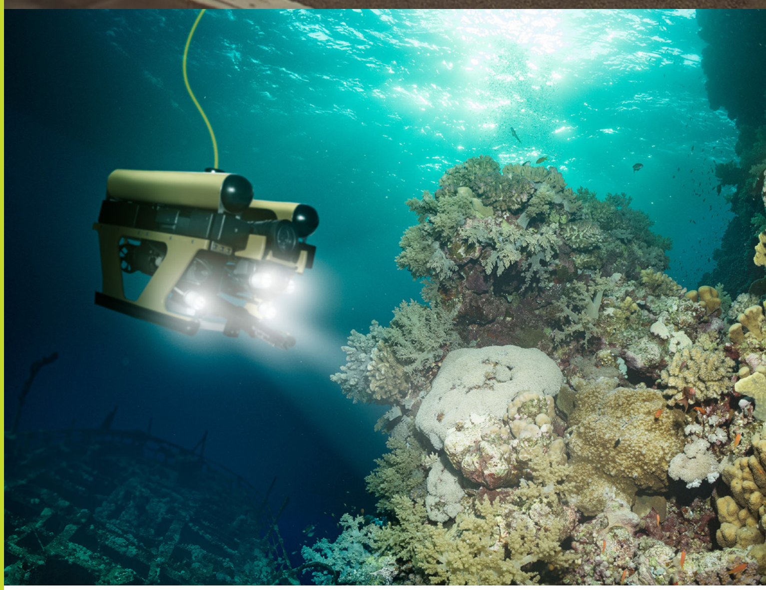


Robotics eBook

Advancing mobile robotics with modular power delivery networks

VICOR

Contents

Robotics eBook Introduction

Robotics are a vital part of the economy, with almost every product touched by a robot at some point in its lifetime. Whether it's during manufacture, delivery, warehouse inventory management, or agriculture harvesting, robots are crucial to efficient manufacturing and supply.

Most mobile robots are fueled by batteries, which means a limited amount of energy is available before the system must be recharged. That makes power conversion efficiency a critical factor. But efficiency is only one aspect of power conversion that can significantly impact the performance, functionality and reliability of mobile robots. A well designed power delivery network (PDN) not only improves efficiency, it also reduces weight and size, enabling extended range and freeing up space for larger payloads and more functionality.

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

Today's demands exceed the capabilities of traditional power system designs. Robotics designers need a better way to deliver power using PDNs based on leading-edge topologies, architectures, and packaging. High-performance, high-density power modules from Vicor enable new PDNs that are smaller, lighter and more efficient than conventional solutions, enabling mobile robots to take on larger and heavier payloads with greater range. Module-based PDNs are also more flexible than conventional bricks and easier to implement than discrete solutions, accelerating time-to-market.

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.

Next, in-depth articles start with a robotics Q+A, and then white papers that explain different approaches to various robotic power system requirements, how packaging differentiates PDNs, and how high-density, high-performance power modules can improve time-to-market.

Lastly, you'll be provided with links to a variety of comprehensive technical resources including online design tools and application notes.

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

VICOR

Case study:
Security robot

More patrolling, less recharging

Customer's challenge

The addition of new sensors like LIDAR (light detection and ranging), together with sophisticated onboard AI processors, has allowed autonomous robots to interact more safely with humans. This manufacturer of security robots needed to integrate the new technologies into an upgraded robot platform that could support the higher processor loads while traveling further after a recharge. This required a larger battery and a smaller and scalable power supply to free-up space for it. The key goals were:

- Extend the operational range and duration
- Free-up space by minimizing power supply size
- Flexibility to accommodate power requirements of future sensors

