your production volume.

For additional information on RECOM's current power ICs, transformer families, and related discrete solutions, please visit RECOM's Discrete Power Solutions product highlight

Video spotlight



ABRACON

Mini Molded Inductors

Abracon's Mini Molded Inductors deliver high power density and superior EMI suppression in ultra-compact, low-profile packages. Built with metal alloy powder cores and shielded molded construction, they offer low DCR, high saturation current, and excellent thermal performance, ideal for space-constrained power designs in industrial, automotive, and portable electronics.

Learn more

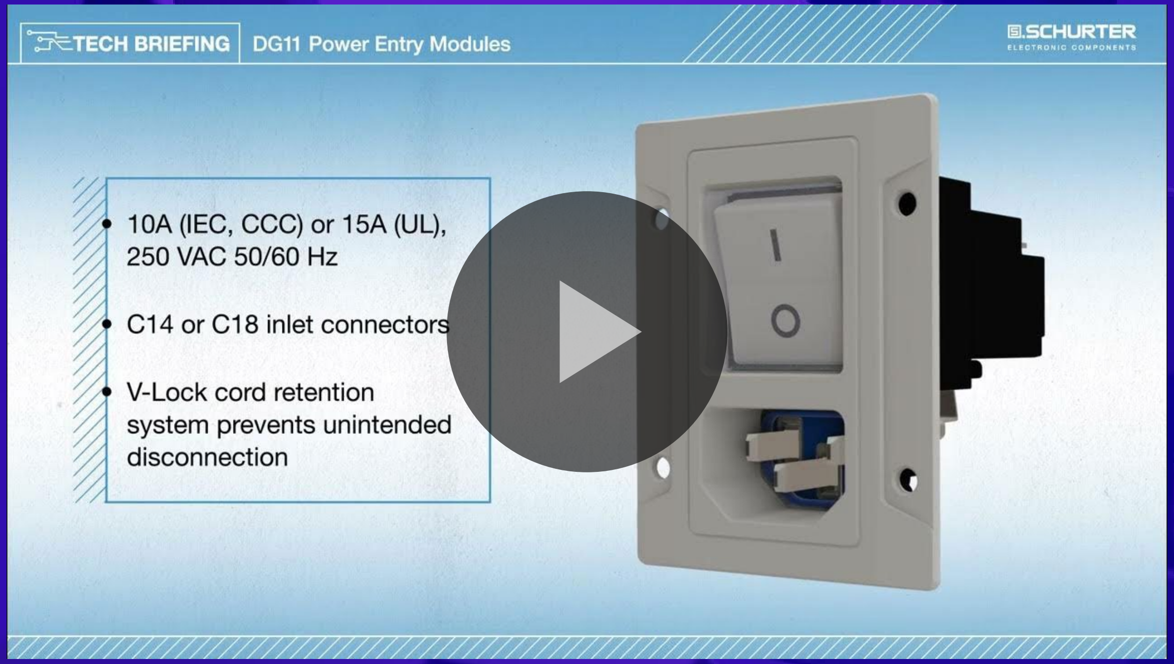
RENESAS

TP65B110HRU High-Voltage GaN Bidirectional Switch

The TP65B110HRU is a 650 V, 110 m? common-drain bidirectional switch built on the Renesas SuperGaN® Gen I platform. It conducts current and blocks voltage in both directions in a compact footprint with excellent switching performance. The device combines high-voltage GaN with normally off silicon MOSFETs for standard gate-drive compatibility, easy integration, and reliable operation.

Learn more

Video spotlight



SCHURTER ELECTRONIC COMPONENTS

SCHURTER's DG11 Power Entry Module

The SCHURTER DG11 power entry module now features an added magnetic release for faster short circuit protection. Combined with the integrated TA35 thermal circuit breaker, the DG11 helps improve response time to high overcurrents while maintaining reliable resettable protection for industrial and medical equipment.

Learn more

TDK·Lambda

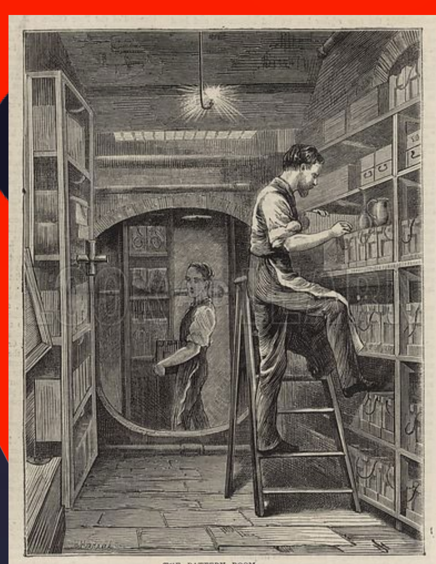
PFE1500FB Series AC/DC Power Modules

TDK Lambda's PFE1500FB delivers 1500W in a compact, 5 sided metal cased module for sealed, fanless, conduction cooled or liquid cooled systems. A wide 85 to 305 Vac input with 50/60/400 Hz operation, PMBus digital control, and up to 92% efficiency simplify power design in harsh industrial environments.

Learn more

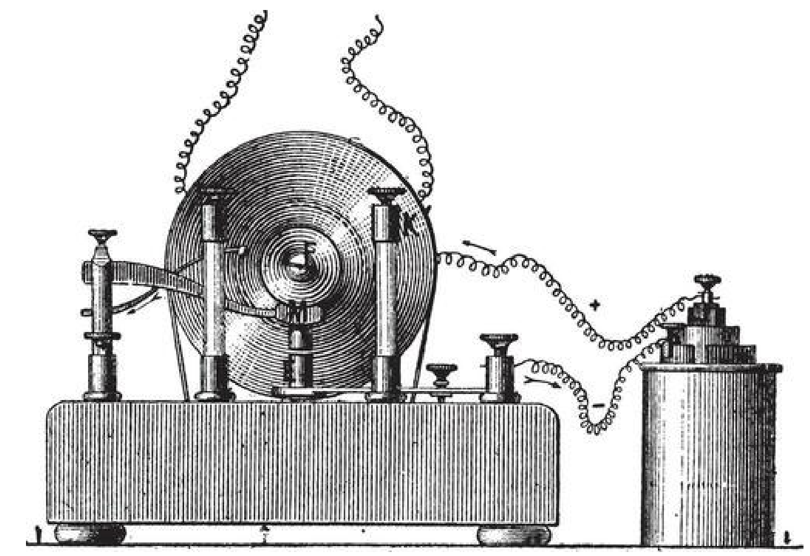
How the battery enabled the Victorian age

Written by David Ray, Cyber City Circuits



Sparks, shocks, lightning rods, and friction machines

The battery changed everything. Instead of a spark that appeared and vanished in a blink, experimenters finally had a source of current that could keep flowing long enough to be studied, measured, and put to work. From Volta's wet stack of metal discs came electrochemistry, electromagnetism, telegraphy, signaling, lighting, and the battery rooms that quietly powered the Victorian world.



An example of an early-1800s friction machine charging a Leyden jar

To understand why it mattered so much, you need to know what electricity looked like before the battery. If someone was able to build up a charge with a machine, it wouldn't last long, often lasting less than a second. Having no utility, it appeared suddenly, flashed dramatically, and vanished very quickly. It snapped from glass globes, leaped off charged rods, cracked through the air, occasionally injured the overconfident and, most importantly, stunned lecture audiences.

The tools of early electrical science looked nothing like the batteries and power supplies the reader is familiar with today. Experimenters used friction machines with large glass cylinders or globes, which were turned by hand while leather, silk, or other materials rubbed against them. With enough cranking, the machine built up a charge that could be drawn off with metal conductors.

The phenomenon was real, but it was difficult to control. A friction machine could produce a high voltage, but it required constant, vigorous mechanical effort.

The Leyden jar

In 1745, the Leyden jar gave experimenters something they had never really possessed before: a way to hold electricity for later use. Before then, the charge produced by an electrical machine was fleeting. It appeared, snapped, shocked, and disappeared. The Leyden jar changed that. Invented independently by both Ewald Georg von Kleist in Pomerania (modern-day Poland) in 1745 and Pieter van Musschenbroek in Leiden, Netherlands in early 1746, the Leyden Jar could store an electric charge like a standard capacitor, with dual conductors and a dielectric in the form of a glass jar.

The jar was filled with water, brine, or sometimes beer. Not at all understanding what he had made, Musschenbroek thought the electrical fluid, 'effluvia,' was being injected and stored within the water. Only later did they understand that the glass itself was the essential insulating layer and that the water didn't do very much of the work.

Charge could now be collected, combined with other jars, saved briefly, and released on demand. Benjamin Franklin quickly understood the value of arranging multiple jars together. By grouping Leyden jars, he could produce a stronger discharge, much like a

Benjamin Franklin's Leyden jar battery

group of cannons firing together. He called this arrangement an electrical 'battery,' borrowing the artillery term for a group of cannons.

Franklin used his battery of Leyden jars for many of his experiments, including some of his lightning experiments. Franklin's lightning experiments pushed the field even further. By arguing that lightning and laboratory electricity were the same phenomenon at different scales, he helped collapse the old distinction between artificial and natural electricity. The lightning rod was the practical result, but the scientific result was equally important.

Electricity now was a natural force that could be harnessed and studied, but the Leyden jar had a fundamental limitation. It could discharge electricity, but it could not supply it. It delivered a dramatic static burst, not a steady flow.

To eighteenth-century eyes, this was astonishing, but every tool available to electrical experimenters produced electricity in bursts. Friction machines had to be cranked, Leyden jars had to be charged and discharged, and lightning rods only worked during storms.

Luigi Galvani and the dancing frogs

The story of the battery cannot be told without Doctor Luigi Galvani. In the late eighteenth century, Galvani was a physician and professor at the University of Bologna (modern-day Italy). In a world where electricity lived somewhere between physics, medicine, religion, and philosophy.

Galvani gets credit for discovering electrophysiology, the science of how electricity interacts with biological tissue such as muscles, nerves, and the heart. Galvani found that Leyden jars could shock muscles into motion, and it did not matter if the test subject was alive or not. In fact, it did not matter if the limb was still attached to the rest of the body.

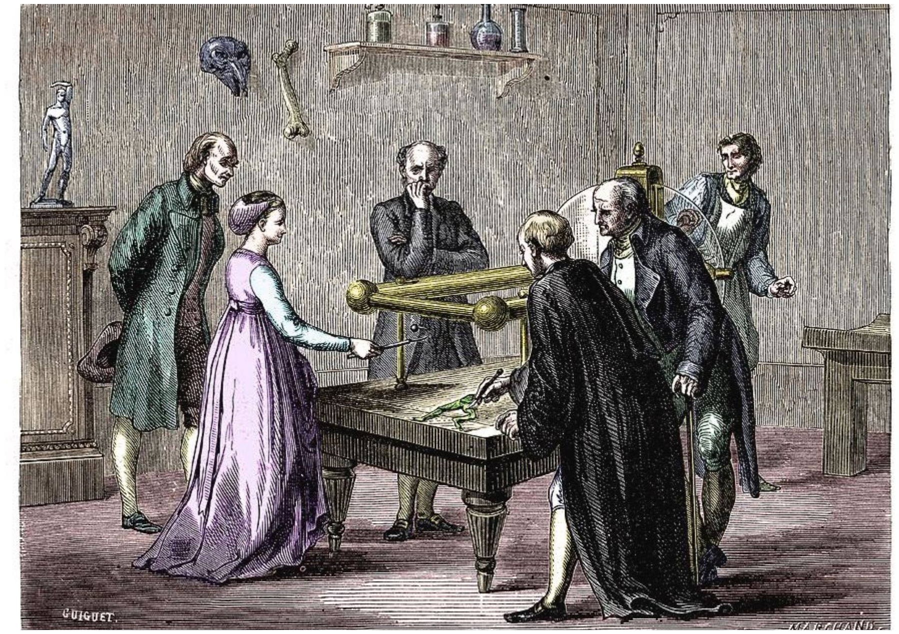
While studying dissected frogs around 1789, Galvani found that the frog's legs twitched when touched by metal instruments under certain 'electrical conditions.' By some accounts, the motion appeared, and a spark would pop nearby from a spark gap he had set up with his electrical machines and Leyden jars. He would build a charge, sometimes using friction machines and lightning rods, and as soon as enough voltage was collected, the current would jump the spark gap, thundering with a loud pop and a flash of light as Galvani made a dead animal move by candlelight as if some hidden force had briefly returned to its lifeless body.

Galvani concluded that animals have internal electricity produced by the brain and transmitted through nerves to muscles. The frog was not simply responding to electricity from outside the body. In Galvani's interpretation, the animal itself contained a newly discovered type of electricity.

Animal electricity

Artificial electricity was generated by a machine. Natural electricity was seen in lightning. Galvani felt he had discovered the phenomenon he named 'animal electricity,' a natural electrical force produced

A battery of Leyden jars



Galvani gave many public demonstrations of his frog leg experiments

Luigi Galvani at his lab bench, using frog legs as test equipment

within living tissue.

