Robotics eBook

Build better robots using high density power conversion in 48V architectures

VICOR

Contents

3 Introduction

4 Case studies

Logistic robots

Delivery robots

Harvesting robots

Security and inspecting robots

OLogic robotics field printer

Saab Seaeye all-electric work-class ROV

18 Technical articles

Why choose power modules over discrete power solutions?

Attributes of high-performance power module packaging

High-density, modular power delivery networks optimize mobile robot performance

40 Tools

Power System Designer

Whiteboard

Robotics eBook Introduction

In the rapidly evolving world of robotics, power delivery has become a critical factor in determining the performance, efficiency, and reliability of these machines. Traditional discrete power solutions often fall short in meeting the demanding requirements of modern robotics, such as compact size, high efficiency, and thermal management.

Vicor high performance power modules offer a revolutionary solution to these challenges. By combining advanced power architecture, exceptional thermal management, and unparalleled efficiency, Vicor power modules enable robotics engineers to design and build more powerful, agile, and reliable robots using high density power conversion in 48V architectures.

This eBook provides a guide to developing better PDNs to meet the needs of today's robotics systems. Starting with case studies, you will see how other companies have leveraged Vicor technology to overcome design challenges.

> Vicor enables a better way to deliver power for longer range and run time, more payload and functionality, and faster time-to-market.

Next, in-depth articles and whitepapers will guide you through the key advantages of power modules over traditional discrete power solutions, how packaging impacts PDNs, different approaches to various robotic power system requirements, and how high-density, high-performance power modules can improve time-to-market.

Lastly, you'll be provided with links to a variety of sophisticated online tools for easy adoption and integration of these innovative power modules.

Whether you wish to improve features and functionality, scale for the future or shorten your time to market, this eBook will help you identify ways to improve your design by taking a better approach to power delivery networks.

Case studies

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Case study: Logistic robots

High-efficiency power modules maximize system run-time and improve productivity

Customer's challenge

Logistic robots like AMRs and AGVs provide inventory management and order fulfillment tasks within large warehouse environments and can have different sizes and functionalities. These robots are fueled by 24V to 72V batteries with charging performed on an as-needed basis, making power conversion efficiency – along with size and weight – critical. Power conversion is more challenging with navigation, sensing and safety requirements increasing. The key goals were:

- Scalable power so the platform could be quickly reconfigured for different use cases
- High efficiency to extend run time
- Support for a variety of point-of-load voltages without added weight

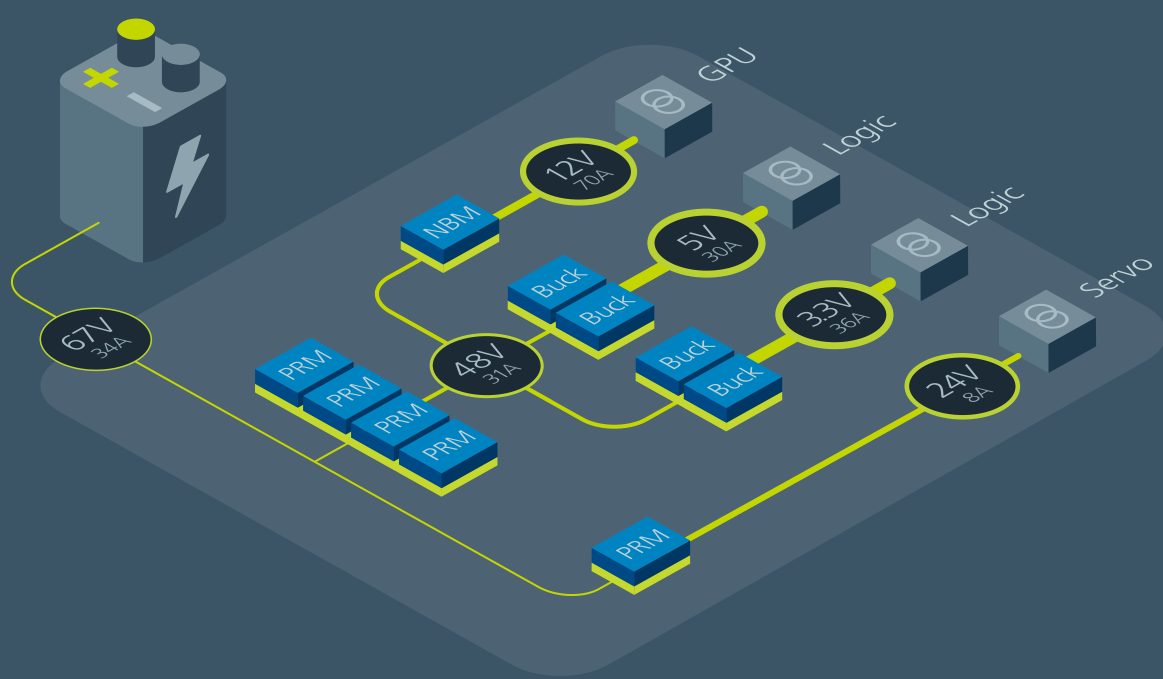
The Vicor solution

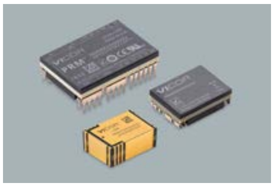
A logistics robots' job is to be productive and move safely through warehouses full of obstacles. Vicor high-performance power modules help save weight and space on board, allowing for more accessories to ensure safe operation. The power delivery network can be easily reconfigured and used for other platforms with different power requirements by simply changing or adding modules. Key benefits were:

- Zero-Voltage Switching topology provides 97.4% efficiency
- Power modules can be scaled to meet diverse power requirements
- Compact, high-density power modules optimize available space

Power delivery network for robots using a 67V battery

The PRM™ power module, a high-performance buck-boost regulator creates an intermediate bus of 24V to 48V with 96 to 98% efficiency to power servos and additional downstream power modules, including fixed ratio NBMs, ZVS buck and ZVS buck-boost regulators. All modules can also be paralleled for higher power conversion.





PRM buck-boost regulators

- Input: 48V (36 – 75V)
- Output: 48V (5 – 55V)
- Power: Up to 600W
- Efficiency: Up to 97%
- As small as 22.0 x 16.5 x 6.73mm

vicorpower.com/prm

NBM fixed ratio DC-DC converter

- Input: 36 – 60V
- Output: 7.2 – 15.3V
- Power: Up to 2400W
- Efficiency: Over 98%
- As small as: 23 x 17 x 5.2mm

vicorpower.com/nbm

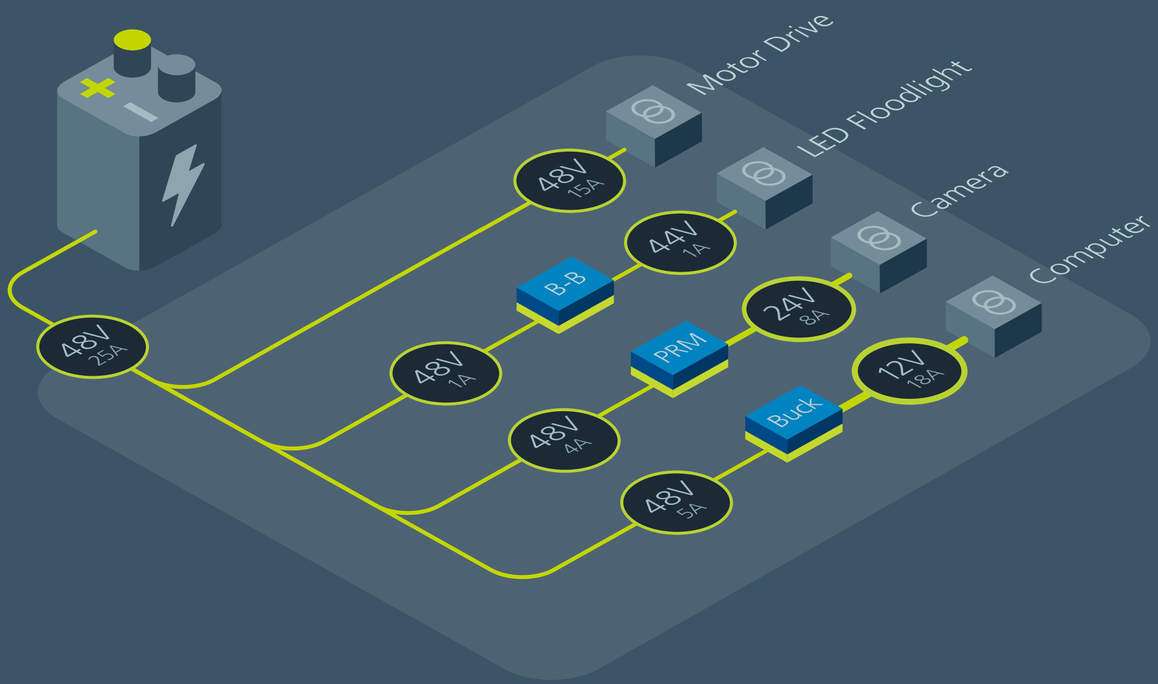
ZVS buck regulators

- Inputs: 12V (8 – 18V), 24V (8 – 42V), 48V (30 – 60V)
- Output: 2.2 – 16V
- Current: Up to 22A
- Peak efficiency: Up to 98%
- As small as 10.0 x 10.0 x 2.56mm

vicorpower.com/zvs-buck

Power delivery network for robots using a 24 to 48V battery

The second powertrain architecture highlights the use of direct conversion from the battery to the point-of-load. PRM, ZVS Buck, and ZVS Buck-Boost regulators support these applications. One example is the PI3740 ZVS Buck-Boost regulator which provides more than 100W of power from a 10 x 14 x 2.5mm SiP package with peak efficiencies of up to 96%.



ZVS buck-boost regulators

- Input: 8 – 60V
- Output: 10 – 54V
- Power: Up to 150W continuous
- Efficiency: Over 98%
- 10.5 x 14.5 x 3.05mm

vicorpower.com/prm

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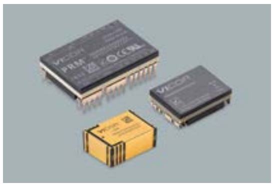

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vicorpower.com/prm

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Case study: Delivery robots

Lightweight and efficient power modules extend delivery routes and save space to carry more goods

Customer's challenge

Last-mile consumer delivery of groceries, take-out food and online consumer items is the mission-critical task of these autonomous robots. While payloads vary in size and weight, these robots typically have long run times and are typically powered by 48V to 100V batteries. Delivery robots are equipped with a variety of sensors, cameras, and GPS technology to navigate their surroundings safely and efficiently. These robots depend on batteries, which pose a challenge for their operational range. The key goals were:

- Extend range and run time
- Compact and lightweight solution to save space
- Supporting a variety of point-of-load voltages