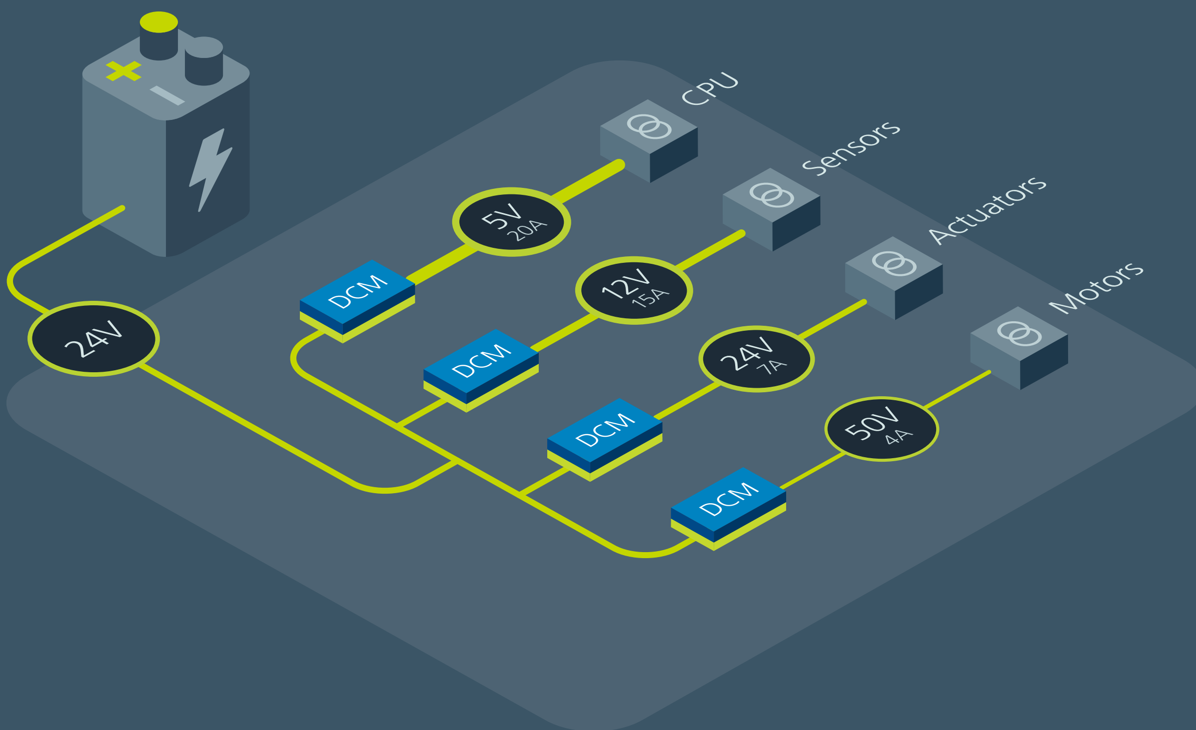
The Vicor solution

The new design employed DCM DC-DC converters for each power rail. These small, highly efficient converters reduced the footprint and weight by 70% compared to the previous brick-based design. It also improved the system efficiency by 30%, reducing power losses and therefore increasing battery range. The DCM's wide input voltage range allows compatibility with future battery technologies. Key benefits were:

- Low loss conversion to maximize performance from battery
- High power density freed up space
- Modular solution to allow future scaling-up of power

The DCM Converters saved space

Power delivery network: Separate DCM DC-DC converters provided each of the four output rails. The converters isolated and regulated the fluctuating battery input voltage. Simple paralleling allows further DCMs to be added in future to meet a higher output power requirement on any rail. To analyze this power chain go to the Vicor Whiteboard online tool.



DCM modules

Input: 9 – 420V

Output: 3.3, 5, 12, 13.8, 15, 24, 28, 36, 48V

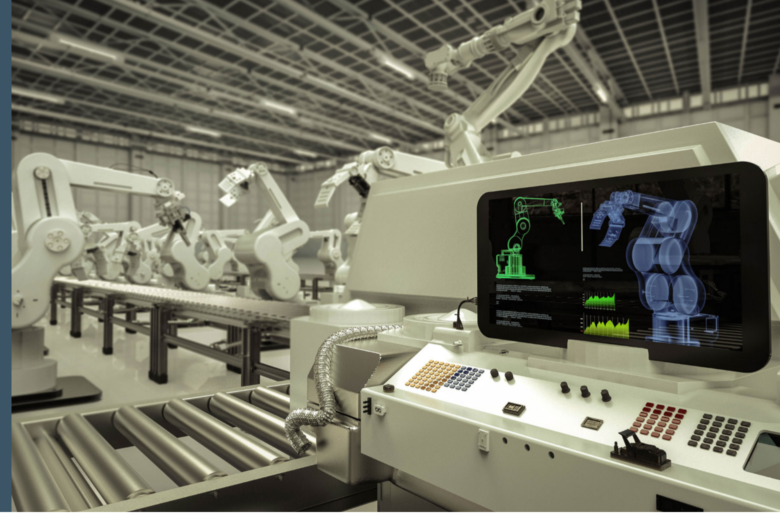
Power: Up to 1300W

Peak efficiency: Up to 96%

As small as 24.8 x 22.8 x 7.2mm

vicorpower.com/dcm

Case study:
Machine vision system



More power within the same space

Customer's challenge

Machine vision systems have dramatically increased the throughput and improved the quality of products built on automated production lines by reducing inspection time and improving accuracy. This manufacturer was looking to improve throughput further by upgrading the computing power of the image processing system. However, there was no additional space for expansion as the equipment form factor was already fixed. The key goals were:

- Faster, more powerful image processing required increased power
- Space for larger power supply not available
- Future upgrades will require even more power

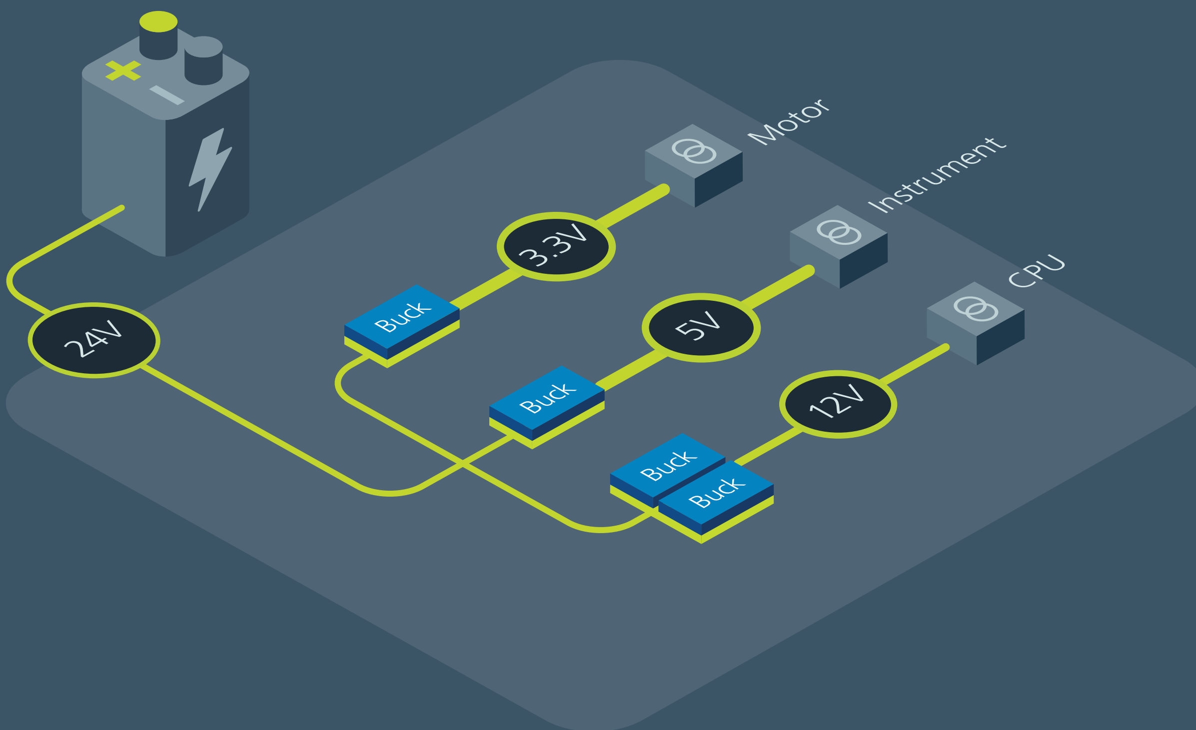
The Vicor solution

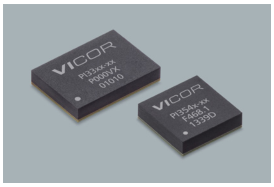
The three output rails were converted down individually directly from the 24V input supply. The requirements of the two low-voltage, low-power (50W) rails were met by Vicor ZVS Buck regulators. The higher power 12V rail (170W) was provided by two ZVS Buck regulators in parallel. Key benefits were:

- Extremely small sized solution (10 x 14mm per regulator, with few external components)
- Low waste heat reduced space required for managing heat (95.5% efficiency)
- Regulators easily paralleled for increased power

Vicor ZVS Buck Regulators maximized power available within a tight space

Power Delivery Network: ZVS Buck regulators directly converted the 24V input to each individual output, increasing system efficiency, reducing waste heat and improving reliability. To analyze this power chain go to the Vicor Whiteboard online tool.