These experiments were revolutionary. He published his findings in 1791. Suddenly, there was a clear connection to how a body worked that nobody had seen before. The news traveled quickly, published in many scientific journals throughout central Europe and England. Many thought that Galvani could harness a soul or spirit. Galvani was sometimes accused of necromancy, which would have been a high crime in 18th-century Bologna. Could Galvani touch God? What if Galvani discovered vitality itself? Perhaps Galvani had found a way to interact with the Aether.

Electricity was already strange and interesting enough to tempt mad doctors. Physicians and traveling doctors started using electric shock as a treatment for all manner of complaints.

The world was fascinated.

Retro Electro fun fact:
In 1802, a traveling doctor in Saratoga, New York, wrote a detailed book on using electricity, or as he calls it, "ethereal fire," claiming to treat a range of ailments and diseases like madness, asthma, and dysentery, using primitive electroshock therapy. You can read all about that in the Retro Electro article "Electricity or Ethereal Fire Considered."

Some were sincere. Some were confidence men and snake oil salesmen. They were all working in a world where the boundaries between experiment and medical treatment were thin. Galvani and his frogs created a fundamental misunderstanding of electricity that an Italian natural philosopher and professor, Alessandro Volta, would spend several years trying to correct.

Volta did not deny that the frog legs moved. The motion was real. It existed. The question now was, where does the electricity actually come from? Galvani figured the frog's muscles were the source. While trying to reproduce Galvani's experiments, Volta found that the frog's legs only jumped when the tools to hold the frog in place were made of certain metals. To Volta, the frog was responding to the current produced by the contact

Portrait of Alessandro Volta

In a memorial in Bologna, Italy, is a life-size statue of Doctor Luigi Galvani, inventor of the first piece of benchtop test equipment

of different conductors. The animal tissue made the electrical effect visible, but the source was somewhere else. That's right. Galvani didn't discover 'animal electricity,' but he did invent the first pieces of electrical benchtop test equipment.

Luigi Galvani died in Bologna, Italy, on December 4, 1798, at the age of 61.

The artificial electric organ

If the frog only moved when certain metals were involved, then perhaps the animal could be removed from the experiment altogether. Instead of using nerves and muscles to manipulate some ethereal concept of vitality or spirit, he would reproduce similar effects using only different metals and liquids.

Historians all agree that he was correct in reckoning that the metals produced the electric effect in Galvani's experiments. He tested combinations such as zinc, copper, silver, tin, and iron, trying to determine which pairings produced the strongest effect. The effect he was trying to produce was later named the 'electromotive force.' The electromotive force is a fundamental phenomenon that, as an effect, generates the electric current that drives the modern age.

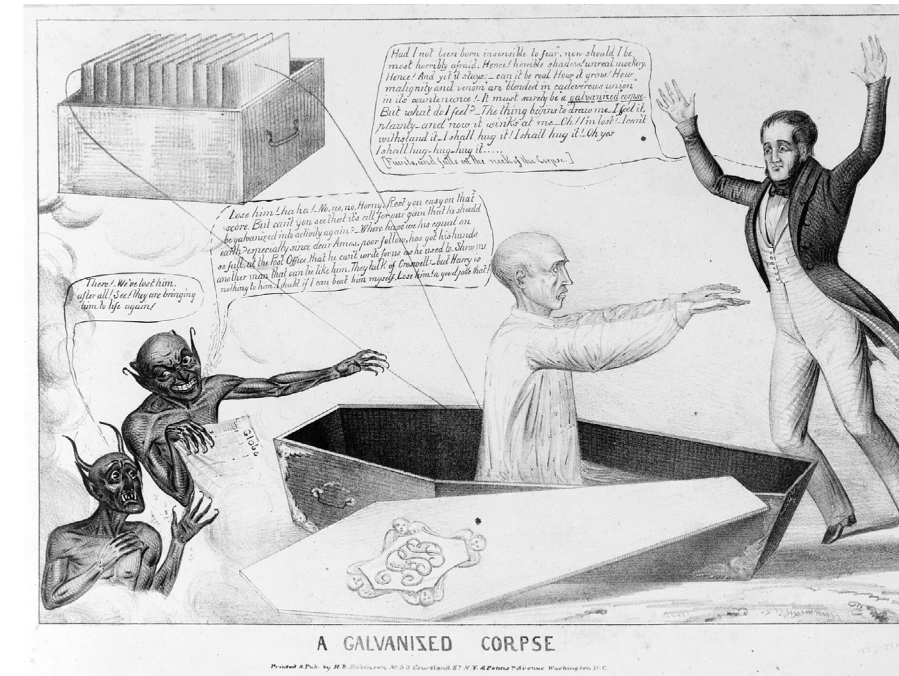
By early 1800, Volta had built a stack of alternating metal discs separated by pieces of cloth soaked in saltwater or another conducting liquid. The pile was disappointingly plain and ugly. Volta named it the 'artificial electric organ' as a contrast to the use of biological organs by followers of Galvanism. This new apparatus would later be renamed to the less dramatic Voltaic Pile. It had no spinning glass globe, no lightning storm, and no Leyden jar waiting to snap. **Volta had reduced Galvani's miraculous discovery of 'animal electricity' to a bubbling, smelly, and ugly *pile* of wet metal.**

DigiKey fun fact: DigiKey is a major distributor for most brands and types of test equipment. While you will not find frog legs in the catalog, you will find its descendants.

An example of an early Voltaic pile.

This did bruise more than a few egos. Galvani's nephew and strongest defender, Giovanni Aldini, would be the face of animal electricity in place of his uncle. While Galvani never wanted to get involved in any controversy between himself and Volta, after his death, Aldini was much more passionate and less reserved. Aldini publicly applied electricity to animal and human corpses, most famously the executed criminal George Forster in London in 1803.

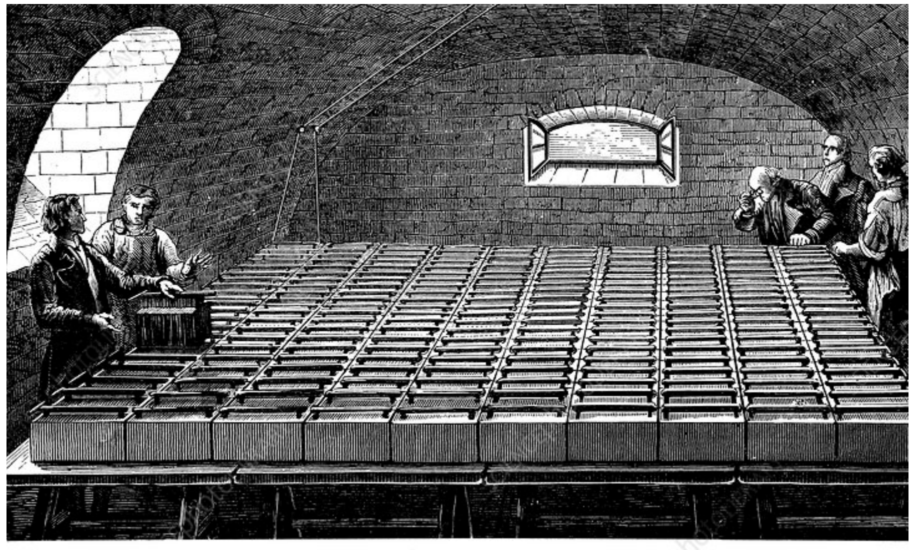
Until 1832, the bodies of executed murderers in London were taken to the College of Surgeons for dissection. According to a 1752 law, which was enacted to curb murder, these remains were among the few legally available for medical study, with dissection or gibbeting serving as additional forms of punishment after their execution. The dissections at the College were often public events, sometimes carried out in a theatrical, macabre manner. Afterward, the bodies were used for experiments or donated to leading surgeons elsewhere. During the infamous public experiments involving the murder of George Forster, witness accounts described the jaw quivering, an eye opening, limbs moving, and the body seeming almost alive. This sort of demonstration inspired the imagination of Mary Shelley, the



Aldini's macabre demonstrations were published in newspapers around the world

Natural philosopher Humphry Davy

Retro Electro fun fact: It was a British telegraph engineer named Latimer Clark who suggested immortalizing Volta by naming the unit 'volt' after him. This effort took many years, but in 1881, at the First International Electrical Congress in Paris, it was adopted by the world's brightest minds as the international unit for electromotive force. You can read the story of how Latimer Clark made this possible in the Retro Electro article "Ohm's Day."



Humphry Davy's cellar full of batteries

Retro Electro fun fact: At this time, French scientist André-Marie Ampère was in France, working as a young mathematics tutor and preparing the ideas that would soon become his 1802 publication, The Mathematical Theory of Games. Several years earlier, as a teenager, his father was guillotined by revolutionaries during the Reign of Terror. Read that story in the Retro Electro article ['Genius and Tragedy.']

author of *Frankenstein*.

In March 1800, Volta wrote to Sir Joseph Banks, president of the Royal Society of London, describing his new apparatus. The letter sent the pile into Europe's scientific bloodstream. A Leyden jar could store a charge but would only release it in a single dramatic burst. A friction machine could produce a charge, but only while someone was cranking it. A voltaic pile sat on the bench, producing a steady electric current long enough for experimenters to study electricity intimately for the first time.

Volta demonstrates the Voltaic pile to Napoleon Bonaparte

The first major follow-up discoveries happened quickly. In Britain, William Nicholson and Anthony Carlisle used the pile for electrolysis of water, separating hydrogen and oxygen. Humphry Davy was making larger and larger voltaic batteries to light brighter and brighter arc lights. Davy would continue to use batteries to help isolate the elements potassium, sodium, calcium, barium, and magnesium for the first time.

Concerning the term 'battery,' Benjamin Franklin had already used the word for a group of Leyden jars. In his writings, Volta compared the effects of his pile to a battery of Leyden jars because those were the most powerful electrical devices his readers would already understand. Soon, reports of the new 'galvanic apparatus' were using the same word, 'battery,' for the voltaic pile. This does not seem to have really bothered Volta.

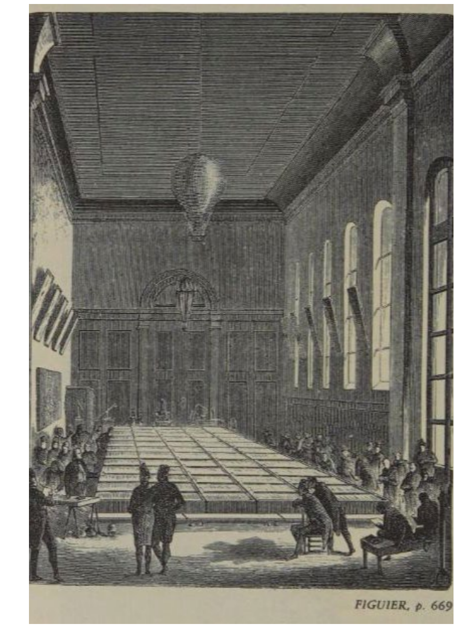
Napoleon Bonaparte: the unlikely champion of electricity

In 1801, Volta demonstrated the pile in Paris before the French scientific establishment, gaining the attention of Napoleon Bonaparte, then First Consul of France. Napoleon praised Volta publicly and awarded him money and honors.

The country was still rebuilding after the bloody French Revolution. France had spent the previous decade tearing itself apart, reorganizing its government, executing its royalty, surviving the Reign of Terror, and watching the old institutions of monarchy, church, and aristocracy collapse, slowly becoming the First French Empire. By the time Volta arrived in Paris, the Revolution was officially over, but the country was not at rest. Napoleon was busy turning France into a disciplined machine. His government focused on improving every aspect of French capabilities, like the military, education, industry, and science.

After becoming Emperor in 1804, Napoleon recognized that France's power depended on more than armies. The First French Empire's strength depended on institutions that could absorb discovery, reward useful minds, and turn new knowledge into national strength. Napoleon knew Volta's pile was more than a clever academic toy or an amusing demonstration, and he made Paris the grand stage for the voltaic pile.

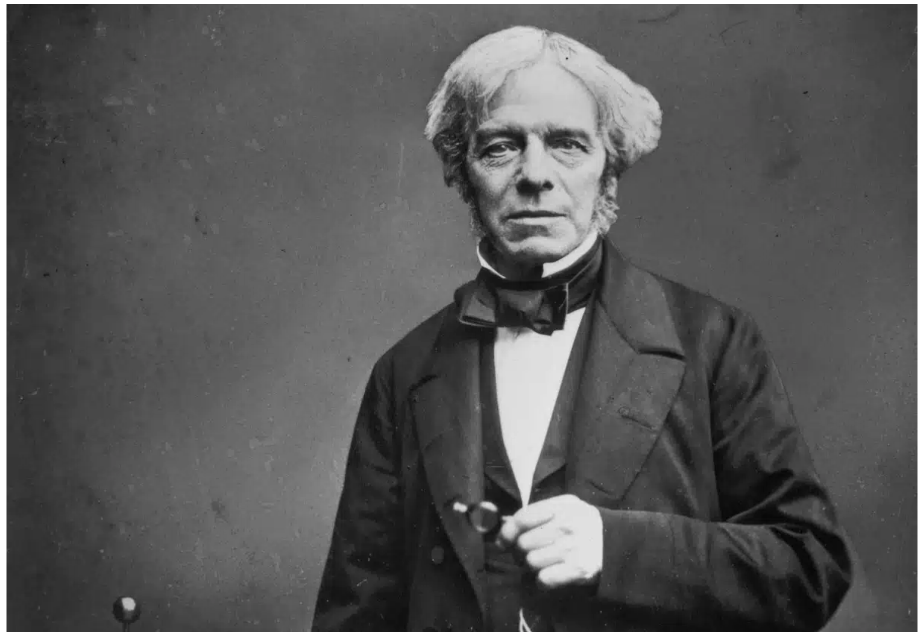
Napoleon publicly honored Volta,



In 1813, Napoleon Bonaparte ordered the largest battery that had ever been made at that time

and that mattered. In an age when scientific work still depended heavily on patrons, academies, prizes, appointments, and public reputation, state attention could change the fate of anybody. Volta's

Retro Electro fun fact: While Europe was erupting with new electrical discoveries, it was an American, Joseph Henry, who invented an insulated wire needed for the first high-power electromagnets. You can read that story in the Retro Electro article ["How Joseph Henry Made Electricity Work at a Distance: The Story of the First Electrical Relay."]