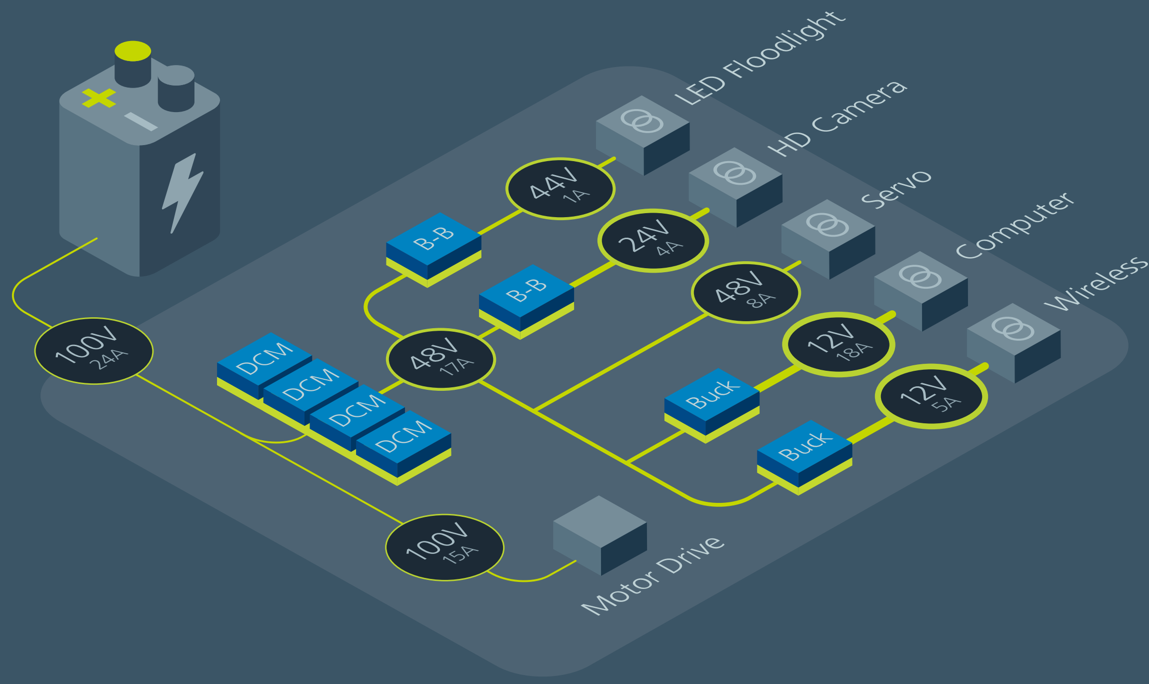
The Vicor solution

Vicor high-performance power modules reduce space and weight on board, increasing space for sensors and navigation systems and enabling delivery robots to carry larger loads and objects. The high efficiency levels of Vicor power modules increase operating time allowing them to reach more distant destinations safely. Key benefits were:

- Modular design supports flexible design requirements
- Compact high-density power modules optimize available design space
- High efficiency solution extends available battery life

The Power Delivery Network

The DCM™ converter series fits the needs for this class with operation from 43 – 154V input. The DCM3623 enables a regulated 24 or 48V distribution from the battery for servo drives, other payloads and downstream converters. The DCM3623 provides 240W of power at 90% efficiency from a 36.38 x 22.8 x 7.26mm package. With a 24 – 48V rail established, ZVS buck or buck-boost regulators can typically be used to power lower voltage rails.



DCM DC-DC converters

- Input: 9 – 420V
- Output: 3.3, 5, 12, 13.8, 15, 24, 28, 36, 48V
- Power: Up to 1300W
- Efficiency: Up to 96%
- As small as 24.8 x 22.8 x 7.21mm

vicorpower.com/dcm

ZVS buck-boost regulators

- Input: 8 – 60V
- Output: 10 – 54V
- Power: Up to 150W continuous
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vicorpower.com/zvs-buck-boost

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vicorpower.com/zvs-buck

VICOR

Case study: Harvesting robots

Rugged, reliable, and efficient power modules maximize uptime in harsh environments

Customer's challenge

Harvesting robots are machines designed to perform various tasks on farms, often autonomously. They are equipped with sensors, cameras, and GPS systems to navigate and understand their environment. These large robotic vehicles or equipment are typically powered from a high-voltage DC source of 400V or more. The key goals were:

- Increase productivity
- High power density to support higher voltage inputs
- A robust and reliable design to maintain continued operation

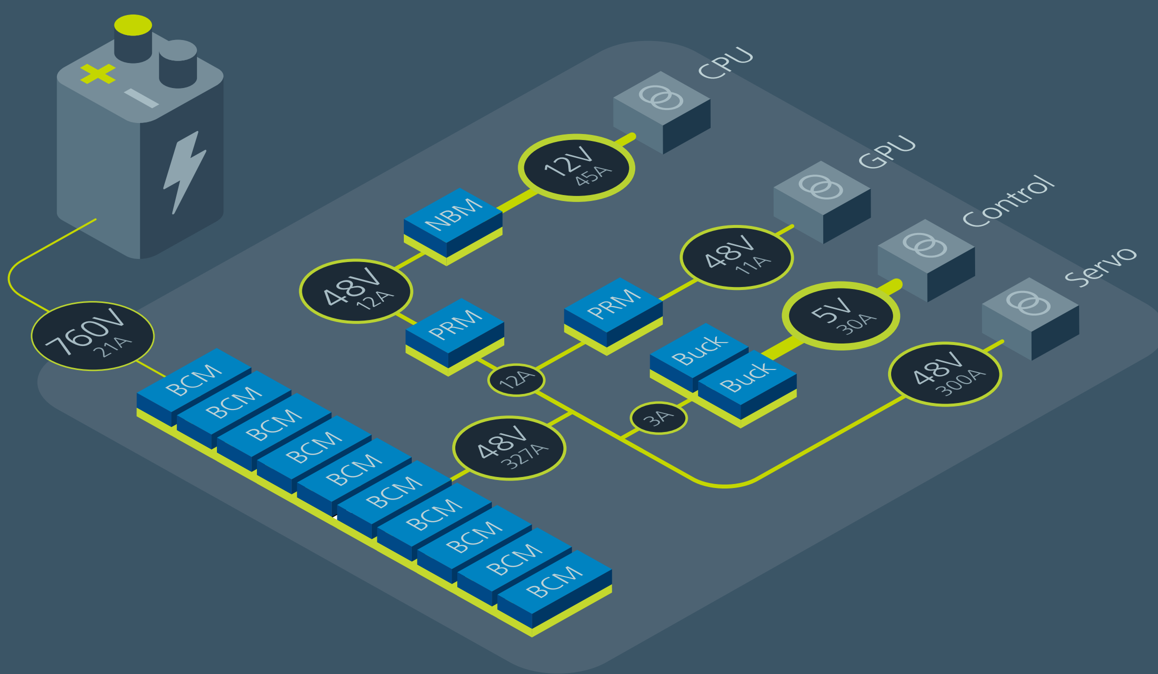
The Vicor solution

Vicor fixed-ratio power modules enable safe conversion of 400V or 800V batteries typically used in these applications to 48V SELV and reach more than 1,600W of power. The high efficiency of these modules, along with downstream Vicor PoL converters and regulators, greatly reduces power losses and simplifies thermal management, increasing productivity and reliability. Key benefits were:

- Safely convert high-voltage power to SELV
- Rugged, highly integrated power modules for high reliability
- Higher efficiency reduces power losses

The Power Delivery Network

In this type of design, the Vicor BCM® converter series can provide high-voltage battery conversion to a safe, nominal 48V. One example is the BCM4414 capable of more than 1,600W at greater than 97% efficiency from its 111 x 36 x 9mm package. The BCM is a fixed ratio converter with an output voltage 1/16 of the input voltage. Fixed ratio or regulated point-of-load converters such as Vicor NBMs™, PRMs™, ZVS Buck and ZVS Buck-Boost regulators power individual, downstream, lower-voltage rails as needed.



BCM bus converter modules

- Input: 800 – 48V
- Output: 2.4 – 55.0V
- Current: Up to 150A
- Efficiency: Up to 98%
- As small as 22.0 x 16.5 x 6.7mm

vicorpower.com/bcm

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vicorpower.com/zvs-buck

VICOR

Case study: Security and inspecting robots

Compact power modules allow space for advanced sensors that improve security and performance

Customer's challenge

Robots can go where people cannot, keeping them out of harm's way while maintaining safety and security. Inspection robots can monitor infrastructure more frequently and allow for rapid remediation before problems occur, saving lives, time, and money. Some, with tethers, operate at high voltages of 400V with conversion down to 12V and 1.5kW for propulsion. The key goals were:

- Highly efficient to extend run time
- Capable of managing high-temperature operations
- Supporting a variety of point-of-load voltages

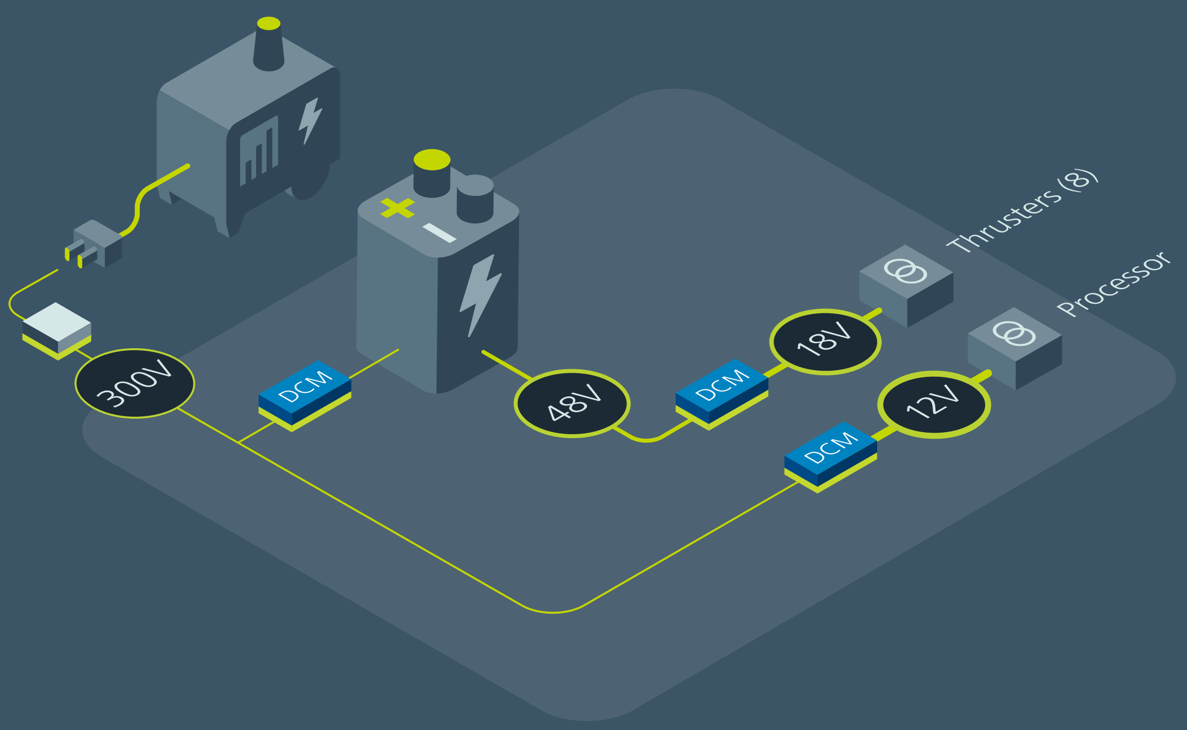
The Vicor solution

Security robots need to support a host of sensors and actuators to monitor efficiently and effectively and Vicor DCM™ power modules are a thermally adept and very power-dense solution that can power a variety of point-of-load voltages. The power density of the Vicor DCM also helps with routing the wiring and cable assembly and increasing battery efficiency, performance, and runtime. Key benefits were:

- Improved power density and efficiency extend the run time
- The DCM offers advanced packaging and topologies to manage thermal loads
- The DCM can be paralleled easily to accommodate additional system expansion

The Power Delivery Network

In this example, one DCM4623 isolated, regulated DC-DC converter module converts the 300V tether voltage to 12V to power the controller while another provides a 48V bus that is further converted down to 18V using DCM3623 modules to power a set of thrusters to propel the robot. This modular PDN is smaller than a couple of mobile phones but supplies 1.5kW at 92% efficiency.