ZVS buck regulators

Inputs: 12V (8 – 18V), 24V (8 – 36V), 48V (30 – 60V)

Output: 2.2 – 16V

Current: Up to 22A

Peak efficiency: Up to 98%

As small as 10 x 10 x 2.5mm

vicorpower.com/buck

VICOR

Case study: Modular multi-purpose ROV (VideoRay)

Flexible solution enabled by modular power

Customer's challenge

For optimum maneuverability and to offset the drag from ocean currents, 1kW of thruster power is required over the tether of an underwater ROV, yet the tether needs be light and thin. When used in very deep water, to maximize performance, this manufacturer further reduced the tether diameter by powering the ROV from an onboard 48V battery. This eliminating the weight of the power cables, enabling the tether to be used only for communication purposes. Modularity of the ROV power solution was a key goal so the platform could be quickly reconfigured for different use cases. Key goals were:

- Adapting to different power sources required a flexible power solution
- Free up space onboard for payload
- Eliminating down time and associated costs requires a highly reliable solution

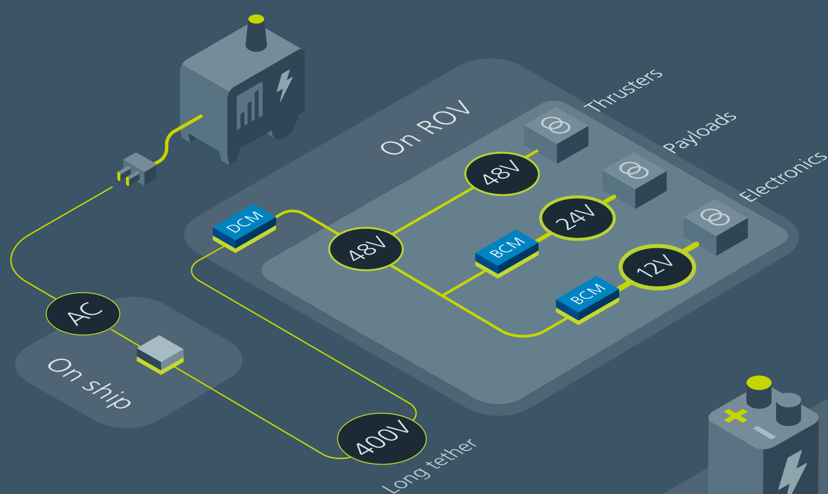
The Vicor solution

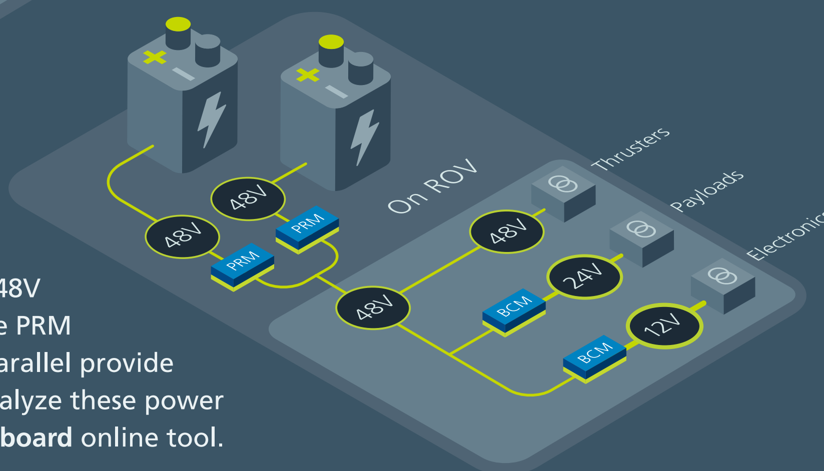
For the tethered option an array of three 400V input DCM DC-DC converters deliver an isolated, stable, 48V rail. For the ROV configuration powered by internal batteries three highly efficient PRM regulators are used to provide each of the redundant 48V rails.