Michael Faraday

demonstrations placed the battery in front of the French scientific establishment at exactly the right moment. The pile had already reached Britain through Volta's letter to Sir Joseph Banks, and British experimenters were already using it to study chemistry.

The Institut de France and the École Polytechnique in Paris gave the pile a lot of regional attention. In 1813, under Napoleon's directive, the École Polytechnique constructed the largest voltaic battery in the world. Joseph Louis Gay-Lussac and Louis Jacques Thénard used the large batteries in their state-supported laboratory to advance electrochemical research, studying substances under conditions that earlier experimenters couldn't imagine.

Napoleon is not usually remembered as a grand benefactor of electrical science, yet history does owe him this credit.

The voltaic pile becomes a discovery engine

Once experimenters had a steady current, they could do something that had been impossible with friction machines and Leyden jars. They could keep electricity flowing long enough to watch what it did. They could run it through water, salts, acids, metals, wires, coils, nerves, muscles, and instruments. The pile made electricity more of a tool.

Retro Electro fun fact: Following Ørsted's repeatable experiment that moves a compass needle with an electric current, the news traveled through Europe very quickly. This is the moment that forever shifted civilization to the modern age. In the Retro Electro article "Experiments on the Effect of a Current of Electricity on the Magnetic Needle," the writer traces the specific path the news took through Europe and its effects along the way.

In 1820, while using a voltaic pile, Hans Christian Ørsted found that an electric current could move a compass needle. That sounds simple today, but it was one of the greatest milestone moments in the history of civilization.

The spread of the discovery is almost as important as the discovery itself.

In Bavaria, Johann Schweigger read Ørsted's report and immediately realized that the effect could be made stronger. If one current-carrying wire could move a compass needle, then many turns of a coil might multiply the effect. By coiling wire around a frame and placing a compass needle inside, Schweigger created the multiplier galvanometer, moving a needle instead of frog legs.

Portrait of Queen Victoria

Retro Electro fun fact: Read the story of how one man's arrogance may have destroyed the Victorian Age's first million-dollar project, the First Atlantic Cable, in the Retro Electro article "Wildman Whitehouse and the Twenty-Five-Hundred-Mile-Long Capacitor."

In France, François Arago carried Ørsted's discovery back to Paris and demonstrated it before the scientific community. Among the people watching was André-Marie Ampère. Ampère saw the moving compass needle and understood that the problem was not merely experimental. It needed mathematics. Within weeks, he began building the foundations of electrodynamics.

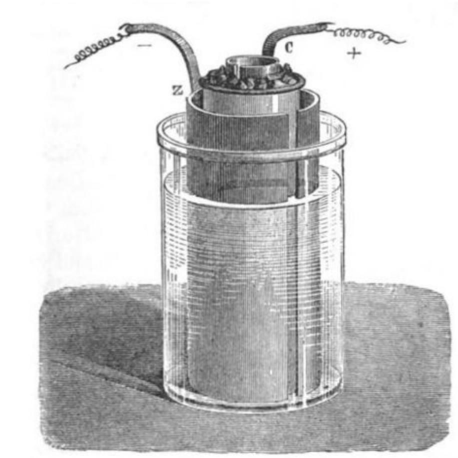
Again, in Bavaria, Georg Ohm used improved galvanometers and voltaic piles to pull the mathematics out of his experiments. His work eventually produced the mathematical relationship between voltage, current, and resistance. Once electricity could be measured, it could be engineered.

Then came Faraday.

In Britain, Michael Faraday, Davy's protégé, pushed the experiment in the opposite direction. Ørsted had shown that current could produce magnetism, and Faraday found that a changing magnetic field could produce current. In 1831, his work on electromagnetic induction pointed directly to the discovery that batteries could generate current, that current could generate magnetism, and, most importantly, that magnetism could generate current once again.

Queen Victoria and the Victorian age

Queen Victoria reigned as Queen of the United Kingdom from 1837 to 1901, a period so long and so transformative that it still carries her name, ***the Victorian Age***.



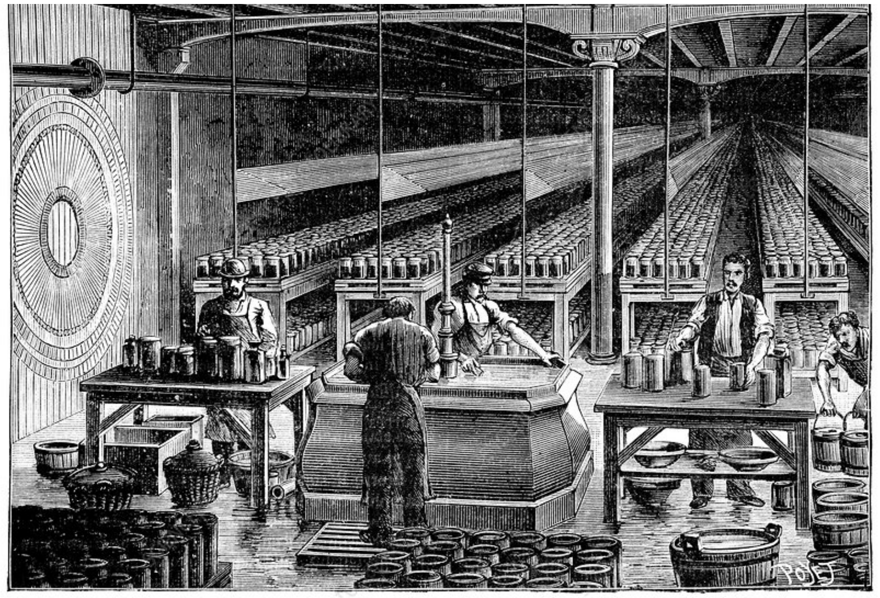
Daniell cells made batteries more reliable and mass producible

During those sixty-four years, Britain moved from the age of stagecoaches and candles to railways, telegraphs, telephones, electric lighting, submarine cables, and the second industrial revolution.

Early in the Nineteenth Century, nearly all groundbreaking innovations in electromagnetism came from France, Denmark, Italy, etc, but during the Victorian Age, history sees the rise of great British minds like Charles Bright, Lord Kelvin, John Daniell, Oliver Heaviside, Michael Faraday, and many others, including several prominent American and Canadian inventors, like Joseph Henry, Samuel Morse, Edison, and Elisha Gray.

A room full of jars of acid

For much of the Victorian electrical age, a "battery" was not a neat



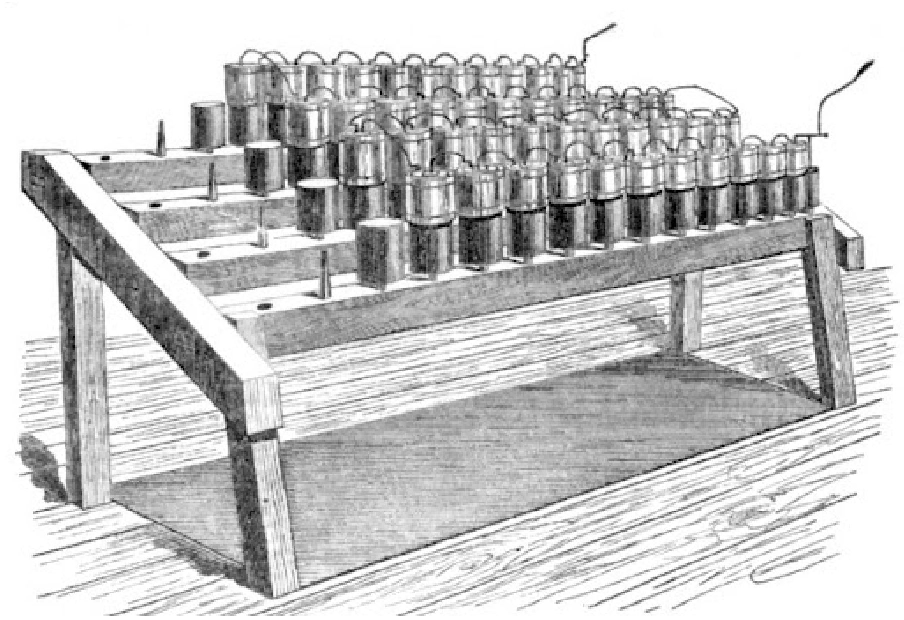
Larger telegraph systems required warehouses of battery cells that needed constant maintenance

cylinder or rectangular pack like what you'll find in a retail environment. It was often a room, rack, cabinet, or cellar full of wet cells. Glass jars, zinc plates, copper plates, carbon rods, porous pots, acids, salts, fumes, corrosion, and sweat.

Imagine the smell.

The modern battery disappears into a device. A phone battery hides behind a glass screen. A lithium pack disappears under the floor of an electric vehicle. A coin cell vanishes inside a remote control or sensor node. Victorian batteries could not vanish. They were big. They demanded attention. They were infrastructure that had to be constantly fed, cleaned, inspected, and replaced to keep telegraph systems running.

By the middle of the nineteenth century, electrical work had outgrown Volta's original pile. The pile was brilliant as a proof of concept, but it was not a practical industrial supply. Its wet separators dried out. The weight of the stack squeezed the electrolyte from the cloth. The voltage sagged. Chemical byproducts accumulated. The whole thing was unstable, dirty, and inconvenient. Engineers needed cells that could work longer, more predictably, and with less constant attention.



The Daniell cell, introduced in the 1830s, was built within a jar. Instead of a simple pile of wet metal, it used copper and zinc in separate sections, divided by a porous barrier. It produced a steadier and dependable current, hour after hour, day after day, which is very important for telegraphy.

A Victorian battery room was a chemical workspace attached

to the telegraph system. Jars had to be filled. Zinc had to be replaced. Copper deposits had to be managed. Acid spills had to be cleaned. Floors and shelves suffered under its massive weight. The people maintaining these systems were not just "using batteries." They were tending a chemical machine.

Telegraph offices, railway stations, cable stations, laboratories, workshops, and private installations all depended on cells that had to be consistently managed and maintained. This is the part of the early electrical infrastructure that doesn't get much attention.

The battery room made electricity dependable enough for telegraph operators and railway signalmen. The United Kingdom ran telegraph

DigiKey fun fact:
DigiKey offers an array of batteries and accessories, from alkaline cells to the latest lithium-polymer rechargeables. Please review the 'Battery Products' section of the DigiKey catalog next time you need quality name-brand batteries.

lines all over the world. Being connected to India, Ireland, the United States, Canada, and likely anywhere else they would want to send a message allowed the British Empire to grow throughout the world in a way no other empire could.

What if France had wired the world?
Napoleon treated the battery as a symbol of scientific power, but Britain inherited the age in which batteries became useful to an empire. It is tempting to wonder what might have happened if France had remained politically stable enough to turn its early scientific momentum into a global electrical network. Had French institutions, engineers, and industry dominated telegraphy the way Britain eventually did, the map of power in the nineteenth and twentieth centuries might have looked very different.

Under Napoleon, the battery was a scientific marvel worthy of an emperor.

Under Victoria, the battery became one of the quiet machines stitching an empire together. So many civilization-changing inventions emerged from the British Victorian Age. Electric railways, underwater cabling, arc lighting, the mirrored galvanometer, along with almost all modern electrical standards.

Suggested reading

- "Battery History: the Origin of the Name" by Kathy Loves Physics
- Memorials to Luigi Galvani on FindAGrave
- "Luigi Galvani" by The University of Bologna
- "Galvanising George Foster (Forster), 1803" by Helen MacDonald
- "March 20, 1800: Volta describes the Electric Battery" by the American Physical Society
- "The bicentennial of the Voltaic battery (1800–2000): the artificial electric organ" by Marco Piccolino
- "Experiments and Observations Relative to the Influence Lately Discovered by M. Galvani and Commonly Called Animal Electricity" by Richard Fowler

1746
Pieter van Musschenbroek demonstrates the Leyden jar at Leiden, helping spread one of the first widely useful electrical storage devices through European science.