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Power: Up to 1300W

Efficiency: Up to 96%

As small as 24.8 x 22.8 x 7.21mm

vicorpower.com/dcm

VICOR

Case study: OLogic robotics field printer

Enabling the next generation of robotic innovation

Customer's challenge

Designing the next world-changing robot requires expertise in many disciplines — electronic, mechanical, software, and power systems engineering. A new class of mobile robots means carrying a larger payload, longer run times, and improved efficiency are all critical specifications and competitive advantages. And for mobile robots, power is often the limiting factor for next-generation innovations. Size, weight, and power efficiency are integral to power design, enabling or limiting the robot's performance. The key goals for OLogic were:

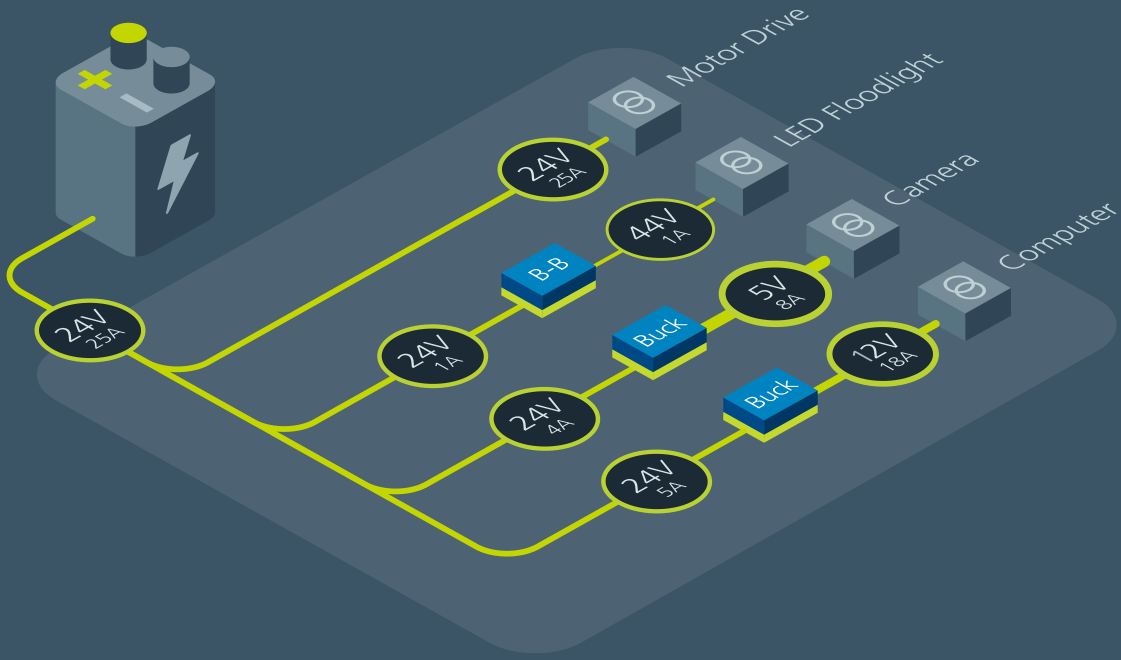
- Increased run time to increase productivity
- Improved accuracy to eliminate errors and costly rework
- Improve work site safety

Mobile robots require small, lightweight and efficient power to maximize performance. Designing a power delivery network with power modules is easier and more scalable than discrete power designs. OLogic uses Vicor power modules because they are power-dense, efficient, and easy to use. Working with Vicor, these printer robots are able to eliminate the conventional, labor-intensive process of physically transferring building plans onto the floor. Key benefits were:

- Compact high-density power modules optimize available design space
- Easily used in series and 5x faster with near flawless accuracy
- High efficiency solution extends available battery life

Power density and efficiency is key in robot ROI

OLogic realizes that they can only design the most operationally and thermally efficient **power delivery networks** by taking advantage of the wide operating range of a Vicor power module. Vicor modules, such as the the zero-voltage switching (ZVS) buck regulator, are extremely cost-efficient given the 200 to 300 watts of power they deliver and their 97% efficiency.



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vicorpower.com/zvs-buck

ZVS buck-boost regulators

Input: 8 – 60V

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Power: Up to 150W continuous

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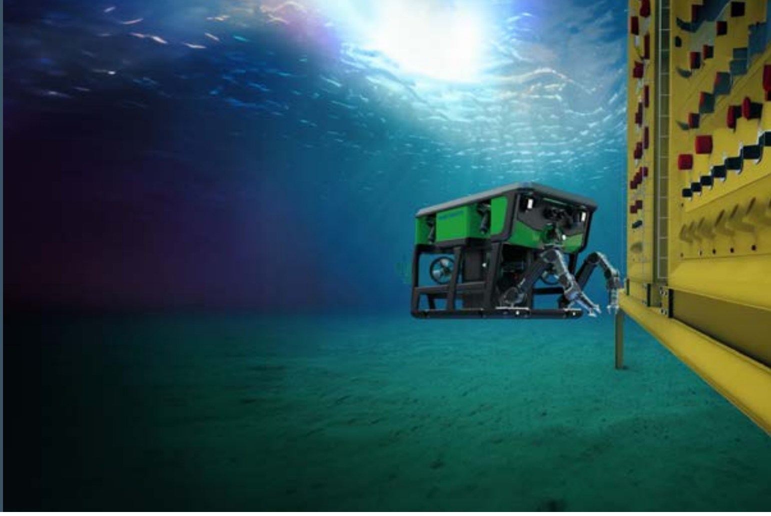
VICOR

Case study: Saab Seaeye all-electric work-class ROV (eWROV)



Higher power density enhances payload capacity and overall maneuverability

Customer's challenge

It's difficult to design remote missions that include inspecting underwater oil and gas pipelines, high-voltage electrical cables, wind turbines, and other critical infrastructure. For an ROV to adapt to a broad array of missions requires that it be very maneuverable and able to accommodate immense payloads. Also, powering ROVs poses inherent challenges with heat dissipation, and it must maintain a small and lightweight footprint. The key goals for Saab Seaeye were:

- Enhanced maneuverability and precise control
- Increased payload capacity to extend eWROV capabilities
- Improved thermal management to minimize premature system failures

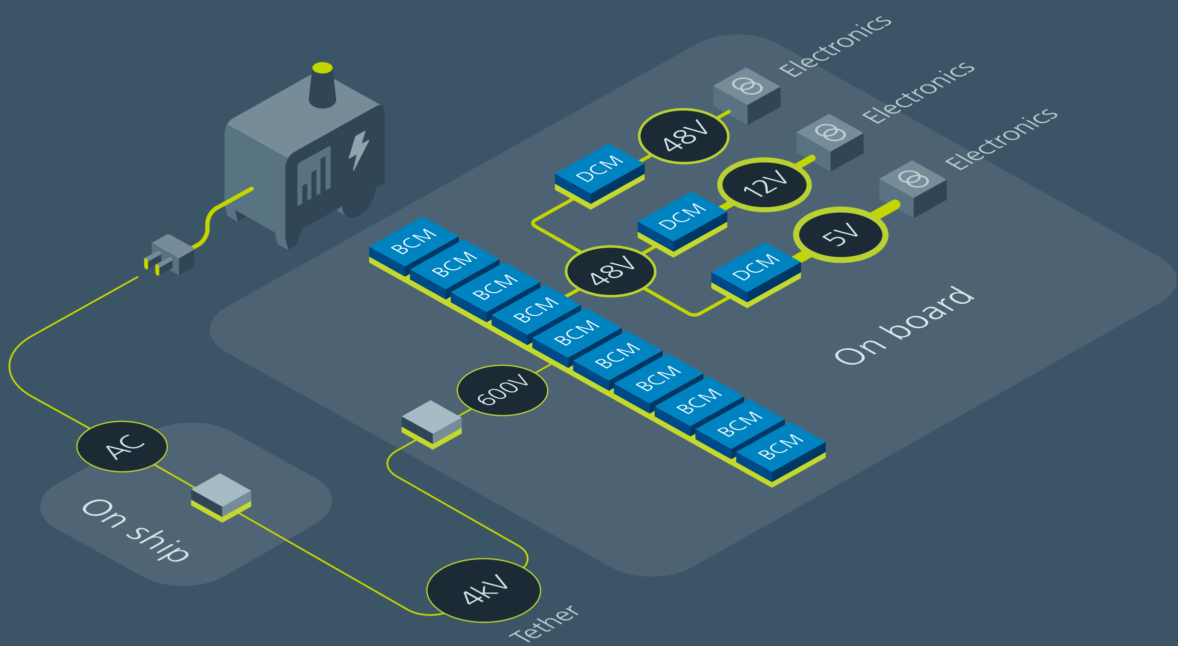
The Vicor solution

The Vicor solution delivers performance equivalent to a 250-HP undersea hydraulic vehicle. Unlike traditional hydraulic ROVs, the eWROV all-electric system eliminates the need for large volumes of hydraulic fluid, thereby reducing environmental risks. Vicor power modules use the cold seawater temperature to cool the power system using convection in a small, confined space. Key benefits were:

- Higher voltage cables result in much lighter tethers, enhanced agility
- Exceptionally high-power density enables advanced features
- Optimized thermal characteristics minimize the effects of excessive heat

Lightweight, power-dense power solutions enhance ROV deep sea capabilities

The wide selection of Vicor thermally-adept power modules allow Saab to customize the PDN subsystems according to industry standard 24V and 48V supply voltage levels required by onboard computers, sensors, video cameras, lights and navigation equipment. The compact power design frees up space within the eWROV, enabling the integration of additional electronics and improving overall performance and data transmission speeds.



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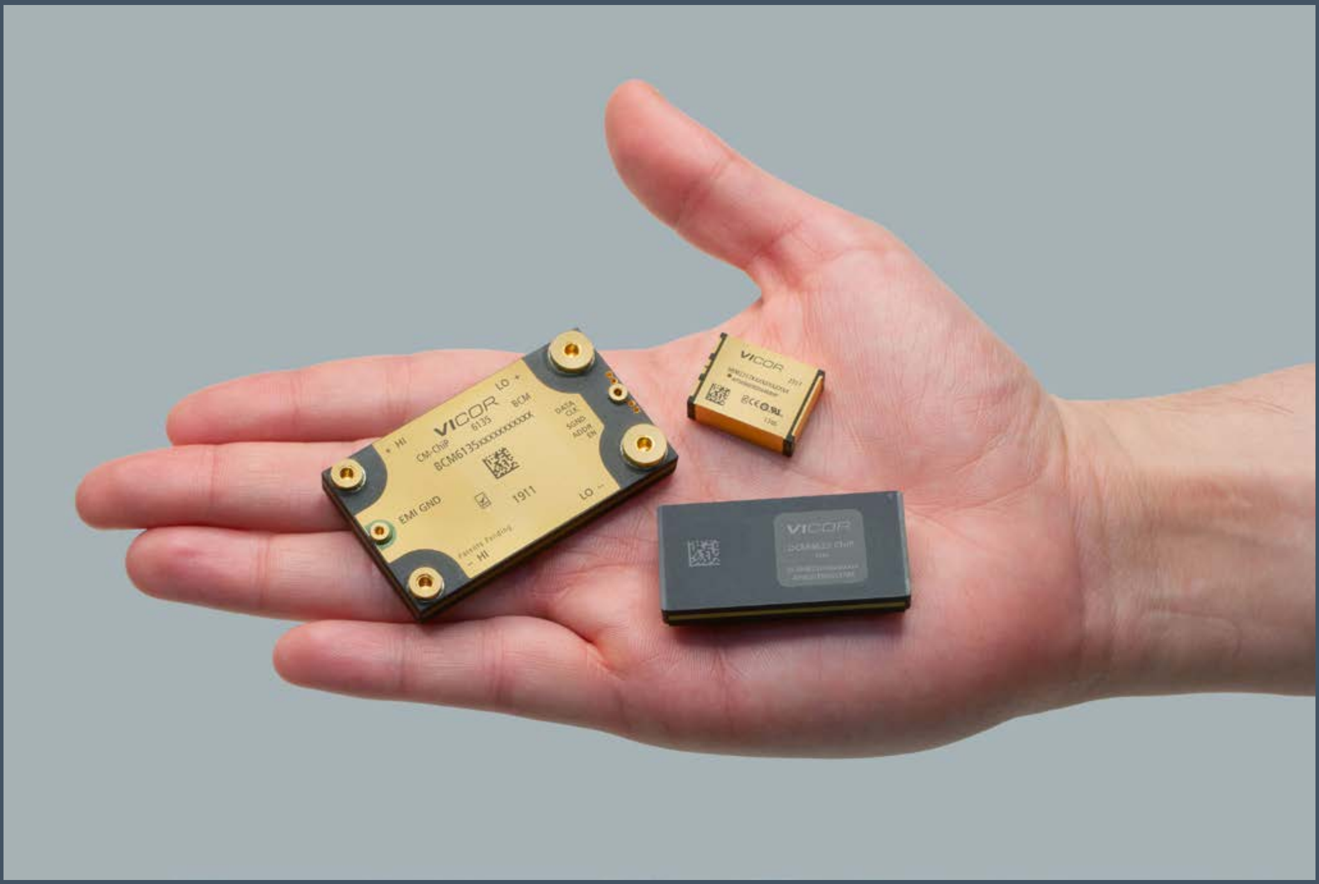
Technical articles



Article

Why choose power modules over discrete power solutions?