- Modular power components that can be changed to meet diverse requirements
- Highly dense solution occupies just 25% of the space required for a brick-based solution
- Rugged, highly integrated power components for high reliability (>1.85M hours MTBF)

Flexible power components optimize conversion for multiple use cases

Power delivery network: On the ship the AC supply is rectified to provide the 400V DC tether voltage. On the ROV, the tether voltage is isolated and regulated to 48V by an array of three DCM DC-DC converters. The regulated 48V rail directly powers the thrusters and two BCM DC-DC transformers with 95% efficiency provide the 24V and 12V outputs for onboard loads.



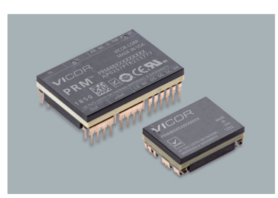


When, for redundancy, the ROV is powered by two 48V batteries, two arrays of three PRM regulators with outputs in parallel provide the stable 48V output. To analyze these power chains go to the **Vicor Whiteboard** online tool.

DCM converters

- Input: 9 – 420V
- Output: 3.3, 5, 12, 13.8, 15, 24, 28, 36, 48V
- Power: Up to 1300W
- Peak efficiency: Up to 96%
- As small as 24.8 x 22.8 x 7.2mm

vicorpower.com/dcm



PRM regulators

- Input: 48V (36 – 75V)
- Output: 48V (5 – 55V)
- Power: Up to 600W
- Peak efficiency: Up to 97%
- As small as 22 x 16.5 x 6.73mm

vicorpower.com/prm

BCM bus converter modules

Inputs:	36 – 60V	38 – 55V
200 – 330V	200 – 400V	240 – 330V
260 – 410V	330 – 365V	360 – 400V
400 – 700V	500 – 800V	

- Output: 2.4 – 55V   Current: Up to 150A
- Peak efficiency: Up to 98%
- As small as 22.0 x 16.5 x 6.7mm

vicorpower.com/bcm

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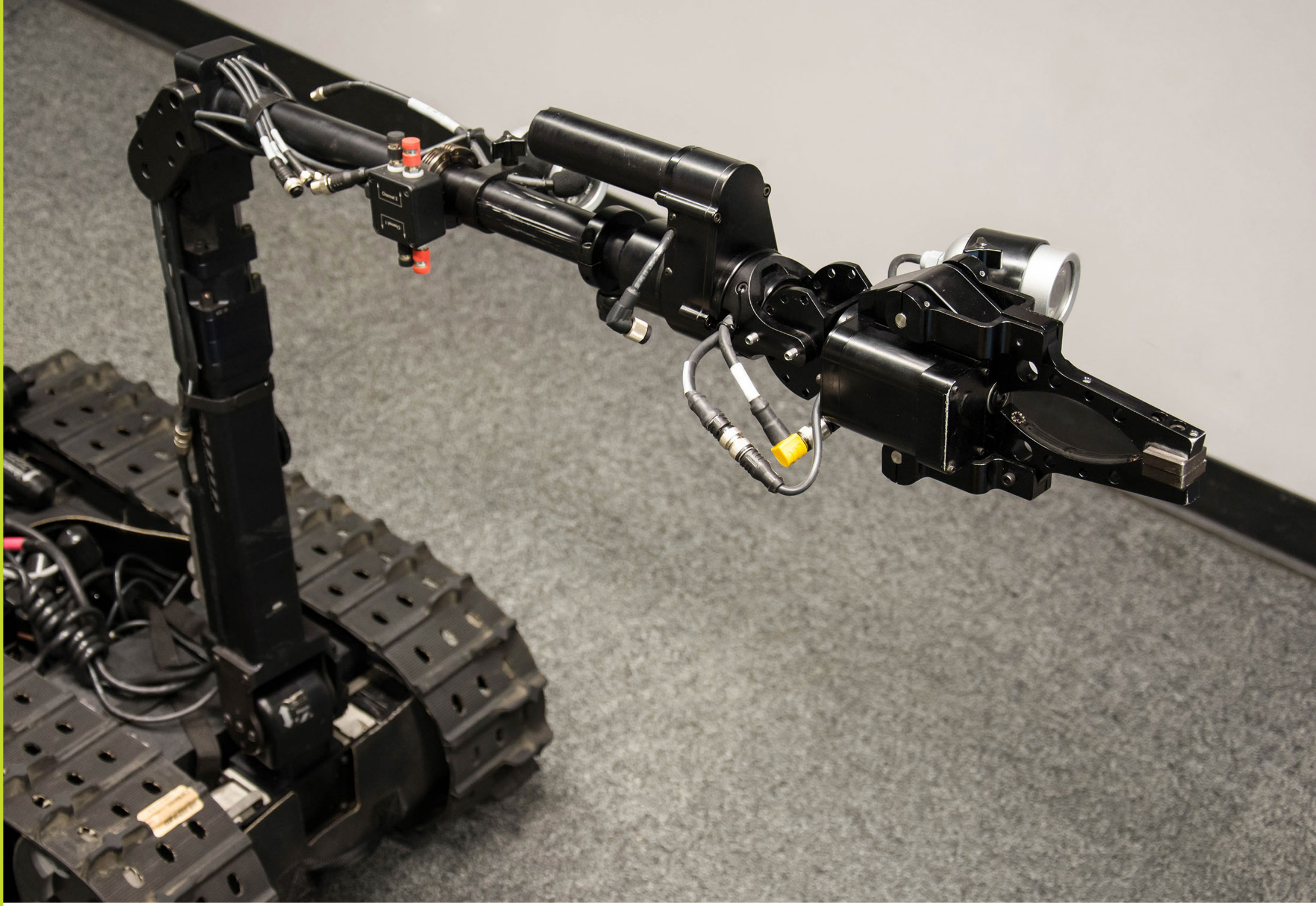
Technical articles