1740s-1750s
Benjamin Franklin groups Leyden jars together and calls the arrangement an electrical "battery," borrowing the artillery term for a group of cannons.

1752
Franklin's lightning experiments help show that lightning and laboratory electricity are the same phenomenon at different scales.

1780s
Luigi Galvani studies frog preparations and observes that dissected frog legs twitch under certain electrical conditions.

1791
Galvani publishes his work on animal electricity, arguing that living tissue contains its own electrical force produced by the brain and carried through nerves to muscles.

1790s
Alessandro Volta challenges Galvani's interpretation, arguing that the frog is not the source of the electricity but a sensitive detector responding to current produced by different metals.

1798
Luigi Galvani dies in Bologna, leaving his nephew Giovanni Aldini to become one of the most visible defenders of animal electricity.

March 1800
Volta writes to Sir Joseph Banks, president of the Royal Society of London, describing his new apparatus and sending the pile into Europe's scientific circles.

1800
Volta announces the voltaic pile, a stack of alternating metals and wet separators that produces a steady electric current.

1801
Volta demonstrates the pile in Paris before the French scientific establishment and gains the attention of Napoleon Bonaparte, then First Consul of France.

1804
Napoleon becomes Emperor of the French, continuing to attach political prestige to science, technical education, and state-backed research.

1813
Under Napoleon's directive, the École Polytechnique constructs one of the largest voltaic batteries in the world, giving French researchers a state-backed electrical laboratory instrument.

1820
Hans Christian Ørsted discovers that an electric current can deflect a compass needle, revealing the direct connection between electricity and magnetism.

1836
John Daniell introduces the Daniell cell, a more stable wet cell that becomes especially important for telegraphy.

1837
Queen Victoria begins her reign over the United Kingdom, marking the beginning of the Victorian Age.

1881
At the First International Electrical Congress in Paris, the volt is adopted as the international unit of electromotive force, honoring Volta's contribution to electrical science.

1901
Queen Victoria dies after a reign that saw electricity move from laboratory curiosity to telegraphy, railways, lighting, standards, and industrial infrastructure.

Configuring four-switch buck-boost μModule regulators for versatile applications: step-up, step-down, or inverting output

Written by:
Ling Jiang, Senior Manager; Wesley Ballar, Senior Engineer;
Anjan Panigrahy, Product Applications Engineer;
Henry Zhang, ADI Fellow

ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Many power conversion applications need to support wide input or output voltage ranges. Analog Devices has introduced the LTM4712, a high current, high efficiency, fully integrated four-switch buck-boost power module for such applications. It integrates the controller, MOSFETs, power inductor, and capacitors within an advanced 3D package, enabling compact design and robust performance. This μModule regulator delivers high power density, exceptional efficiency, and excellent thermal performance across a wide range of input and output voltages.

This article further highlights its versatility, and demonstrates its ability to operate in various topologies, including buck (step-down), boost (step-up), and inverting buck-boost configurations for negative output applications.

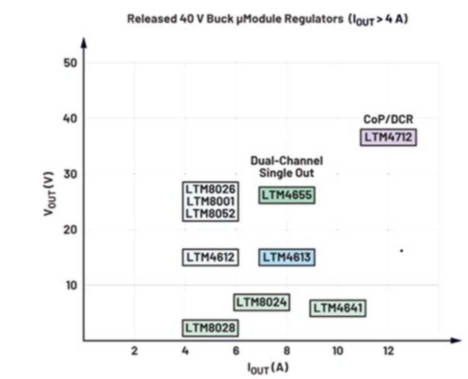
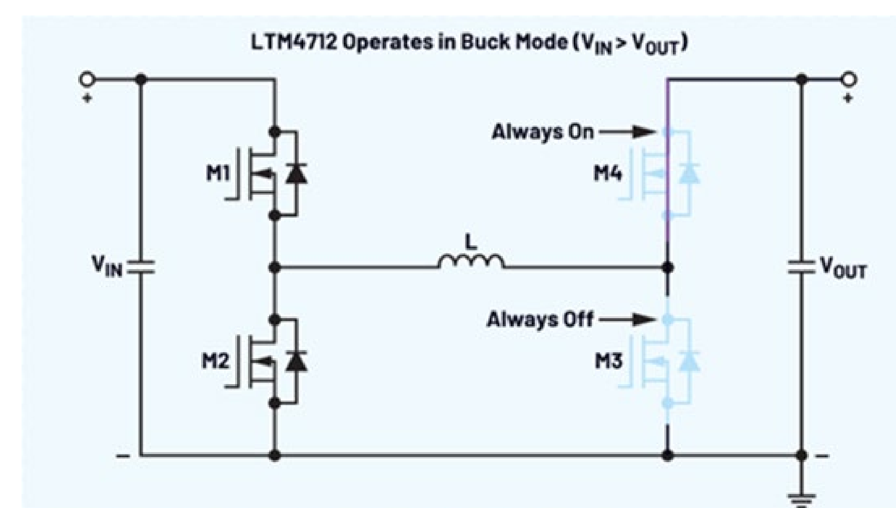


Figure 1. 40 V_{IN} (>4 A) buck μModule regulators. Image source: ADI

Utilizing the four-switch buck-boost topology as a buck (step-down) regulator

ADI has introduced multiple 40 V step-down μModule regulators. Figure 1 highlights the available regulators capable of supporting a maximum load current exceeding 4 A. However, these buck regulators are limited in their voltage and current range. By employing the LTM4712 as a step-down converter,

Figure 2. Utilizing the LTM4712 as a buck regulator. Image source: ADI



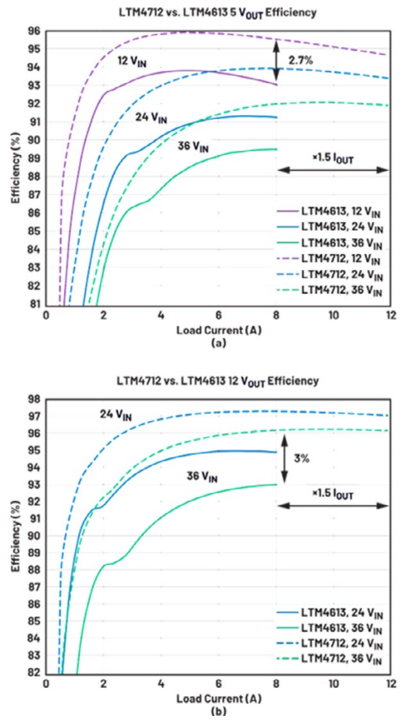


Figure 3. Buck mode efficiency and current capability comparison between the LTM4613 and the LTM4712: (a) 5 V_{OUT} efficiency and (b) 12 V_{OUT} efficiency. Image source: ADI

the operating range can be significantly extended, simplifying system design for customers.

The four-switch buck-boost converter can be effortlessly

Table 1. Buck Mode Thermal Performance Comparison, TA = 25°C, No Forced Cooling

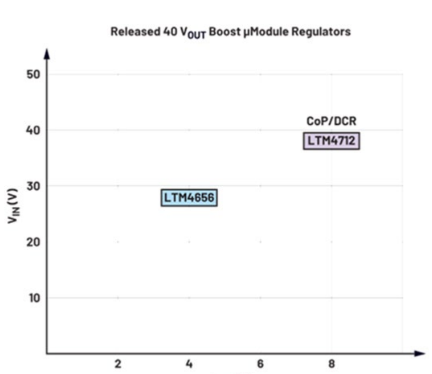
Operating Condition	Parameters	LTM4712	LTM4613
12 V_{IN}/5 V_{OUT}	Max I_{OUT}	12 A	8 A
	Efficiency at I_{MAX}	94.7%	93%
	Thermal at I_{MAX}	58°C	70°C
36 V_{IN}/12 V_{OUT}	Max I_{OUT}	12 A	6 A
	Efficiency at I_{MAX}	96.2%	93%
	Thermal at I_{MAX}	80°C	101°C

configured as a buck converter without requiring any special adjustments. When $V_{IN} > V_{OUT}$, the internal controller keeps power FET M3 off and M4 continuously on. M1 and M2 regulate the output, operating like a standard buck converter, as illustrated in Figure 2.

Compared to the previous step-down regulator, the LTM4613, the LTM4712 achieves superior power efficiency, despite the additional conduction loss introduced by M4, as shown in Figure 3. This improvement is made possible by advancements in MOSFET and inductor technologies.

The thermal comparison without forced cooling, shown in Table 1, underscores the efficiency advantage of the buck-boost converter. Despite delivering significantly higher power than the buck regulator, the LTM4712 operates at a cooler temperature with a similar footprint area.

Figure 4. The ADI 40 V boost regulator families. Image source: ADI



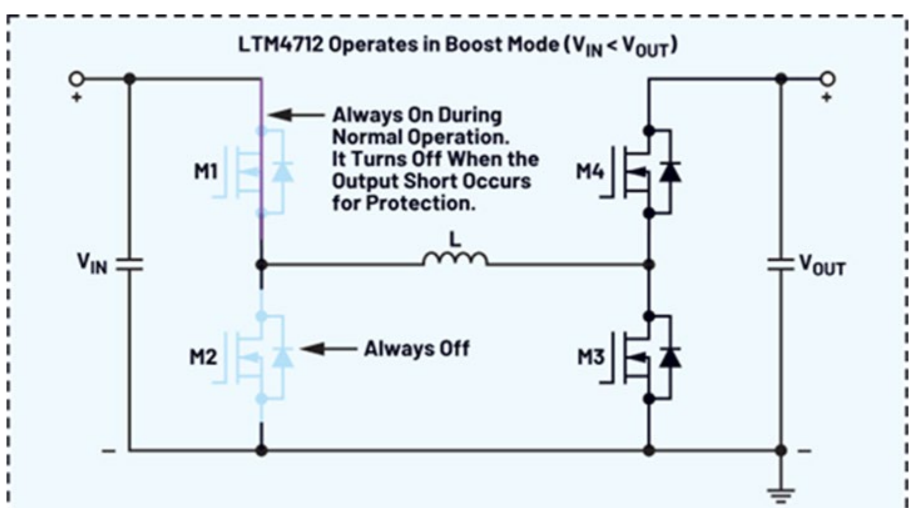
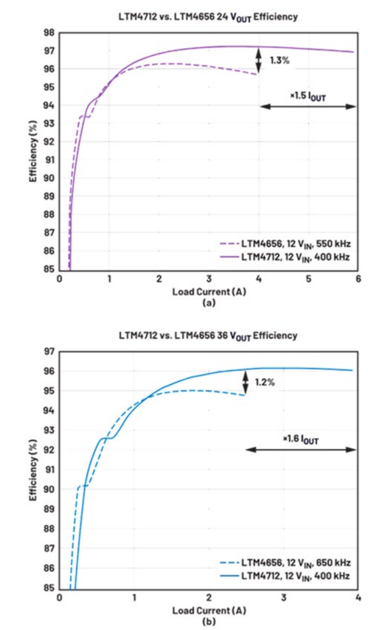


Figure 5. Utilizing the LTM4712 as a boost regulator with inherent output short protection. Image source: ADI

Figure 6. Boost mode efficiency and current capability comparison between the LTM4712 and the LTM4656: (a) 24 V_{OUT} efficiency and (b) 36 V_{OUT} efficiency. Image source: ADI



Utilizing the four-switch buck-boost as a boost (step-up) regulator

As shown in Figure 4, ADI has previously released one 40 V boost μModule regulator. While the LTM4656 supports a maximum current of 4 A, the newly released four-switch buck-boost converter can handle a higher load current when it functions as a step-up regulator.

When using the four-switch buck-boost converter in applications where VIN < VOUT, internal switch M1 remains on, while M2 stays off. M3 and M4 naturally regulate the output as a typical boost converter, as shown in Figure 5. Unlike standard boost converters, which lack output short-circuit protection, the four-switch buck-boost offers inherent short-circuit protection. If the output is shorted to ground, M1 and M2 begin switching as a buck converter, limiting the current flowing from input to output. The maximum short circuit current is restricted by either the RSENSE resistor placed in the input or output paths, or the peak inductor current limit, whichever is lower. In addition, during the initial fast VIN ramping up stage, a conventional boost converter usually has uncontrolled, high inrush current through the boost diode to charge up COUT. As the four-switch buck-boost always starts in buck mode when VOUT is low, its input inrush current is tightly controlled and limited by the soft start of the inductor current. In summary, the four-switch buck-boost offers a more reliable step-up converter than a conventional boost regulator.