VICOR

When designing a power delivery network (PDN), the decision to use power modules vs discrete power solutions requires careful consideration of design variables. Understanding the advantages of using power modules, particularly high-density modules offered by Vicor, over home-grown discrete solutions is important. By examining factors such as reliability, scalability, size, weight, and power design expertise requirements, we will delineate the differences between design options and distill the benefits of a modular approach to power system design.

Less is more when developing power delivery networks

Power modules have fewer points of failure because there are fewer design components. Compared to discrete designs, power modules require fewer connections, reducing the likelihood of quality defects during assembly. Moreover, with fewer assembly stages, there is a decreased need for board handling by operators, mitigating the risk of electrostatic discharge (ESD) damage during the manufacturing process. These factors contribute to improved reliability, making power modules a more dependable choice for power system design.

Room to grow without the growing pains

Vicor power modules are small and power dense (Figure 1). Given most power designs must fit into a very confined space, small power modules add flexibility. The compact design offers the ability to scale and accommodate changes in power requirements without costly and time-consuming redesigns. By reusing prequalified modules, designers can avoid additional testing, recertification and sourcing efforts associated with a complete redesign. This flexibility and scalability of power modules enables design changes to be implemented quickly and efficiently, resulting in shorter development cycles and cost savings. Ultimately, this translates into faster time-to-market.

Easing the product life cycle dilemma

Figure 1: Vicor power modules are small and power dense with an extended variety of available input and output voltages; hundreds of components tightly arranged within a miniature footprint; and isolation, regulation, conversion, and transformation in different combinations.

When evaluating the choice between power modules and discrete designs, it is crucial to consider the entire life cycle of the product. In the case of a discrete design the burden of design, testing and validation falls solely on the in-house power design team. Furthermore, obtaining the necessary certifications from third-party agencies and managing the complex manufacturing and sourcing processes introduces significant risks and potential delays. Any scaling requirements can necessitate a complete redesign, further prolonging the development timeline.

In contrast, using power modules simplifies supply chain logistics and reduces the stress on the organization. These prequalified modules, such as the ones from Vicor, have undergone thorough testing and quality control, ensuring their reliability and compliance.

Additionally, as power requirements increase, reusing the same modules allows for seamless scalability, eliminating the need for extensive redesign efforts.

Power modules offer a simpler approach to power system design that requires less expertise. With their miniaturized form factor and high power density, they occupy less physical space, leaving more room for other components on the PCB (Figure 2). The high efficiency of these modules also simplifies thermal management, reducing the complexity of cooling solutions. This simplicity translates into faster and easier design iterations, updates and overall system maintenance.

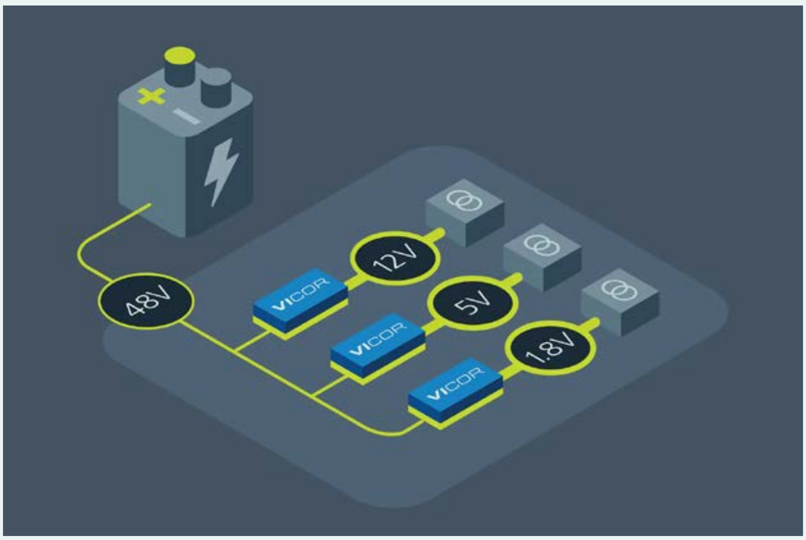


Figure 2: A simple, modular approach is flexible, easily scalable and requires less technical expertise to optimize a power delivery network

Figure 3: Discrete solutions have more components to manage which increases design complexity.

On the other hand, discrete power solutions present a complex landscape that demands extensive expertise, time and effort throughout the design process. These solutions involve the procurement, validation, and integration of many components (Figure 3). Even minor design modifications require a high-touch approach and can disrupt the project schedule and introduce unwanted risk.

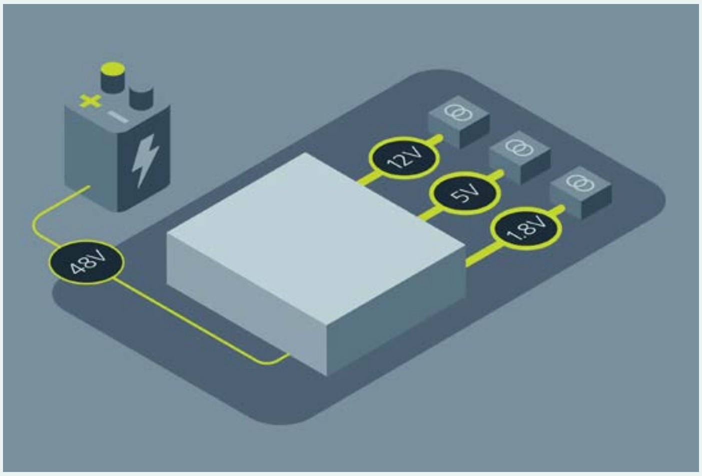


Figure 4: The silver box is a nice plug-and-play solution, but often is large, heavy, and inflexible.

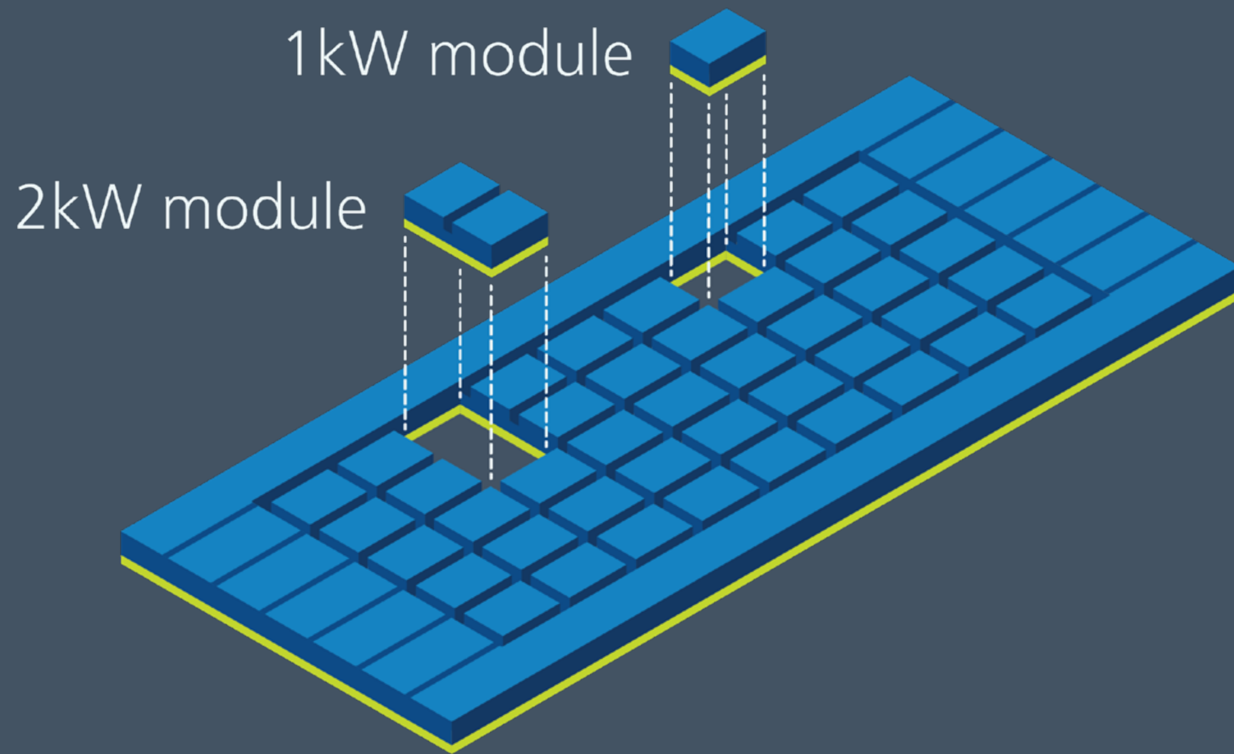
Discrete designs also suffer from inflexibility when it comes to adding more loads or adjusting power and voltage levels (Figure 4). Routing additional voltages consumes valuable space and adds weight to the system due to the requirements of larger boxes and cables. Moreover, these discrete solutions are susceptible to noise and external interference, impacting their overall performance and reliability.

Conclusion

In conclusion, when evaluating power system design options, power modules offer several significant advantages over discrete power solutions. Vicor power modules, with their advanced topologies, miniaturization, and thermally adept packaging, provide superior power density, efficiency and reliability compared to alternative discrete designs or silver-box options.

The use of power modules simplifies the design process, reduces the component count and likelihood of technical design errors, and enables faster time-to-market for new products. Additionally, the modular approach allows for easy scalability and flexibility, eliminating the need for time-consuming redesigns when power requirements change.

With the assurance of prequalified modules, simplified supply chain logistics and the ability to easily reuse modules and quickly scale PDNs, power system designers can focus on innovation and optimization rather than grappling with the complexities of a home-grown discrete solution. By choosing Vicor high-density power modules engineers can achieve efficient, reliable and scalable power delivery networks while saving valuable time and resources to get to market faster.



White Paper by Phil Davies, Corporate Vice President

Attributes of high-performance power module packaging

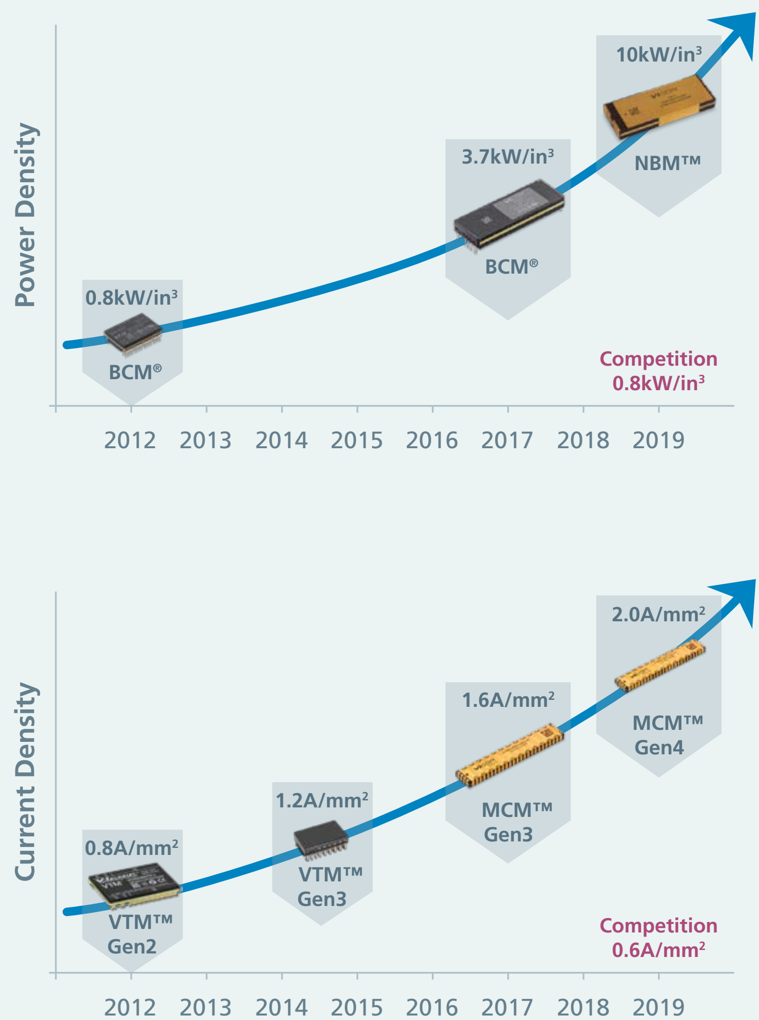
VICOR

From the first Brick to today's ChiP™ (Converter housed in Package), Vicor has been continually innovating to deliver higher-performance solutions to power-system engineers. These innovations are a result of a steadfast focus on advancing four essential technology pillars: power delivery architectures, control systems, topologies and packaging.