By Tom Curatolo, Principal Field Application Engineer,
and David Berry, Principal Applications Engineer

Robotics Q+A

VICOR

Robotics Q+A

Q. What are the key challenges faced by engineers working on Robotics, which your proposed solutions aim to solve?

A. The key challenge we see facing engineers today is the demand for smaller, lighter weight, higher power designs. In many applications there is a need to carry a larger payload (a variety of enhanced and complex electronics such as sensors, cameras, tools with communications and control) plus the robot needs to be smaller and lighter to make it easier to transport, and robust enough to deal with various environments. Often these applications involve remote operation, intricacy of tasks and risk from failure leading to the need to improve data transmission speed, sensor accuracy and image quality. Management of the EMI from the power supply often is a fundamental requirement as well.

> "The key challenge we see facing engineers today is the demand for smaller, lighter weight, higher power designs."

The world of manufacturing is changing, driven by various Industry 4.0 initiatives. With this development, closely coupled, internet worked robotic solutions have to be addressed. The flexible networking of previously sequential, belt-supported production processes using mobile robots, so-called AGVs (autonomously guided vehicles), and the direct collaboration of humans with robots using flexible, collaborative robot systems are of particular significance for the change. In addition to making these production systems more flexible, engineers are striving to further increase the uptime of installed systems due to the rising cost of electricity and $CO2$ emissions leading to the use of energy as efficiently as possible. The demands on automation solutions: individual subsystems such as robots, drives, charging systems for mobile autonomous robots as well as power distribution contribute to improving the energy balance.

We aim to solve these challenges through our next-generation power modules that deliver higher density and higher efficiency than other DC-DC converters.

Q. How many products are focused on the Robotics space?

A. We currently have a variety of products that address the demands of Robotic applications with either DC or AC input requirements. The DCM (DC Converter Module) product family offers significant improvement over competitive DC-DC converter solutions. In addition, further power density can be achieved with the PRM (Pre-Regulator Module), a high-performance buck-boost regulator. The PRM 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 (Non-Isolated Bus Module), ZVS (Zero Voltage Switching) Buck and ZVS Buck-Boost regulators. These modules can also be paralleled for higher power conversion.

Q. Can you also indicate for each product, the applications for which they are best suited?

A. Typically each product has specific attributes and the design goal of the engineer will dictate which product(s) provide the overwhelming advantage. Our products and strategy have been ideally suited for many robotic applications utilized in bomb disposal, agricultural harvesting, warehouse inventory movement, campus delivery and consumer delivery. Some of these applications are tethered or employ wiring harnesses for power delivery. Other applications employ robots that are powered by batteries, making power conversion efficiency – along with size/weight – critical. With a power component approach challenges are easily addressed in regards to load capacity, placement and user functionality requirements. Vicor offers an online product selector tool to aid in selecting the appropriate product(s) given application needs. This tool is called the Power System Designer and is located on our website.

Q. If design engineers want to review your solutions for designs they are working on currently—is there any simulation or assistance that you offer?