Table 2. Boost Mode Thermal Performance Comparison, TA = 25°C, No Forced Cooling

Operating Condition	Parameters	LTM4712	LTM4656
12 V_{IN}/24 V_{OUT}	Max I_{OUT}	6 A	4 A
	Efficiency at I_{MAX}	96.9%	95.7%
	Thermal at I_{MAX}	69°C	81°C
12 V_{IN}/36 V_{OUT}	Max I_{OUT}	4 A	2.5 A
	Efficiency at I_{MAX}	96.1%	94.8%
	Thermal at I_{MAX}	84°C	89°C

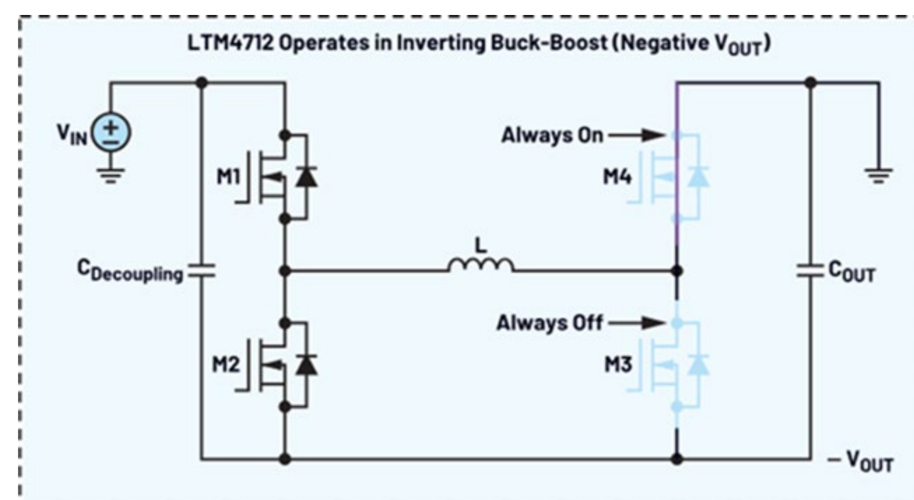


Figure 7. The LTM4712 configured as an inverting buck-boost regulator. Image source: ADI

Figure 6 and Table 2 compare the efficiency, power capability, and

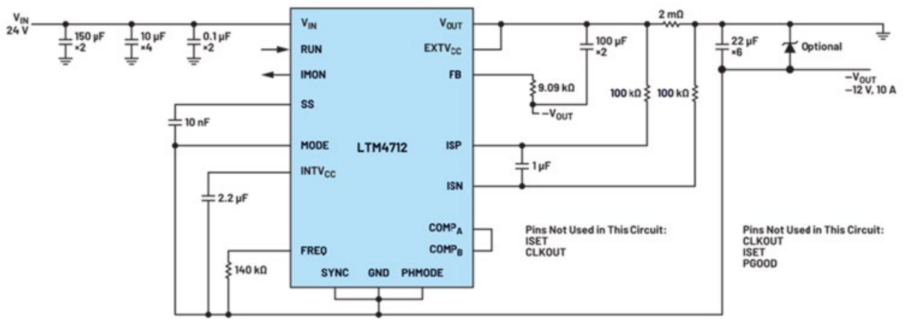


Figure 8. Example circuit of an inverting configuration. Image source: ADI

thermal performance between the four-switch buck-boost μModule regulator and the boost μModule regulator. The first device demonstrates superior efficiency, extended current handling, and significantly better thermal performance. Both regulators share the same 16 x 16 mm footprint.

Utilizing the four-switch buck-boost as an inverting buck-boost regulator for negative output voltage

Similar to standard buck converters, the four-switch buck-boost can also be configured in an inverting buck-boost topology for negative output applications. As shown in Figure 7, M1 and M2 switch complementary, with M3 off and M4 on during this operation. Note that the maximum voltage, $V_{MAX} = |V_{IN}|+|V_{OUT}|$, must be less than 40 V, which is the maximum voltage rating for the device. The magnitude of the DC through the inductor, I_L, is given by $I_L = I_{OUT}/(1-D)$, where D is the duty cycle of the phase leg with M1 and M2, and M1 is the primary switch.

Figure 8 illustrates an example circuit of the inverting configuration, designed for a 24 V input and –12 V output, capable of delivering up to 10 A of load current. Figure 9 presents the efficiency curves obtained from bench testing.

In the inverting buck-boost converter, the output voltage may rise slightly above zero during startup. This same behavior is observed when configuring the four-switch buck-boost regulator in inverting mode.

Figure 10 illustrates the mechanism behind the reversal of the output voltage during startup. When the input supply is turned on, but before all four MOSFETs begin switching, the input current starts charging the output capacitor in reverse through two paths: via the C_{IN} decoupling capacitor placed across M1 and M2, and through the INTVCC capacitor path. If C_{IN} or C_{INTVcc} are significantly larger than C_{OUT}, a higher reverse output voltage is likely to occur.

However, an inherent clamping circuit is present inside the μModule regulator, as shown in Figure 11. V_{SD3} and V_{SD4} represent the source-to-drain voltages of M3 and M4, respectively. When $-V_{OUT} > V_{SD3} + V_{SD4}$, the body diodes of M3 and M4 conduct, taking over the charging current. These two body diodes create a natural clamping circuit. In other words, the maximum reverse output voltage is VSD3 + VSD4.

Figure 12 displays the bench-tested reversed output voltage waveforms during startup. In Figure 12a, the magnitude of reversed -VOUT is approximately +0.75V, with a limited C_{IN} (50 μF) presented in the circuit compared to C_{OUT} (330 μF). When increasing C_{IN} to 350 μF, a higher reserved $-V_{OUT}$ of +1.5 V is observed, as shown in Figure 12b.

The ratio of C_{IN} to C_{OUT} can be adjusted to minimize the positive output voltage. A smaller ratio results in a lower positive output voltage before reaching the internal clamping voltage, V_{SD3} + V_{SD4}. Additionally, an external low forward drop clamping Schottky diode can be added at the output to limit the positive voltage to a desired level, as previously shown in Figure 8.

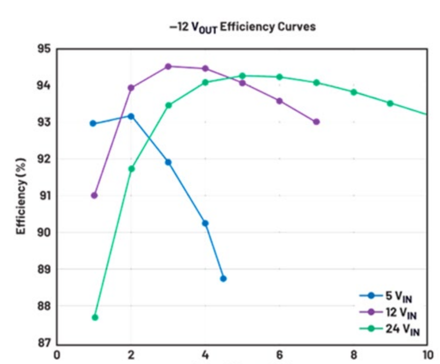


Figure 9. Bench tested efficiency curves for -12 V_{OUT}. Image source: ADI

Conclusion

The LTM4712 four-switch buck-boost regulator can naturally be used as either a step-down or step-up regulator without requiring any special configurations. Bench testing has verified that this μModule delivers the highest efficiency, best thermal performance, and extended current capability compared to other available buck or boost μModule regulators. Additionally, this four-switch buck-boost can be easily configured as an inverting buck-boost regulator for applications requiring a negative output.

For comprehensive guidance on implementing the newly released LTM4712, it is recommended to refer to the data sheet and the associated evaluation kit design. It is also supported by the LTpowerCAD design tool and the LTspice simulation tool, which provide valuable insights and specifications essential for optimizing the performance in diverse applications.

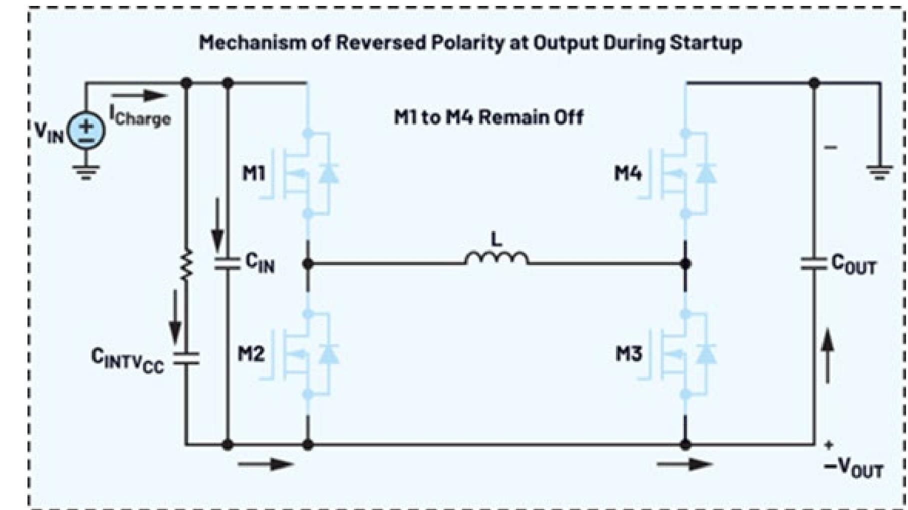
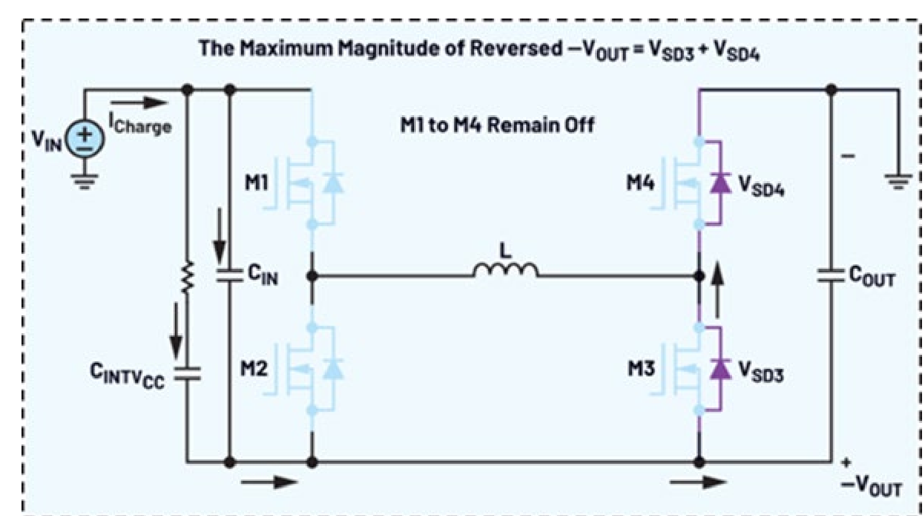


Figure 10. Charging current flow paths during startup. Image source: ADI

Figure 11. The natural clamping circuit in the four-switch buck-boost. Image source: ADI



Reference

Jiang, Ling, Wesley Ballar, Anjan Panigrahy, and Henry Zhang. “μModule Regulator Achieves Highest Power Efficiency.” Electronic Products, October 2024.

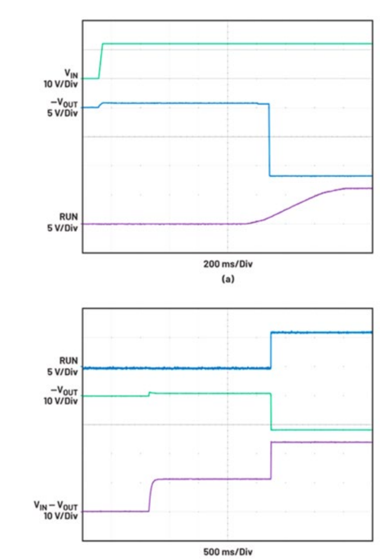


Figure 12. Reversed $-V_{OUT}$ waveforms during startup: (a) relatively small C_{IN} (50 μF) compared to C_{OUT} (330 μF) and (b) relatively large C_{IN} (350 μF) compared to C_{OUT} (330 μF). Image source: ADI

Vicor power modules simplify high-voltage conversion for the shift to 48 V

Power delivery networks for high-performance computing, automotive, robotics, and industrial systems are shifting from 12 V to 48 V architectures, and the reason is rooted in basic physics. Power lost in a distribution path P is I squared times R, so the loss rises with the square of the current. Raising the distribution voltage from 12 V to 48 V cuts the current needed to deliver the same power to a quarter, which drops the conduction loss significantly and lets you use lighter, thinner conductors. The challenge, however, is that decades of systems have been optimized around 12 V distributions, and the loads usually run at low voltages, so you must bridge your high-voltage source to a 48 V bus, and onward to the point of load, without giving back the efficiency you set out to gain. Vicor tackles this issue with its high-performance power modules and a power architecture built specifically around 48 V.

Fixed-ratio conversion with Vicor's bus converter module

The primary component of Vicor's high-voltage to 48 V story is the Bus Converter Module (BCM). A BCM is a fixed-ratio converter whose output is a fixed fraction of its input, defined by a conversion factor Vicor calls the "K factor," rather than a value the converter actively regulates. This distinction is what allows a fixed-ratio stage to achieve exceptional efficiency and density. The BCM (Part number: BCM6135CD1E5165T00) is built on Vicor's Sine Amplitude Converter topology, which operates in three stages: primary-side switching converting DC input into a sinusoid; an ideal-transformer stage scaling the voltage by its turns ratio, and secondary-side switching converting the sinusoid back to DC.

Since it behaves much like a transformer with a fixed turns ratio, a BCM is often described as a DC transformer. Consequently, Vicor's high-voltage BCMs can step 800 V or 400 V down to a 48 V safety-extra-low-voltage (SELV) output at peak efficiencies up to 98%, and with a very high power density. The BCMs can be paralleled into arrays to increase power and series-connected at their outputs to reach even higher voltages, giving system architects a flexible building block rather than a fixed-function product.

Eliminating intermediate stages

What makes the fixed-ratio bus converter useful is how it simplifies the rest of the system. Vicor BCMs transform a high-voltage battery into a virtual low-voltage battery, presenting a lower impedance path and a fast transient response, allowing the HV source to directly and responsively feed a 48 V network. In an electric vehicle, this fast response lets the BCM replace the 48 V battery, reducing weight and saving space. The same property also serves robots and unmanned vehicles where a BCM can isolate and step down a high-voltage battery or tethered high-voltage feed to a 48 V SELV bus.