The fourth pillar, power module packaging, has been a unique differentiator for Vicor since its inception. There are several attributes that enable a high-performance power module package, and Vicor consistently leads the industry in advancing each one:

- High power and current density
- Thermal adeptness
- Integrated magnetics
- Compatibility with high-volume PCB assembly techniques
- Automated and scalable high-volume manufacturing

Figure 1: Continual advancements in the four pillars of innovation have reduced power losses by 25% every 2.5 years enabling significant power- and current-density improvements.



High current and power density

Each step of Vicor power module package development leveraged new materials, active and passive components and, most notably, improvements in magnetic structures based on higher switching frequencies. The higher frequencies are enabled by topology and control system improvements incorporated in proprietary Vicor control ASICs. The recent launch of the fourth generation (Gen4) of these ASICs has enabled power density and current density numbers of $10kW/in^3$ and $2A/mm^2$ respectively, enabling a new family of AC and DC high-power front-end converters and point-of-load (PoL) current multipliers. These latest generations of modular power solutions are changing the way power delivery networks (PDNs) are architected and designed in numerous industries.

> "Vicor fixed-ratio converters capitalize on the thermally-adept ChiP package by utilizing both chassis-mount and through-hole board-mount package options for up to 50kW arrays of 800V-to-400V bidirectional conversion at up to 98.8% efficiency."

Thermally-adept packaging

The multi-layer circuit boards within the power module on which components are placed are complex designs. They require special materials for optimal thermal conduction and to manage the flow of high currents and high voltages in tightly-packed spaces, all while minimizing power loss. The circuit boards also play a critical role in the assembly of the planar magnetics, which can be a source of major power loss.

Significant innovation has occurred over the years in the area of power module development. In 2015 Vicor introduced a new ChiP™ package which advanced power density with full double-sided component placement. It delivered heat extraction from both sides of the ChiP to maximize performance and power ratings. Two years later, the introduction of the copper-plated ChiP further advanced ChiP packaging, significantly simplifying thermal management by means of a wrap-around copper jacket.

High-voltage and high-power Vicor fixed-ratio converters capitalize on the thermally-adept ChiP package by utilizing both chassis-mount and through-hole board-mount package options for up to 50kW arrays of 800V-to-400V bidirectional conversion at up to 98.8% efficiency.

Integrated magnetics

Materials science plays a big role in advancing power package performance, especially when switching at multiple-MHz levels. Of the several magnetic components in a power module, some are related to the gate-drive circuits for the main power switches and are very small, low-power assemblies. Gate-drive transformers play a major role in minimizing gate-drive losses and have been optimized over many years and cycles of learning.

The main energy storage core for the converter or regulator plays the critical role in overall module performance and can be one of the main sources of power loss. The core, its windings and PCB material compositions are continually optimized for higher switching frequencies, higher power levels and lower output resistances to reduce power losses and increase efficiencies. By integrating the energy storage inductor or transformer into the power module and maximizing its performance, the power-system designer is relieved of the often difficult and time-consuming process of optimizing the power converter magnetics, and they can achieve a reduction in the overall power system footprint. One Vicor power module family that captures all of these critical design elements is the current multiplier, which is now powering some of the most advanced GPUs and AI processors in high-performance computing applications. Vicor VTM™, MCM™ and GCM™ are capable of delivering over 1000 amps, while directly converting 48V to sub-1V levels. The integrated planar magnetics in these devices have been optimized over 20 years and current multipliers now achieve current density levels of 2A/mm^2 with even further advances planned for the near future.

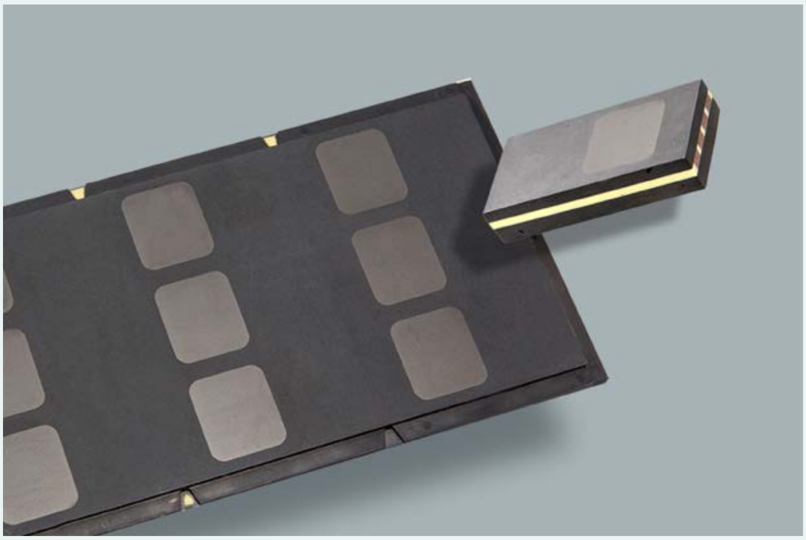
> "The new Vicor SM-ChiP™ is a plated, overmolded package intended for surface-mount attachment to a printed circuit board and is compatible with CM manufacturing techniques and equipment."

Compatibility with high-volume PCB assembly techniques

Surface-mount reflow soldering is used by all of the high-volume contract manufacturers (CMs) around the world. The new Vicor SM-ChiP is a plated, overmolded package intended for surface-mount attachment to a printed circuit board and is compatible with CM manufacturing techniques and equipment. The electrical and thermal connections of the package are formed through soldered connections to plated castellation terminal features along the perimeter of the module and continuous plated surfaces of the main package body. SM-ChiPs are compatible with tin-lead and lead-free solder alloys as well as water-soluble and no-clean flux chemistries; they can also be picked-and-placed onto the PCB. The package has also been designed to withstand multiple reflows for multi-sided PCB assemblies. Detailed SM-ChiP™ Reflow Soldering Recommendations are also provided by Vicor to ensure successful implementation.

High-volume automated power module manufacturing

The original Vicor VI Chip® package was also an overmolded package but was manufactured using individual-cavity construction. In contrast, the new ChiP™ is made and cut from a standard-size panel and make full use of both sides of the module's internal PCB for active and passive components.



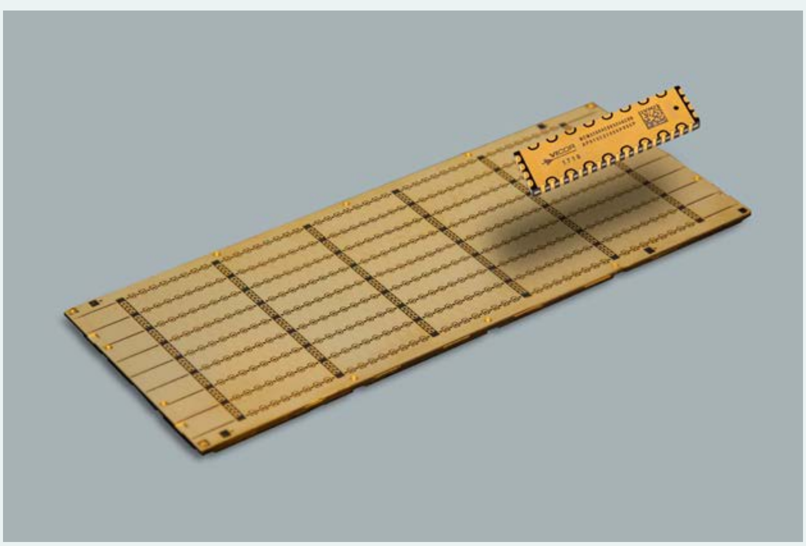
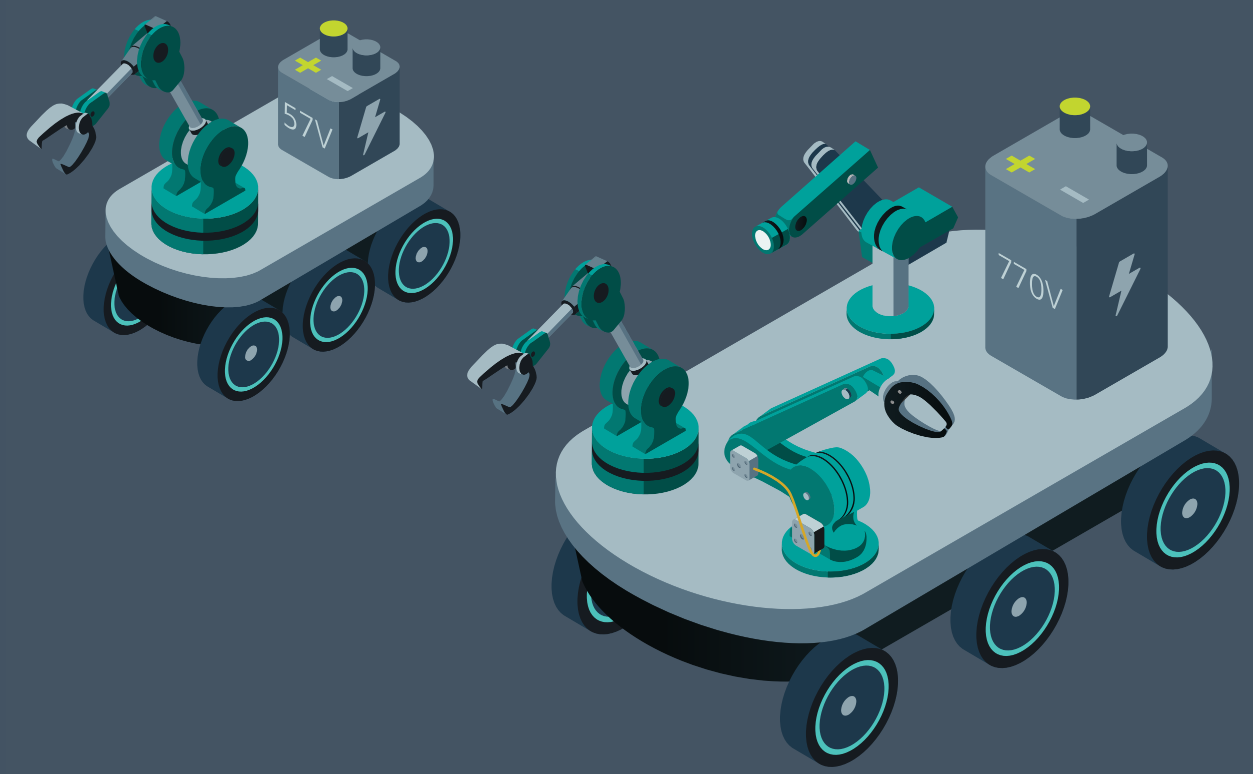


Figure 2: The new panel manufacturing process was another innovation for the power industry. ChiPs are all cut from the same size panel, enabling an automated high-volume manufacturing process.

Thermal management of this package requires double-sided cooling to maximize performance and power density. Making and cutting ChiPs from panels is very similar the way silicon chips are made and cut from wafers, but whatever the power level, current level or voltage level of the module, ChiPs are all cut from the same size panel, enabling a manufacturing operation that is streamlined, high-volume and very scalable.

Conclusion

Vicor will remain on the forefront of delivering modular high-performance power delivery networks (PDNs) by continually advancing its four technology pillars of innovation: power delivery architectures, control systems, topologies and packaging. Each pillar is essential to achieving the performance that customers demand for their advanced systems development in high-performance computing, electrified vehicles, satellite communications and industrial applications. However, the power module package is where all of the elements of innovation come together, and where materials science and a great deal of ingenuity enable the critical performance metrics of density and efficiency.



White Paper

High-density, modular power delivery networks optimize mobile robot performance

VICOR

Fixed-ratio and high-efficiency buck and buck-boost converters enable more range, duration and payload

The range, productivity, and flexibility of a mobile robot can be enhanced by the optimal design of its power delivery network (PDN). There are complex power system design and architecture considerations in such PDNs due to the variation in the battery power source voltage plus the broad variety of loads that may be part of a typical system, such as high-power AI computing systems, motor drives, sensors, communication systems, logic boards and processors. There are also EMI considerations that naturally arise from developing closely-packed and dense systems that use high-power switching regulators. The result is that robotics power systems face many unique challenges and require new approaches to address them.

A modular PDN design approach, using Vicor high-density, high-performance power modules can tackle these challenges. Understanding the fundamental engineering principles and experiences from supercomputing applications to explore how the performance and design flexibility of advanced robotic power systems can be enhanced by leveraging Vicor fixed-ratio power converters and high-efficiency wide-input-range Zero-Voltage Switching (ZVS) buck or buck-boost regulators.

Two approaches to consider:

- The use of buck and buck-boost regulators with wide input voltage ranges in power delivery networks up to 75V, within the $110V_{DC}$ SELV (Safety Extra-Low Voltage) limits per IEC. This allows low-voltage robotic power conversion stages to be smaller than their isolated DC-DC counterparts, and/or be adaptable to higher or lower battery voltages used on larger or smaller platforms.
- The use of fixed-ratio converters to scale the voltage of sources efficiently up or down as well as enhancing their dynamic response capabilities within the same PDN, or to adapt it to a much higher voltage source.

The various power delivery network architectures from these two power topologies provide the designer with multiple options to achieve a mobile system that meets their design goals.

Size, weight, performance advantages of a modular approach

When designing a power system for advanced robots, it is tempting to simply reuse a trusted DC-DC converter for each required load voltage as the need appears in form of new payloads, regardless of whether it is powering LIDAR, a GPU, a servo-drive or even constant-current loads like LED floodlights. While convenient, the evolving complexity of systems shows the need for a more holistic look at the power requirements and architecture. There are significant size, weight, performance and cost advantages to designing power systems with the latest in power converter technologies. These benefits only increase with wide-ranging load tolerances, narrow battery voltage ranges, a smaller number of isolation barriers, and in systems with short durations of maximum power and long idle times. Using newer and higher-efficiency non-isolated buck or buck-boost converters, even with input voltages above 24V, can improve overall system performance.

Fixed-ratio converters have a low-impedance path and fast transient response. The smart placement of these allows loads such as motor drives to draw current quickly without the response delay inherent in regulated DC-DC converters or the voltage droop from long low-voltage cable runs.

Both approaches enable new architectural solutions that will be explored here.

Exploring typical robotic system requirements

Consider two robotics platforms, their battery sources and various high-power loads as outlined in Figure 1. For the sake of simplicity, the battery is of the first comprises a 15-S $LiFePO_4$ with a 57V float voltage, such as is used on an all-terrain last-mile delivery bot with a manipulator or other servo-drive; 57V increases energy density compared with 24V- or 48V-based systems. Imagine also being asked to mount the same or more powerful "brains and brawns" on a much larger platform, such as a self-driving truck or harvester bot with a 200-S battery featuring a 770V float voltage, or designing the latter from scratch.

The load requirements include the following:

- 48V and/or 24V servo-drives with regeneration capability
- 12V GPU & CPU board(s), > 50A
- 5V and 3.3V rails at several tens of amps
- Any lower-power auxiliary voltage needed for additional peripherals

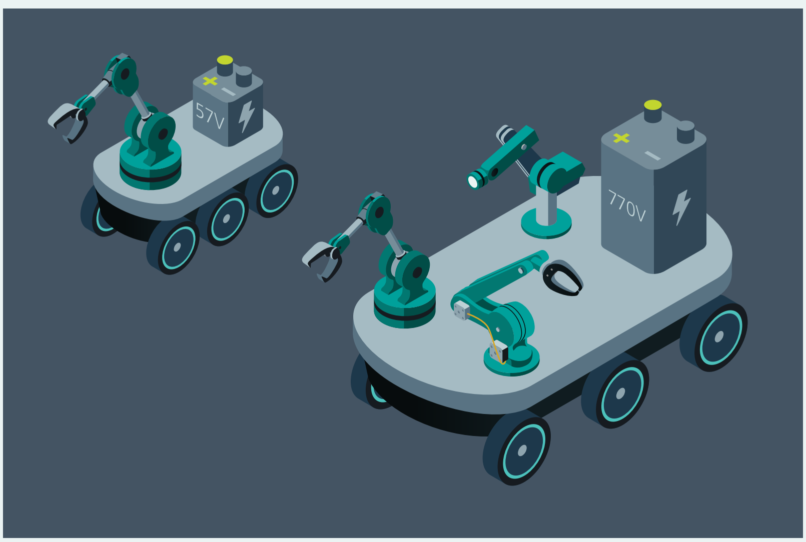


Figure 1: The two robotics platforms are vastly different sizes, but their power delivery networks have much in common. A modular approach offers flexibility in the initial designs and typically faster delivery of subsequent power systems design.

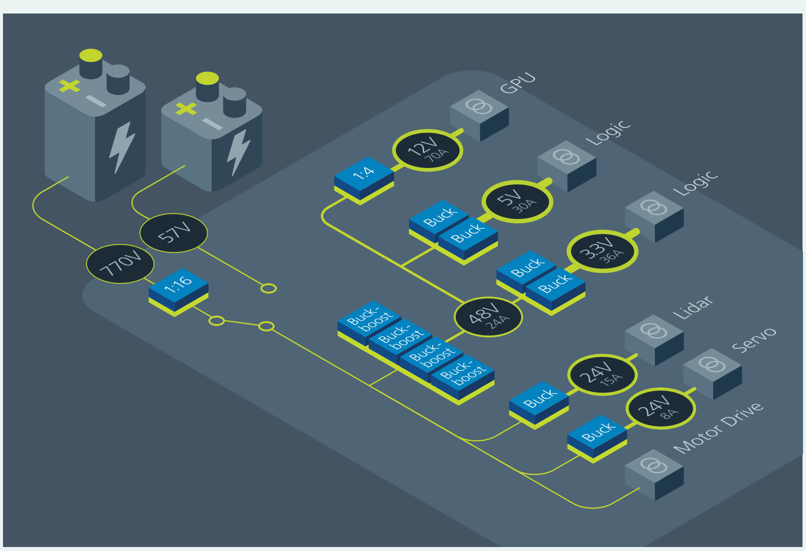


Figure 2: Power delivery network of a lower voltage supply powered by a $110V_{DC}$ SELV (Safety Extra-Low Voltage) battery or a larger vehicle's 770V battery transformed down to ~48V.

By working backwards from the load requirements, a power tree can be constructed to showing how to produce each of the needed voltages (Figure 2). This methodology enables a designer to optimize the number of regulation stages, isolation stages and transformation stages in the design. This can result in a reduction of associated losses of a needlessly complex architecture, noise, stability issues and undesirable voltage drops yielding a scalable and versatile, yet simple and efficient power solution.

Low-voltage sources: higher-efficiency wide-input-range buck and buck-boost converters

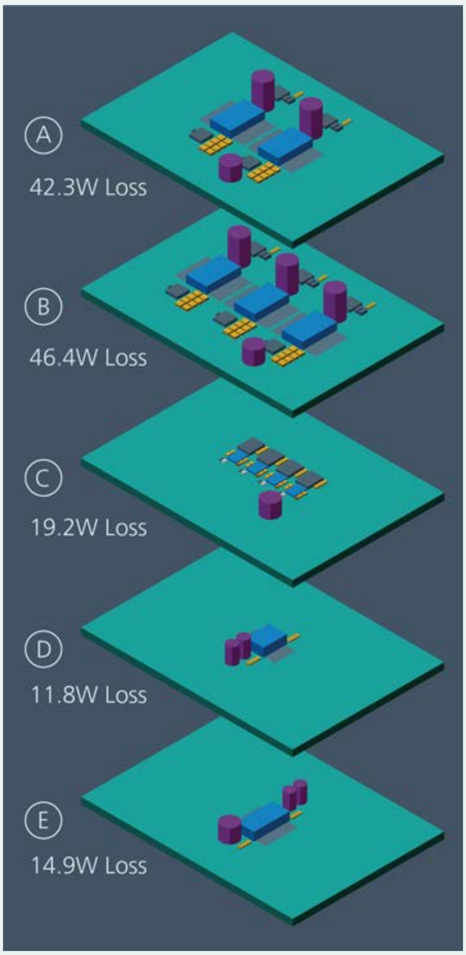


Figure 3: 600W, 48-to-12V solutions to scale, including required external components. (A) 36 – 75V, 320W isolated, regulated modules x2. (B) 43 – 154V, 240W wide-range isolated, regulated modules x3. (C) 30 – 60V, 216W, 18A buck converter x4. (D) 40 – 60V, 750W fixed-ratio converter x1. (E) 40 – 60V, 750W buck-boost + fixed-ratio x1. Power dissipation measured using production units.

When powered from an extra-low voltage source such as a 24 or 57V battery (Figure 2), all loads are often tied to the battery negative, making isolated DC-DC converters unnecessary. A much better design would employ a modern high-voltage buck converter offering 96 – 97% efficiency with low standby power, enhancing battery life. If the input-to-output voltage ratio were to allow the buck converter to operate close to its "sweet spot" in terms of the duty cycle, there would be very little common-mode EMI noise. For this example, optimal buck operation would require stepping the ~57V battery voltage down to ~12V.

Many hard-switching MOSFET-based buck converters overheat when powered from >24V as opposed to the lower V_{IN} at which their "97% efficiency" is specified due to switching losses. The switching losses scale exponentially proportionally to V_{IN} generating significantly more heat when upgrading from a 24V platform to a 48 or 57V platform for example. Reducing switching frequency reduces losses and minimum on-time issues; however, this increases the size of output inductors and capacitors.

Here, the rapid adoption of 48V backplanes in other high-power computing and automotive applications provides a model for similarly improving robotic systems. As a result, some manufacturers have improved buck converter efficiencies to a true 96 – 97% for >48-to-12V outputs, and with similar results for outputs as low as 2.5V.