Why the Sine Amplitude Converter runs so efficiently

The efficiency and density figures a BCM achieves are not incidental, but derived from how the Sine Amplitude Converter operates. While the topology resonates, its switching devices commutate when the voltage across them is near zero, largely suppressing the switching losses that typically rise with frequency. This soft-switching behavior is what permits the converter to run at a very high resonant frequency, reducing the size of the magnetics and filtering. Operating the power transformer at a single resonant point, rather than across the wide range a regulating converter must sweep, also means that the transformer can be wound for one optimized condition.

The fixed-ratio nature of the scaling stage also compounds the advantages. In the case of a regulating converter, it has to hold its output steady against a moving input, which involves carrying control-loop margin, reserving duty-cycle headroom, and tolerating the losses that come with constant correction. A fixed-ratio converter avoids all of that, because it is not trying to regulate at all; it transforms its input by a set ratio and lets the rest of the system handle regulation where it is actually needed. The result is a stage with a very low output impedance and a fast response, capable of feeding a 48 V network without the sag a standard converter would show under a sudden demand.

Figure 1: High-density DCM modules for bridging 48 V and legacy 12 V power buses. Image source: Vicor

Regulating the 48 V bus with DCM

A fixed-ratio bus converter establishes the 48 V bus, but many loads need a regulated voltage, which is where Vicor's DCM converters come in. The DCM is a regulated DC-DC converter; the isolated DCM takes a wide, unregulated input and produces an isolated regulated output, while Vicor's non-isolated DCM modules bridge a 48 V bus to a regulated low-voltage rail. The recent DCM3717 and DCM3735 (Figure 1), for example, operate from a 40 V to 60 V input, produce an adjustable regulated output around 10 to 12.5 V (12.2 V nominal), and can be paralleled to scale system power.

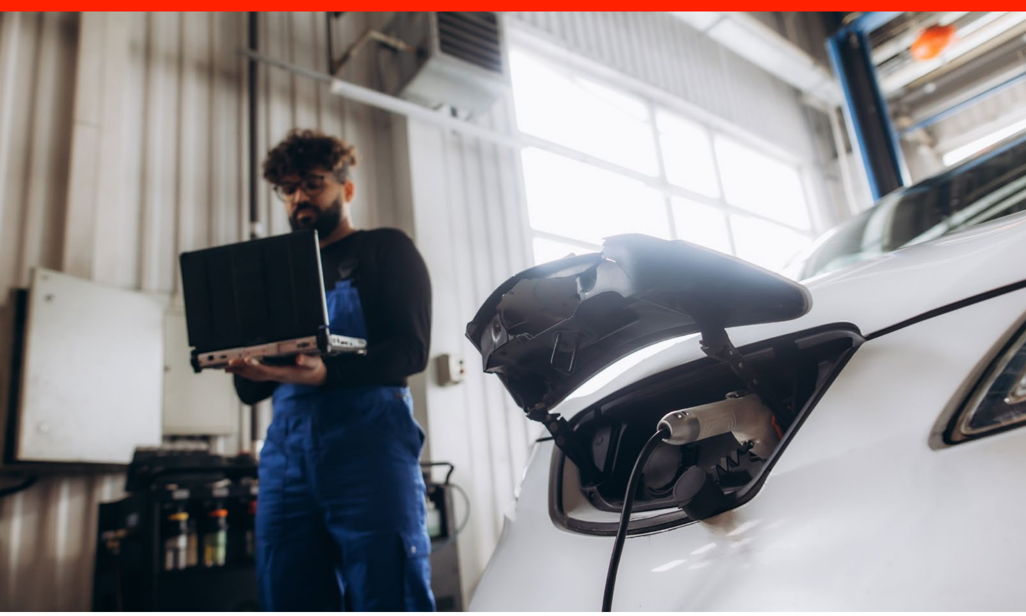
Conclusion

Vicor's ecosystem covers conversions across 800 V, 400 V, 48 V, and 12 V, allowing designers to assemble a path from a high-voltage source down to the point of load with compatible modules, and preserve 12 V investments by bridging 48 V and 12 V rails.

To explore the modules and architectures behind high-voltage to 48 V conversion, visit Vicor's Converting High Voltage to 48V Efficiently product highlight.

How to drive SiC MOSFETs and IGBTs with precision, efficiency, and protection

By Kenton Williston



As power systems evolve to meet the demands of electric vehicles (EVs), renewable energy, and industrial automation, it is becoming more challenging for designers to balance efficiency, performance, and safety. While the integration of high-voltage components such as insulated-gate bipolar transistors (IGBTs) and silicon carbide (SiC) metal-oxide-semiconductor field-effect transistors (MOSFETs) is a critical step toward achieving this balance, these devices require gate drivers that can deliver precise control, rapid switching, and robust protection mechanisms.

This article explores the challenges associated with driving modern power systems, emphasizing half-bridge topologies. It then introduces gate drivers and an evaluation board from Infineon Technologies that can help overcome these challenges.

Design challenges for modern half-bridge topologies

Power systems face mounting challenges as the industry pushes toward higher switching frequencies, elevated voltages, and the adoption of wide-bandgap (WBG) semiconductors. While these advancements enable greater efficiency, they place heavy demands on gate drivers.

Consider the half-bridge topology, which has become standard across many applications, to illustrate the escalating requirements. Half-bridge circuits are essential in EV DC-to-DC onboard chargers and motor drive systems. They enable bidirectional power flow, which is critical during both normal motor operation (forward power flow) and regenerative braking (reverse power flow). The transition to 800V architectures in newer EV platforms intensifies the need for reliable isolation and protection mechanisms while maintaining switching precision.

For renewable energy systems, half-bridge designs are foundational to the three-phase inverters required for grid integration. The higher switching frequencies used with SiC MOSFETs and IGBTs increase efficiency but exacerbate common-mode voltage issues on both high-side and low-side switches, generating significant electromagnetic interference (EMI) that can compromise system performance and potentially violate regulatory standards.

Industrial motor drives face additional challenges, including maintaining balanced DC bus voltage across split capacitor arrangements. The trend toward more compact, higher power density designs increases thermal management difficulties and electrical noise concerns.

Across all these applications, designers need gate driver solutions that deliver precise control, rapid switching capabilities, and comprehensive protection features while providing robust isolation between high and low-voltage circuits.

A dual-channel gate driver built for IGBTs and MOSFETs

Infineon Technologies' EiceDRIVER 2ED314xMC12L series (Figure 1) addresses these challenges with a dual-channel design engineered to control IGBTs and MOSFETs. All series members offer independent channel operation with dead-time control (DTC) to allow the 2ED314xMC12L device to operate as a dual-channel low-side driver, a dual-channel high-side driver, or a half-bridge gate driver.

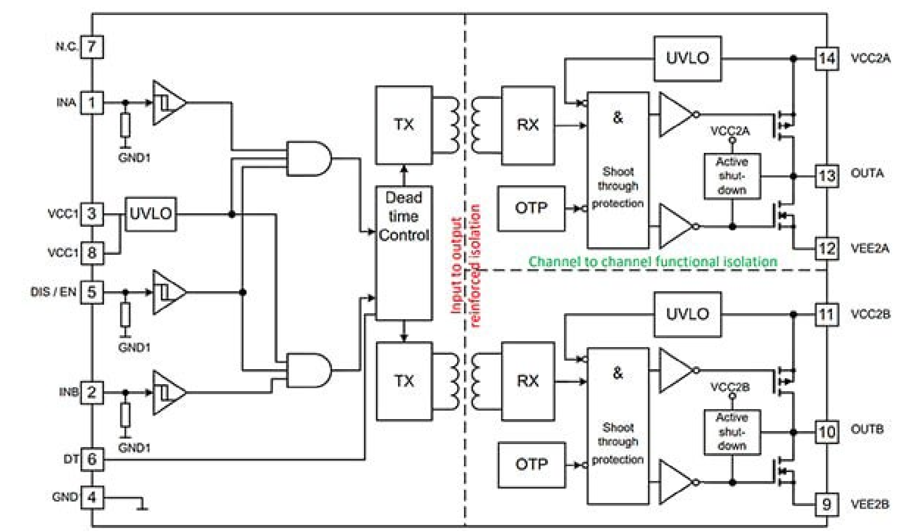


Figure 1: The 2ED314xMC12L series features independent channel operation with DTC, allowing the devices to operate as dual-channel low-side drivers, dual-channel high-side drivers, or half-bridge gate drivers. Image source: Infineon Technologies

In a half-bridge configuration, the dual-channel architecture allows a single gate driver IC to control both high-side and low-side switches efficiently. This integration simplifies printed circuit board (pc board) layout, reduces component count, and supports matched timing characteristics between channels, which is critical for maintaining proper DTC and preventing shoot-through conditions.

A key advantage of the 2ED314xMC12L series is its galvanic isolation through coreless transformer technology. This approach delivers fast signal transmission with high immunity to EMI, which is essential in electrically noisy environments like EVs.

The isolation capability is certified to UL 1577 standards, providing 6.84kV root mean square (kVRMS) for 1 second and 5.7 kVRMS for 1 minute. This robust isolation level is crucial to protect against high-

Figure 2: The 2ED314xMC12L series is offered in a compact PG-DSO-14-71 package. Image source: Infineon Technologies

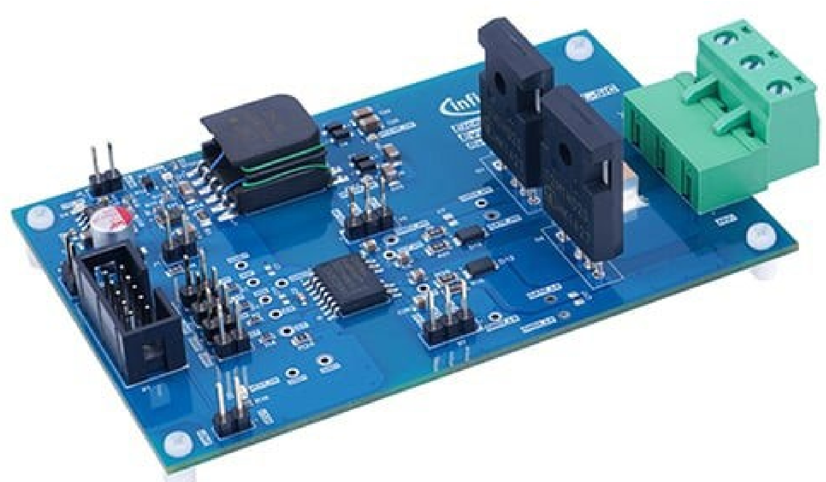


Figure 3: The EVAL-2ED3146MC12L evaluation board provides a half-bridge setup to evaluate the 2ED3146MC12L. Image source: Infineon Technologies

voltage transients in applications such as renewable energy systems, where grid-tie inverters must withstand utility-scale voltage surges.

High-output, high-precision switching

The 2ED314xMC12L series performs well on several relevant benchmarks, starting with its 6.5A peak output current. This high output is particularly beneficial for SiC MOSFETs, which require strong gate-drive signals for efficient switching.

Another key characteristic is a propagation delay of 39ns, which enables precise timing control. This is an important consideration for applications such as industrial automation, where motor speed and torque control depend on high-precision switching.

A tight part-to-part propagation delay skew of 8ns maximum means that when using multiple driver ICs, such as in a three-phase motor drive, the timing differences between the parts will be minimal. An even tighter channel-to-channel propagation delay skew of 5ns maximum helps prevent shoot-through between switches for each half-bridge.

Finally, a common-mode transient immunity (CMTI) rating of more than 200kV per microsecond (kV/μs) helps prevent false triggering due to voltage transients. In renewable energy applications, for example, high transient immunity supports stable operation during grid fluctuations and sudden shifts in power flow.

Reliability features for steady operation

The 2ED314xMC12L series incorporates multiple protection features to ensure reliable operation in demanding power applications. Each feature addresses specific reliability concerns that arise in high-voltage switching environments.

Necessary safeguards are active shutdown and short-circuit clamping. These mechanisms protect against shoot-through currents in half-bridge configurations where the two power switches are stacked between the DC bus voltage. If both switches were to turn on simultaneously, the resulting short circuit could damage components or shut down the system.

Another notable feature is undervoltage lockout (UVLO) protection, which creates a hysteresis “dead band” where the state remains stable despite small voltage fluctuations, preventing oscillation at the threshold. In solar power systems, for example, UVLO provides steady operation under partly cloudy conditions, avoiding unnecessary disruptions. Some variants offer UVLO between 8.5 and 9.3V, while others provide protection between 12.5 and 13.6V.

Options are also available with an enable pin, which adds an extra layer of control for emergency shut down situations. In these variants, each digital input pin includes a pull-down resistor, ensuring that if a pin is desoldered or disconnected, it defaults to a safe state with the channel disabled.

This feature is particularly relevant in high-reliability applications where system integrity must be maintained even in the event of unexpected faults.