For perspective on available choices, Figure 3 shows typical efficiencies, losses and sizes for several 600W, 12V converters using a 40 – 60V input measured under the same conditions at 80% load:

- Solution A: a ZVS isolated flyback converter, a common first choice for many designers during development
- Solution B: another ZVS isolated flyback converter but with higher-voltage transistors for wider input voltage range. This can be useful for covering multiple input voltage platforms
- Solution C: a synchronous ZVS buck converter with low switching losses and no transformer losses

- Solution D: a Sine Amplitude Converter (SAC™) (a type of fixed-ratio DC-DC converter) stepping V_{IN} down by a factor of ¼. This solution requires very few storage elements due to its high bandwidth and no regulation
- Solution E: a SAC as in Solution D co-packaged with a buck-boost converter adding in losses of a regulator but still rivaling a quarter-brick DC-DC in efficiency with 1/16th the size albeit at a narrower 40 – 60V input

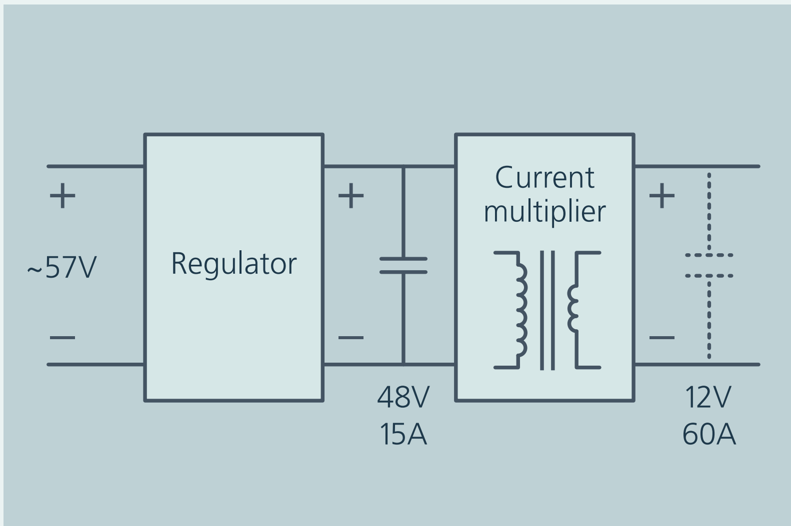


Figure 4: Diagram of a 720W (1kW peak) 48-to-12V buck converter, consisting of two conversion stages.

For larger voltage steps than what typical buck converters can handle without lowering their switching frequency, increasing their size or compromising performance too much, a modular two-step DC-DC approach that is commonly used in data center applications (Factorized Power) can be used (Figure 4). A 36 – 75V buck-boost regulator sets an accurate 48V at 96 – 98% efficiency at the input of a 97.8% 4:1 current multiplier (fixed-ratio converter discussed below), achieving smaller space and high dynamic performance, reliability, and efficiency. For improved voltage regulation, the regulator's feedback can be taken from the output of the current multiplier. The 75V rating was chosen over 60V as the source voltage may see peaks above 60V in motor drive environments as discussed below.

Fixed-ratio converters: higher-performance voltage transformation/ isolation

Fixed-ratio converters such as the Sine Amplitude Converter (SAC™) (Figure 3D) represent the best efficiency performance compared to either buck converters or isolated DC-DC. As the name implies, they convert an input voltage (V_{IN}) to an output voltage (V_{OUT}) at a fixed ratio of $K = V_{OUT}/V_{IN}$ without regulating it. Any fluctuation in the input voltage results in a fluctuation in the output scaled by K without delay of any control loop.

Conceptually, the internal operation of the SAC converter has three stages:

1. An input-side switching stage that converts the DC input into a sinusoid.
2. An ideal transformer stage that scales the ac voltage/current by the ratio of the turns between the input and output side.
3. An output-side synchronous rectifier that converts the sinusoidal transformer output back to DC.

Efficiencies up to 98% in fixed-ratio converters are possible through the use of zero-current, zero-voltage switching (ZCS/ZVS) in the switching stages, minimizing the switching losses and allowing much higher switching frequencies, commonly in the few MHz range, than hard switching converters. The subsequent proportional reduction of reactive components and EMI filters results in a small footprint and much higher power density.

Fixed-ratio converters are analogous to AC transformers which themselves are basically fixed-ratio converters for grid power distribution. Transformers are instrumental to the practical distribution of power throughout the world. Transmitting power over distance at many multiples of the source and load voltage results in much lower current to be transmitted at these high voltages, resulting in lightweight low-cost transmission lines and only short runs of low-voltage cable near the point(s)-of-load. The analogy spans multiple points since fixed-ratio converters are also capable of bidirectional operation/regeneration of step up the battery voltage efficiently to power much higher-voltage loads, essentially creating a virtual higher-voltage battery and/or transmission line. It also allows applications to regenerate braking energy into the high-voltage battery or bus. Fixed-ratio converters can be easily paralleled and inherently share current based on a voltage droop-share method, with current-sharing accuracy based on the impedance of each parallel branch.

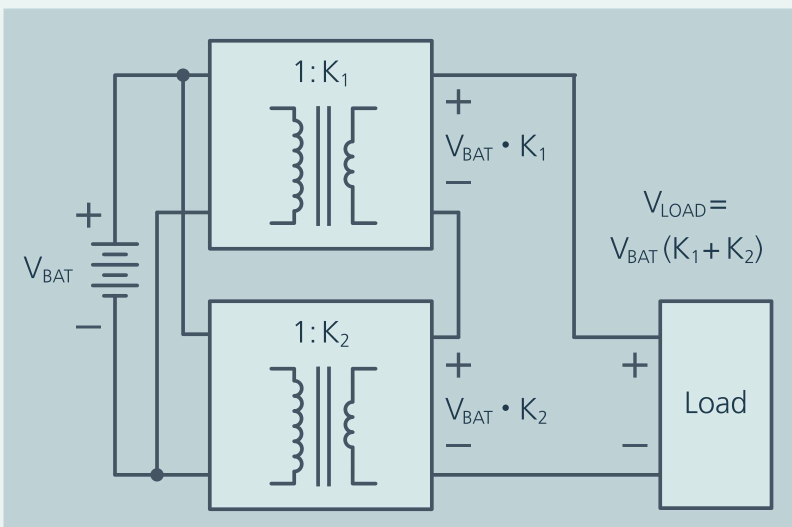


Figure 5: Input parallel, series output connection of isolated, fixed-ratio converters which can sum their output voltages.

Isolated fixed-ratio converters like many DC-DC converters can be connected with outputs in series (Figure 5) to produce multiple isolated outputs from a battery, eliminating the need for auxiliary batteries in the vehicle and reducing the number of converters and system weight, all while simplifying the design of the robotic frame. For example, assume a 400V system needing low-impedance 12V and 24V rails. Two isolated 1:32 converters with outputs in series may create both buses by tapping the series connection or their midpoint. The possibilities are endless.

Impedance reflection can reduce the effective source impedance

Fixed-ratio converters reflect impedance from primary to secondary, resembling grid-tied AC transformers. This is beneficial in robotic applications since when impedances are reflected across the transformer their magnitudes are scaled by the square of their conversion ratio.

The impedance reflection effect can be leveraged to maximize the utility of storage elements such as bulk bypass capacitors, EMI filters, and other circuit parameters even in lower-voltage systems like the two mobile robots in the initial example. Consider the 770V self-driving vehicle system that distributes the high voltage across a large robotic frame before converting it to a low voltage for highly dynamic loads such as servo-drives or AI processors: from the perspective of the load looking back toward the source, the impedance of the battery, in addition to all distribution impedances, would appear to be significantly lower than the actual impedance.

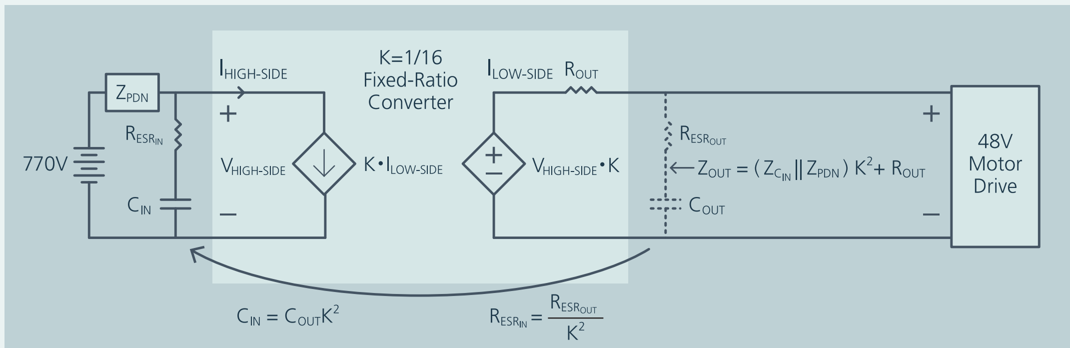


Figure 6: Impedance reflection can reduce the effective source impedance—and therefore the needed capacitance—by a factor of K^2.

When the 770V battery voltage is converted to ~48V using a K = 1/16 fixed-ratio converter (BCM4414), the result is a reduction of the source impedance, and therefore of the input capacitance, by a factor of 256 as illustrated in Figure 6. The physical size of such an input capacitor would be a small fraction of the size of an equivalent output capacitor, considering the R_{ESR}, voltage rating, longevity and performance, while the equivalent output capacitor rivals the size of the converter itself. With regulated DC-DC converters, this is possible to an extent. The regulation loops of these converters have a much lower bandwidth when compared with a fixed-ratio converter. These associated delays in addition to delays related to the discontinuous conduction mode of many converters effectively increase their impedance, limiting the effect.

For highly dynamic powerful loads like these, the reduction in resistive and inductive impedances can improve dynamic as well as static performance. Because motors are typically driven using high-frequency pulses with large instantaneous changes in current, significant source impedance will distort the voltage and current present at their terminals. Similarly, parasitic inductances within an extensive PDN can limit the current available to the motor windings, limiting torque.

Application considerations in robotics

Lightweight low-impedance harnessing, stability of power distribution network

The above bring us to applying simple principles for power distribution routing and harnesses as power needs increase, exploring higher voltage distribution converting to the load voltage near the load with discussed converters so lower currents reduce distribution losses, (dynamic) voltage drops and EMI interference. In addition low inductance layout and wiring utilizing field-cancellation with tight loops, twisted wires or routing on adjacent PCB planes may also help. Converters generally need their source's AC impedance 10x smaller than the load impedance up to the bandwidth of their control loop, particularly with dynamic loads to limit voltage drops as shown in the example with Figure 8, in line with the Middlebrook Criterion of stability analysis. So while optimizing wire gauge for ampacity, its AC impedance can be reduced with appropriately sized capacitors at the input of the converters, also reducing ac current losses and interference in longer wire runs.

Efficiency and battery life

The losses of DC-DC converters may seem negligible in regards to battery life as they tend to be an order of magnitude lower than their loads, but they can deceptively add up in form of no-load losses when the associated payload is in sleep mode. As any data sheet review reveals, transformer-based DC-DC converters tend to draw substantial power when enabled to operate their controls and magnetize/demagnetize the main switching transformer; they can easily add up to 0.5 – 1% of their full power capability. Some regulated converters consume even more power at no-load, requiring or building in a pre-load of a few percent of the maximum load to stabilize output.

Disabling these converters along with their loads when not needed may be a good option, but even disabled, power dissipation can be substantial.

Choosing as few transformer-based converters as possible, ideally one per isolation barrier needed, followed by buck or buck-boost converters for additional outputs to the same return can reduce idle-losses proportionally.

The quiescent current of many buck or buck-boost converters is in milli-amperes due to the utilization of techniques such as pulse-skipping, or more advanced techniques.

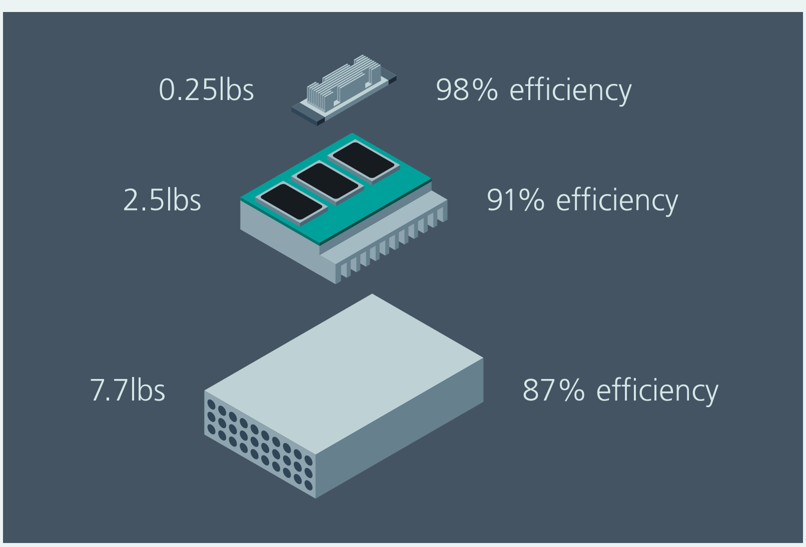


Figure 7: (from top to bottom) K = 1/16 fixed-ratio converter with heat sink, a commercially available regulated DC-DC converter array with heat sink, and a generator-driven AC-DC converter (fan-cooled).