Variants with disable pins are available for applications prioritizing lower current consumption and simplified control. These models allow the gate driver to remain active by default, reducing standby power consumption and simplifying system design.

Examples of the options available are the 2ED3140MC12L, which offers UVLO with hysteresis between 8.5 and 9.3V and a disable pin. In contrast, the 2ED3146MC12L provides UVLO between 12.5 and 13.6V and an enable pin.

Efficient yet reliable packaging

The series is offered in a PG-DSO-14-71 package (Figure 2). This surface-mount package measures 10.3 x 7.5 millimeters (mm), notably compact dimensions for a high-power, dual-channel driver. In EV applications, this package saves valuable powertrain space.

Despite their small size, all variants provide sufficient spacing for safe operation: 8 mm input-to-output and 3.3mm channel-to-channel creepage and clearance distances. These dimensions satisfy isolation requirements while maintaining the compact form factor needed in space-constrained designs.

Get a quick start with an evaluation board

To streamline testing and development, Infineon Technologies offers the EVAL-2ED3146MC12L evaluation board (Figure 3). This half-bridge board is designed to showcase the functionality and capabilities of the 2ED3146MC12L isolated gate driver IC.

Beyond the gate driver, the evaluation board includes two Infineon Technologies IMZA120R020M1HXKSA1 CoolSiC trench MOSFETs, as well as an Infineon Technologies 2EP130R transformer driver IC for the onboard power supply. These components are suitable for evaluation purposes and represent practical choices for real-world designs.

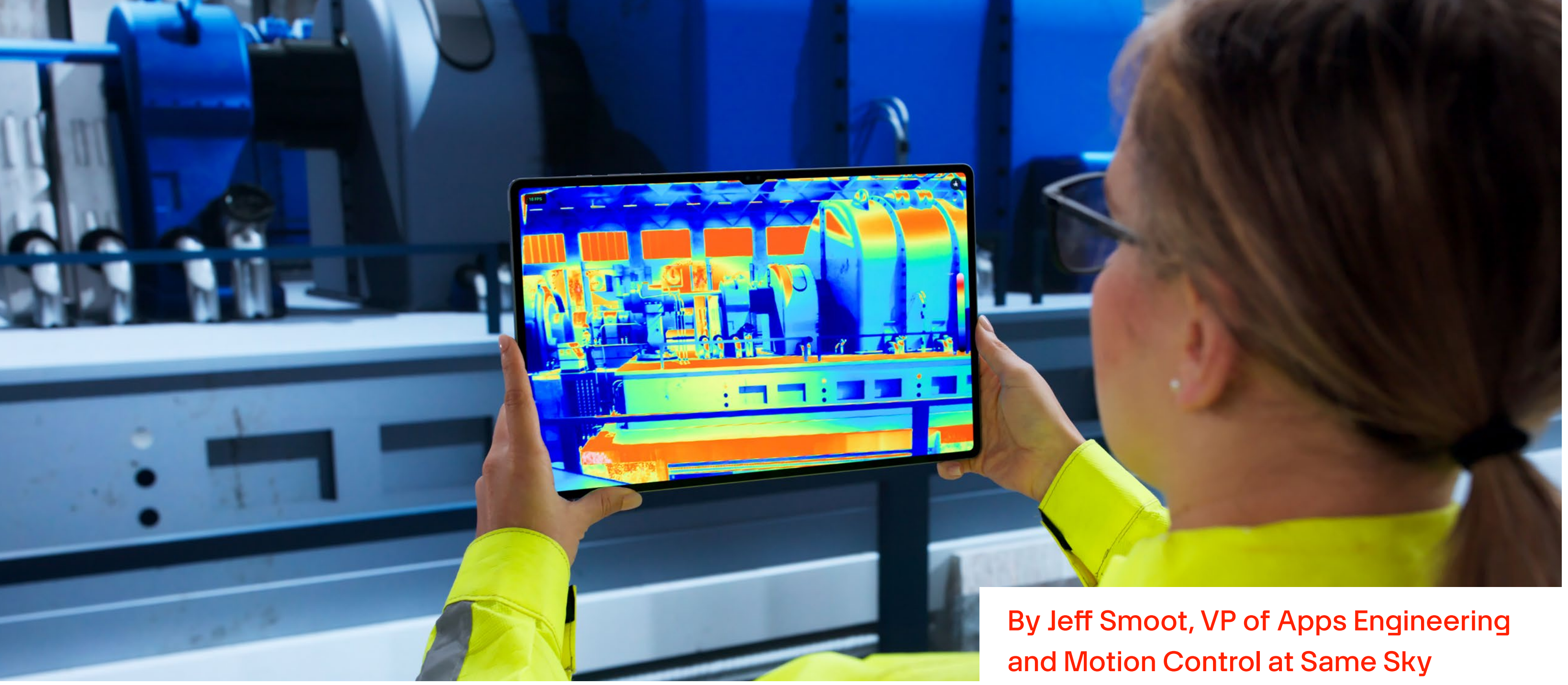
The SiC MOSFETs feature a 1,200V drain-to-source voltage rating, well within the 2ED314xMC12L’s capability to drive 600 to 2,300V power devices. These MOSFETs’ gate-drive voltage requirements of 18V are comfortably accommodated by the 2ED314xMC12L’s 35V absolute maximum output supply voltage. The MOSFETs’ low on-state resistance of 19mΩ at +25°C minimizes conduction losses.

With a maximum power dissipation capability of 375W at +25°C and an operating temperature range of -55 to +175°C, these MOSFETs align with the requirements of high-performance power electronic applications. The gate driver’s fast 39ns propagation delay and high CMTI of >200kV/μs enable efficient high-frequency switching while maintaining reliable operation across the MOSFETs’ full temperature range.

The 2EP130R transformer driver complements the gate driver with its wide switching frequency range of 50 to 695 kilohertz (kHz), working in concert with the 2ED3146MC12L’s fast propagation delay. The transformer driver’s high-accuracy duty cycle adjustment (10 to 50%) pairs well with the gate driver’s precise timing characteristics, a crucial combination for maintaining optimal dead time in half-bridge configurations.

Conclusion

Infineon Technologies’ EiceDRIVER 2ED314xMC12L series delivers the balance of efficiency, performance, and safety features necessary for high-voltage applications in EVs, renewable energy, and industrial automation. Its compact PG-DSO-14-71 package supports space-constrained designs, while the EVAL-2ED3146MC12L-SiC evaluation board enables quick testing.



By Jeff Smoot, VP of Apps Engineering and Motion Control at Same Sky

An introduction to thermal management

Electronics systems are getting denser and hotter, which means many systems will require some method of managing said heat. While developing a thermal management solution is not necessary for every design, a fundamental understanding of how heat is generated, moved, and removed is essential to avoid having key components being damaged by elevated temperatures. In the end, thermal management needs to be considered in the early design stages rather than as a band-aid solution in the final design.

Thermal management basics

As more is demanded of electronic systems, theory states that there are three ways heat is transferred and thus components can be cooled: conduction, convection, and radiation.

Perhaps the most effective energy transfer method, conduction transfers thermal energy through physical contact between two objects where the cooler object naturally draws energy away from the hotter object. In general, this method requires the smallest surface area to move the greatest energy.

Second, convection redistributes thermal energy via the movement of air. As cooler air passes by a hotter object, it draws heat away from the object and carries it away as it continues to move through the device. This method can be accomplished by natural air convection or forced air convection via a fan.

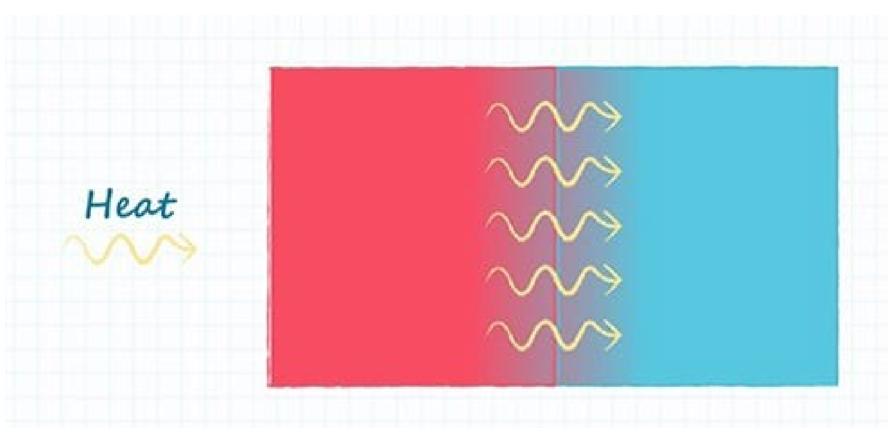


Figure 1: Conduction in practice. Image source: Same Sky

Third, radiation is the emission of energy as an electromagnetic wave. Comparatively, this method is rather ineffective and ignored in most thermal calculations because it generally only applies to vacuum applications where conduction and convection are not options. In principle, radiation is the transfer of heat through the electromagnetic waves created when hot particles vibrate.

Although not one of the three basic thermal concepts outlined above, it is also important to mention thermal resistance, or impedance, which quantifies the effectiveness of thermal transmission between objects and is used extensively in designing thermal management solutions. Simply put, the lower the thermal impedance, the better the transfer of energy. Utilizing thermal impedance and a given ambient temperature, it is possible to calculate exactly how much power can be dissipated before reaching certain temperatures.

Thermal management components

There are three popular approaches to cooling electronic systems: heat sinks, fans, and Peltier modules. Each can be used alone but can reach even greater effectiveness when integrated together.

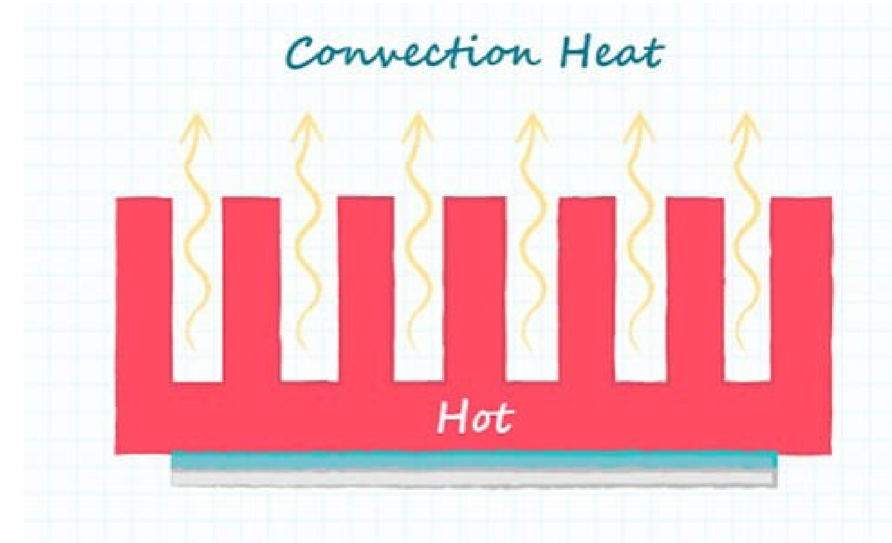


Figure 2: Convection in practice. Image source: Same Sky

Heat sinks are available in many shapes and sizes. They are used to improve the effectiveness of convection cooling by decreasing the thermal impedance between the devices to which they are attached and the cooling medium, usually air. They do this by increasing the convection surface area and are made of a material that has a lower thermal impedance than typical semiconductors. Heat sinks are low cost and almost never fail or wear out but do tend to increase the volume of the electronic systems they are cooling. As passive components, heat sinks are often paired with fans to move the dissipated thermal energy away from the system more effectively. Fans or blowers create a steady flow of fresh cool air over a heat sink to maintain the temperature difference between it and the cooling air to ensure continuing efficient thermal energy transfer.

Fans and blowers are available in a wide variety of shapes and sizes with many different power options. The key specification is the airflow they can generate, typically measured in cubic feet per minute (CFM). Some fans and blowers have controls so that their speed can be adjusted to match current cooling needs, as part of a feedback-based control system. Fans help improve cooling, but designers need to be aware that they require power and sometimes control circuitry. In contrast to heat sinks, fans can also be noisy and

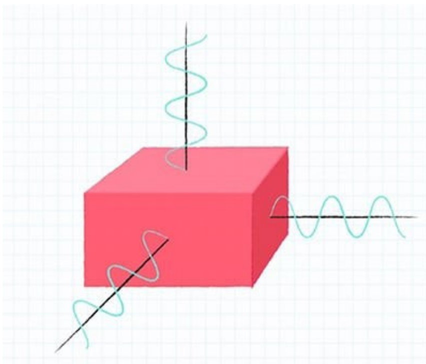


Figure 3: Radiation in practice. Image source: Same Sky

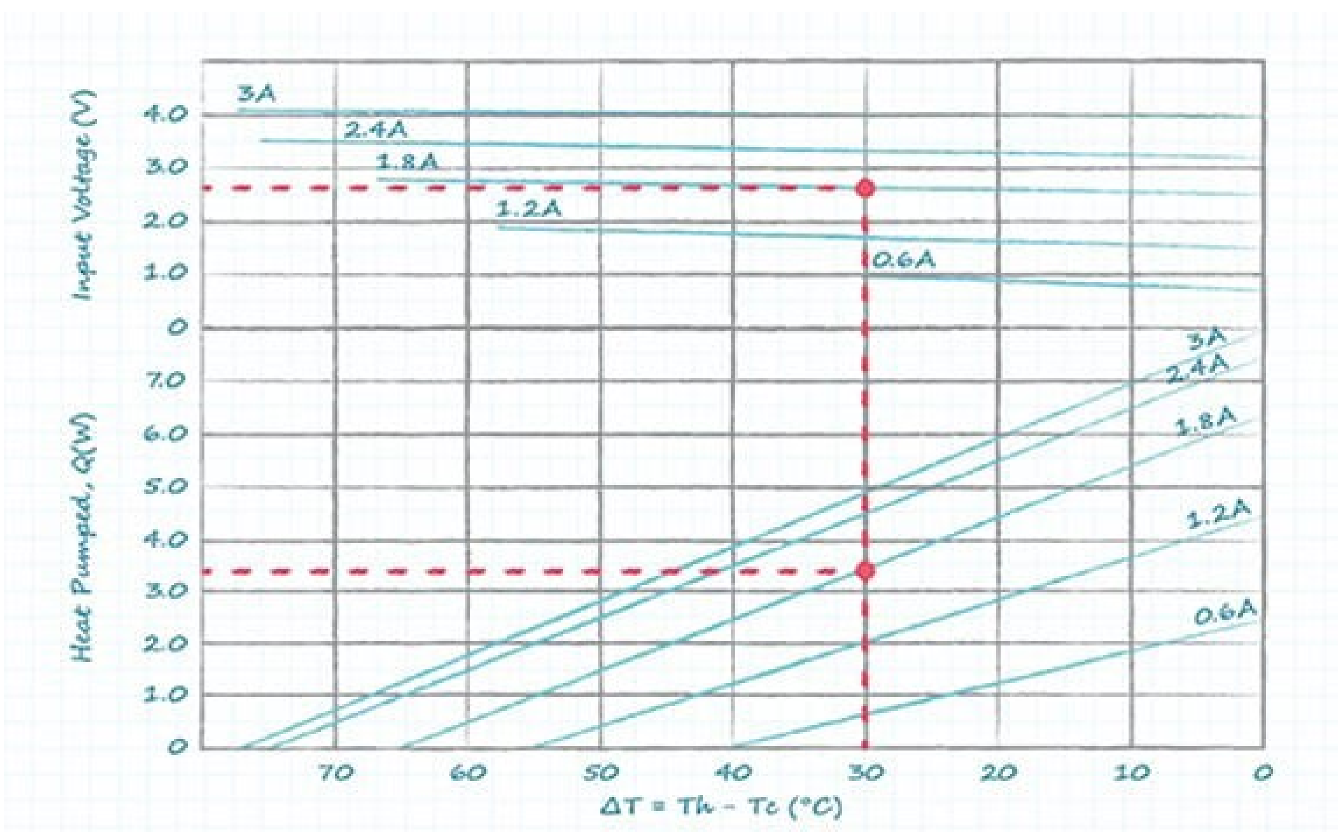
have moving parts that make them more prone to failure.

Peltier devices are semiconductor components that use the Peltier effect to transfer heat from one side of a module to another. Peltier devices must be provided with energy in order to move thermal energy, which actually adds heat to the system, so they are best used with heat sinks and fans. However, Peltier modules can achieve precise temperature regulation and can cool devices below the ambient temperature. Like heat sinks, they do not have moving parts, so they are flexible and robust in themselves, but again they may have to be used with fans, heat sinks, and control circuitry, increasing cost and complexity. For these reasons, Peltier modules are often reserved for the most demanding applications, such as extracting thermal energy from the heart of densely packed electronics systems.

Calculating thermal requirements

Whatever the final design requirements might be, there are well-established approaches to designing an effective cooling solution for electronic systems. To help illustrate how an engineer might approach creating an integrated thermal management solution, here is a hypothetical problem and solution:

Figure 4: Peltier module performance graph from the CP30138H datasheet Image source: Same Sky



This example will use a device in a 10 x 15mm package that generates 3.3W of heat at its steady state. The ambient temperature of the device's operating environment is 50°C, with an ideal operational temperature of 40°C. No part of the system should exceed 80°C.

These specifications mean that a Peltier module is needed to bring the device's temperature below the ambient. Same Sky offers the CP30138H, a Peltier module that can remove 3.3W of thermal energy and reduce a device's temperature to 10°C below ambient. The Peltier module is attached to the device using SF600G, a Thermal Interface Material (TIM) that reduces the thermal impedance between the device and the cooler. The CP30138H datasheet (Figure 4) shows that the Peltier module requires 1.8A at 2.6V, meaning that its operation will add 4.7W of thermal energy to the system.

To remove the total 8W of thermal energy from the Peltier module, a heat sink (the HSB28-606022) is attached to its other side, again using the SF600G TIM as an interface. The TIM has an area of 8.8 x 8.8mm, and a thermal resistance of just under 1.08°C/W.

The heat sink has a thermal resistance of 0.9°C/W, assuming an airflow across it of 400 linear feet per minute (LFM).

This brings the total thermal resistance of the combined TIM and heat sink to 1.98°C/W.

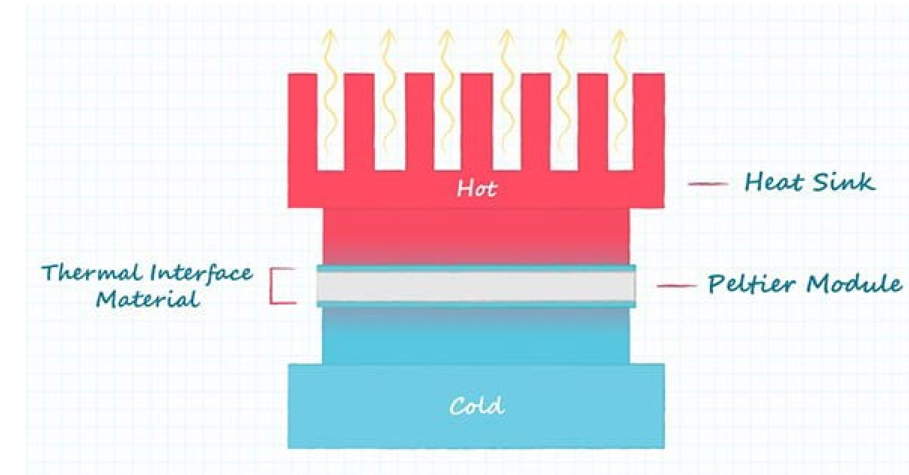


Figure 5: Thermal management solution using a Peltier device, heat sink, two TIM layers, and fan Image source: Same Sky

To provide a consistent airflow of 400 LFM, a fan from the CFM-40BG series could be used.

The setup connects the device to be cooled to a Peltier module via a TIM. The upper surface of the Peltier module is connected to a heat sink via another TIM, and the whole assembly exists within 400 LFM of 50°C air.

Using this data, the steady-state temperature of the device can be calculated. The Peltier module will maintain its cool side at 36°C – at the cost of adding 4.7W of heat to the assembly. The heat sink will have to dissipate 8W of heat into a 50°C airflow environment, with a total thermal resistance between the Peltier module and ambient air of 1.98°C/W. Multiplying 8 W times 1.98°C/W determines the increase in temperature over ambient, which in this case is 15.84 or 65.84°C total. This is well under the 80°C requirement, resulting in a thermal management solution that meets the needs of the system.

Conclusion

Thermal management is already necessary in consumer applications such as refrigeration, HVAC, 3D printing, and dehumidifiers. It is also used in scientific and industrial applications such as thermal cyclers for DNA synthesis and high-accuracy lasers. Heat sinks, fans, and Peltier modules can help to ensure that complex electronic systems remain within their thermal design limits. Same Sky offers a range of thermal management components to simplify this critical selection process.

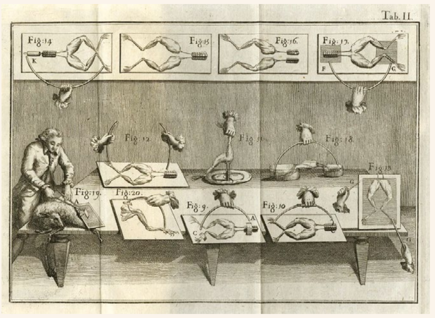
This month in history

1737

September 9

Luigi Galvani is born

Luigi Galvani's experiments with frog muscles and electrical effects helped open the field of electrophysiology. Galvani concluded that animals have internal electricity produced by the brain and transmitted through nerves to muscles. Galvani's work heavily influenced Alessandro Volta and later studies of nerves, batteries, and medical electricity.



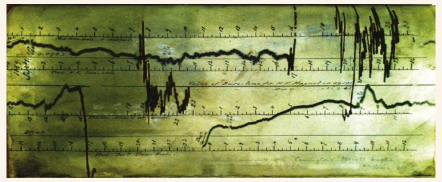
Galvani's benchtop lab equipment is very strange when compared to a modern Fluke meter.

1859

September 1

Carrington Event disrupts telegraphs worldwide

A major solar storm affected the electrical telegraph service and produced unusual currents in telegraph wires. For hours, operators were able to use their telegraphs with no batteries connected at all, simply drawing power from the aurora. Reports say this lasted for many days. It remains an early example of how space weather can interfere with electrical infrastructure.



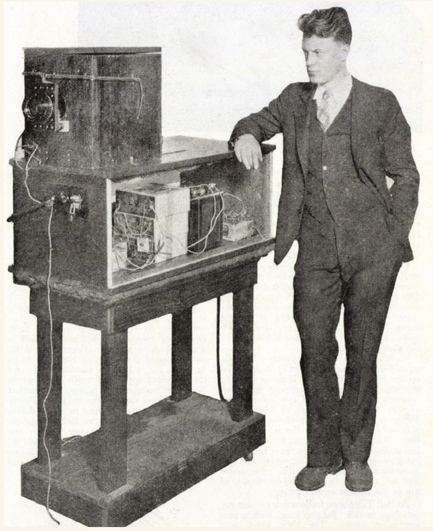
Solar flare chart that was recorded on September 1, 1859, during the Carrington Storm Event.

1927

September 7

Electronic television demonstrated to investors by Farnsworth

The 21-year-old inventor, Philo T. Farnsworth, changed everything when he successfully transmitted the first all-electronic television signal in his San Francisco laboratory with his patented "image dissector" camera tube. Legend has it that the demonstration was for investors, and the transmitted image was of a big, fat dollar sign. He gave a public demonstration for the press a year later, on September 3, 1928.



Farnsworth with the image dissector and amplifier.

1947

September 15

RCA releases the 12AX7 vacuum tube

The 12AX7 became the standard small-signal amplifier tube of the postwar electronics industry. By placing two high-gain triodes in one package, it let manufacturers build more compact radios, amplifiers, tone generators, oscillators and with fewer parts. It appeared in radios, hi-fi equipment, tape recorders, organs, test instruments, and especially guitar amplifiers, where its behavior under overload became part of the sound of early electric guitar.

The 12AX7 could be the single most used vacuum tube in history.

1962

September 12

Kennedy gives his Moon speech

President John F. Kennedy delivered his "We choose to go to the Moon" speech and turned the Apollo program from a technical proposal into a public national commitment, framing the Moon landing as an engineering challenge that would organize American industry, science, education, and government around a clear deadline. Its importance is not in the invention of a single device, but in the mobilization of thousands of technologies: rockets, guidance computers, radio tracking, spacesuits, materials, fuel systems, simulators, and launch facilities.

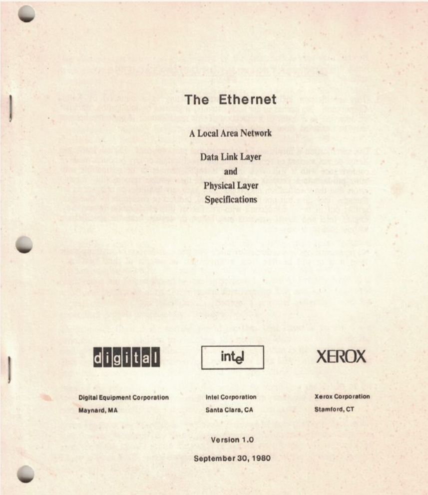
President John F. Kennedy speaks at Rice University in Houston.

1980

September 30

Ethernet specification published in Blue Book

Ethernet's Blue Book specification was built by a consortium including Xerox, Digital, and Intel for computers to talk across a local network. Instead of sending data as one continuous stream, Ethernet organized communication into frames, each carrying a piece of information with the addressing needed to move it between machines. That common structure made it easier for different computers and network equipment to work together.



The Ethernet

A Local Area Network

Data Link Layer
and
Physical Layer
Specifications

digital | intel | XEROX

Digital Equipment Corporation
Maynard, MA

Intel Corporation
Santa Clara, CA

Xerox Corporation
Stamford, CT

Version 1.0

September 30, 1980

The release and proliferation of Ethernet truly revolutionized civilization within twenty-five years.