Fixed-ratio or regulated conversion?

If the input voltage range of the load is equal to or wider than that of the source, a fixed-ratio converter may be the best option due to its size, efficiency and performance.

A 770-to-48V 1.5kW fixed-ratio converter (Figure 7) has about 1/2 – 1/3 of the losses of a regulated DC-DC forward converter as the latter has additional losses in the transformer and due to the regulation stage. A less fair but practical comparison is to the AC-DC converter that previously fed the same drive from the vehicle's AC generator with additional losses generated by the rectifier and typical PFC boost stage. It further illustrates the advantages of utilizing DC grids, whether in buildings, large equipment or robotic vehicles. While for the latter two recent developments may achieve respectively 94% and 91% under comparable conditions, the fixed-ratio converter does not have the same regulation function or the associated losses.

Highly dynamic loads

When powering a motor drive directly from a battery, voltage drops occur due to both battery and cable impedances, and these impedances also limit current. Both voltage drops and current limits are a function of wire gauges and the load's distance from the source.

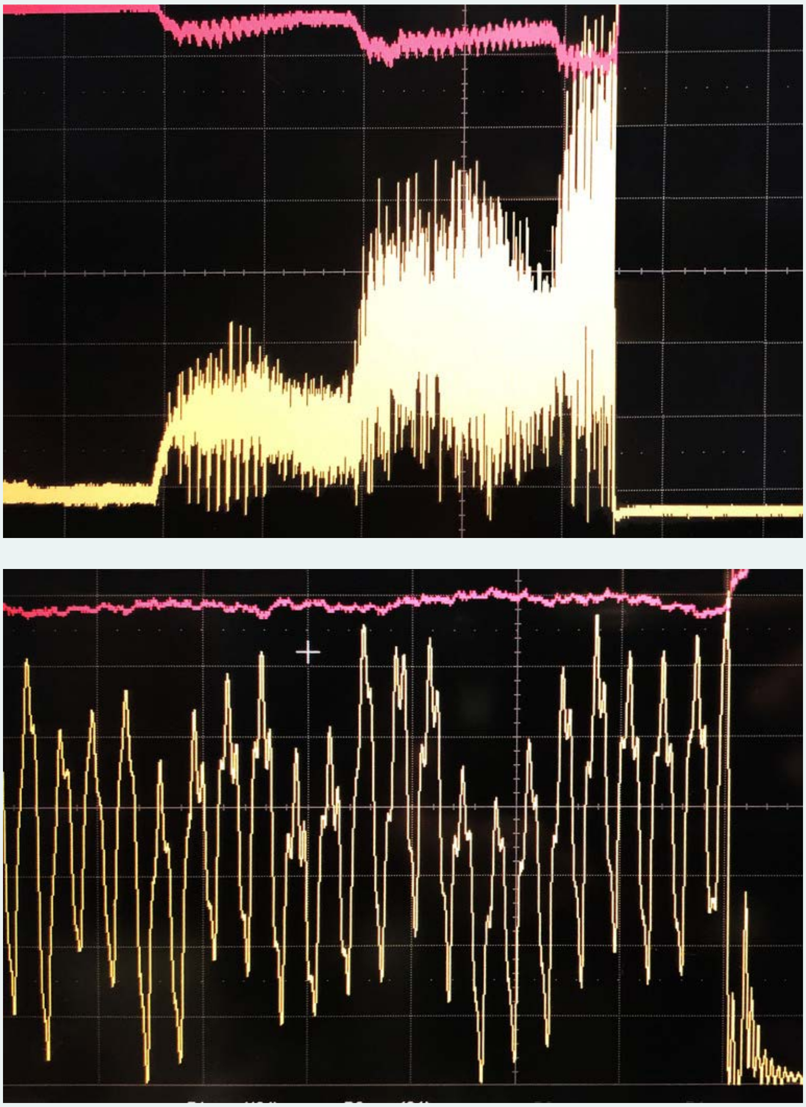


Figure 8: (top) Oscilloscope image at 20ms/div of the 770V input [red] at 100V/div and current [yellow] at 2A/div accelerating a 48V motor through a 6kW [8kW peak] fixed-ratio converter showing acceleration steps and PWM pulses, (bottom) peak detail at 100µs/div.

Using a fixed-ratio converter lowers the effective source impedance seen by the load, but this also increases the peak currents seen by the converter and ultimately by the source. Protections built into the converter to protect against overcurrent and short-circuit faults may be triggered by highly dynamic loads and should be considered during the design.

See Figure 8 for example, the 770V input voltage and current supplying four 35A, K = 1/16 fixed-ratio converters (like the ones in Figure 7) are shown. Using Figure 6 as a block diagram, R_{OUT} = 3.5mΩ and Z_{PDN} = 10Ω (including a negligible battery impedance) to power a 48V motor drive.

Placing the converter near the motor-drive makes it see the 10Ω source as only 10/256 = ~40mΩ, for a total 43.5mΩ including R_{OUT} with no 48V cable. The peak current sourced is 14.7A, as the low-impedance converter provides the PWM current peaks in addition to the average current, necessitating it to be specified at the 4 – 5A higher peak-current capability.

Figure 9 shows impedance reflection in action. A 10µF, 30mΩ R_{ESR} input capacitor is used instead of a bulky 10mF, 3mΩ R_{ESR} capacitor at the output. This reduced input ripple current on the source cable from 11 to 1A_{P-P}, greatly reducing losses due to the reduction in ac impedance from 10 to ~1Ω. The peak current dropped to 9.75A with a small output LC filter — above the converter's 8.75A continuous current limit but well within the 14A short-term current limit.

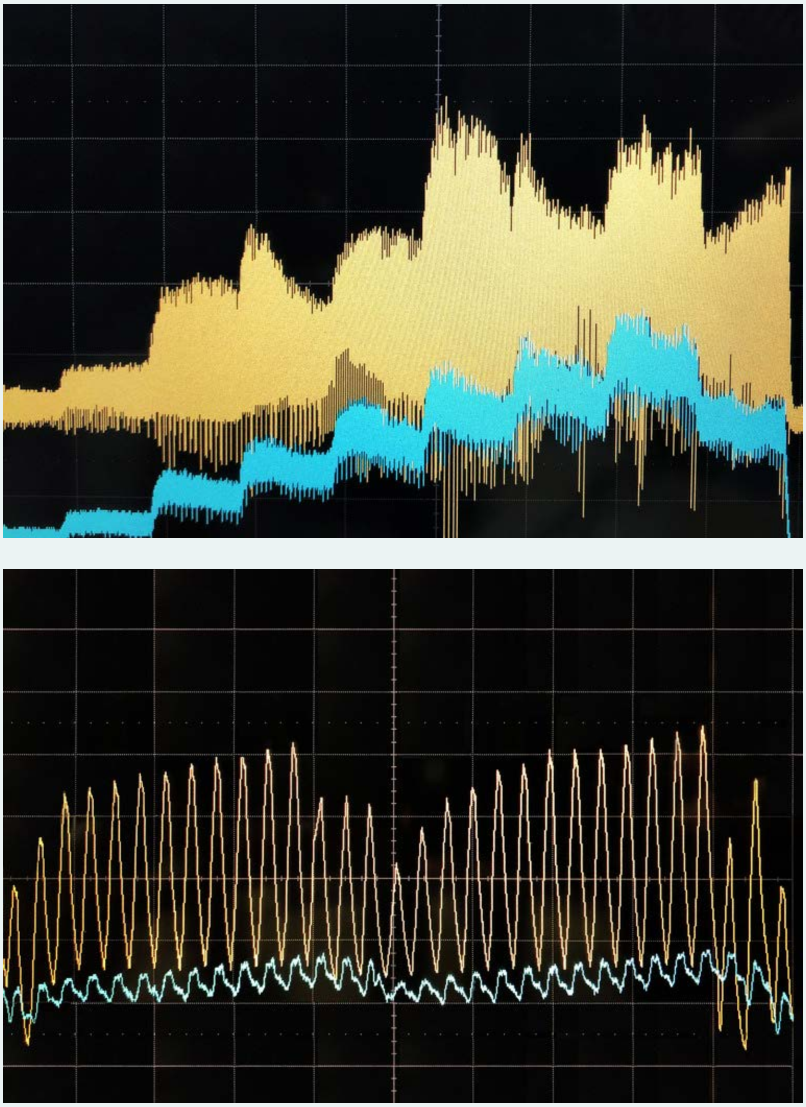


Figure 9: Converter output of $180A_{PK}$ (yellow) at 40A/div, input current (blue) at 2A/div. Ripple is reduced by capacitance placed a the input. (left) 20ms/div (bottom) 0.1ms/div.

Capacitive loads

At start up, motor drives and computing boards act as large capacitive loads. Computing cards may have a large array of onboard buck converters, each equipped with bulk input capacitors, and/or additional LC filters. The DC-DC converter powering them needs to have either a generously specified allowable external load capacitance or to be followed by a form of pre-charge circuit to work with large capacitive loads as is often the case powering motor drives with fixed-ratio converters.

This is an often-overlooked item until late in the design. Some regulators, particularly buck-boosts, are also designed for battery charging and allow for a separate current-control loop and/or adjustable soft-start time, allowing for them to be used with massive load capacitances.

Power regeneration and input voltage considerations

During dynamic operation or braking, a motor drive may act as a generator. In our 57V example, the regenerating primary motor drive's reversing current will charge the battery through the connecting harness, raising its voltage along the path proportionally to the associated impedances, possibly to above 60V. Any DC-DC converter powered by it would then have to be rated not at the commonly available 60V but to a higher voltage.

The schematic in Figure 6 also applies to power distribution networks where a motor drive such is powered by a bidirectional converter, such as our example in Figure 8. Regenerating energy can raise the voltage on both the low voltage and high voltage terminals proportional to Z_{OUT} through the converter. If the converter is unidirectional this regenerative energy is blocked and only the output capacitor C_{OUT} is charged. So the regenerative energy and its resulting voltage rises should be limited if possible to stay within the maximum output voltage specification of the converters and C_{OUT}, or a brake-circuit can be implemented to absorb the energy.

Summary

To optimize performance and increase range, productivity and flexibility, robotic system designers are encouraged to map out the power tree of their application and weigh different types of converter combinations and PDN design strategies. It is advantageous to distribute a higher voltage across a platform and transform it close to point-of-load to the required voltage.

Creative use of Vicor high-density, high-performance fixed-ratio converters modules and buck and/or buck-boost regulator modules likely will achieve optimal performance for each load with efficient and lightweight power delivery. Combining these makes it possible to standardize on highly-efficient, non-isolated end power stages that have a moderately wide input range. These can be connected to higher-voltage battery architectures through fixed-ratio converters deployed with appropriate transfer ratios.

Previously published in IEEE Power Electronics, December 2020, as "Rethinking the power delivery networks of mobile robots."

Tools

This section outlines Vicor tools that provide novice and experienced engineers a digital workspace where they can design and test power module solutions to best fit their application needs.

Power System Designer

The Power System Designer is a user-friendly software which both novice and experienced system designers can utilize to architect end-to-end power delivery networks. This tool harnesses the Vicor Power Component Design Methodology to produce optimized solutions without time consuming trial and error. The Power System Designer also provides a service which is up to 75% faster than traditional methods and allows users to export the final BOM.

Whiteboard

Whiteboard is an online tool with an easy-to-use workspace where users can analyze and optimize the performance of different power chains. Users are able to find the best solution for their application needs using Vicor high density, high efficiency power modules. In addition, users can set operating conditions for each component of the power design and get loss analysis for individual components and the system overall.

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