A. Yes, we offer valuable tools online for simulations and assistance using thermal management and component calculators. In addition, we are offer demo boards and our Applications Engineers are available to assist with design reviews.

> "Vicor offers an online product selector tool to aid in selecting the appropriate product(s) given application needs. This tool is called the Power System Designer and is located on our website."

Q. For design engineers who want samples, do you supply them directly or can they buy from leading catalogue distributors?

A. Standard product samples can be ordered from Digi-Key, Mouser and Arrow, plus solutions for Robotic systems can be discussed thoroughly with our Applications Engineering team.

Q. Why should your customers not look at designing their own modules themselves?

A. We achieve high power density, efficiency and thermal management through proprietary topologies and packaging. Additionally, we achieve high quality and reliability through disciplined, automated manufacturing. It would be difficult to achieve the power density and efficiency of our parts without access to our intellectual property and manufacturing.

Q. Any pricing indicators that you can share with our audience?

A. Pricing depends on a number of factors, including qualification requirements and an OEM's implementation of the power delivery network using combinations of Vicor modules. Customers will realize considerable cost savings using a Vicor modular solution which helps reduce overall system cost.

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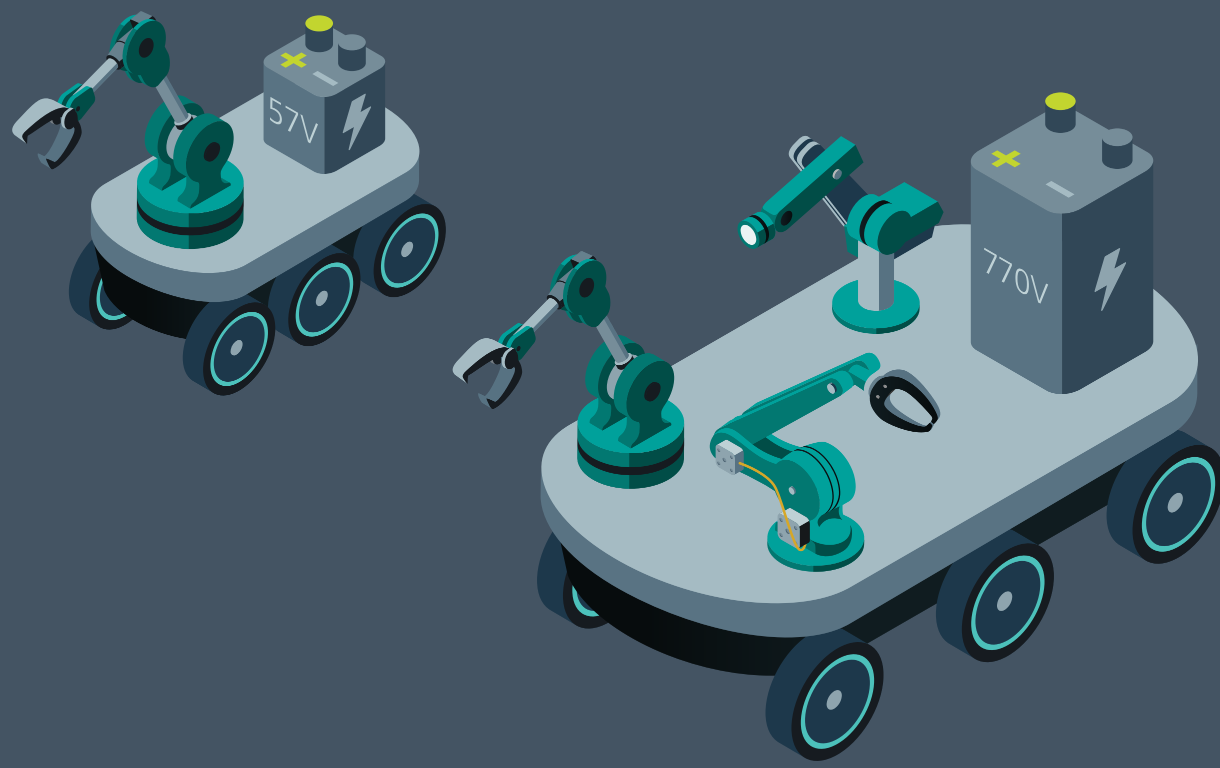
www.vicorpower.com Customer service: custserv@vicorpower.com Technical support: apps@vicorpower.com



White Paper by Anna Giasson and Stavros Dokopoulos

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

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

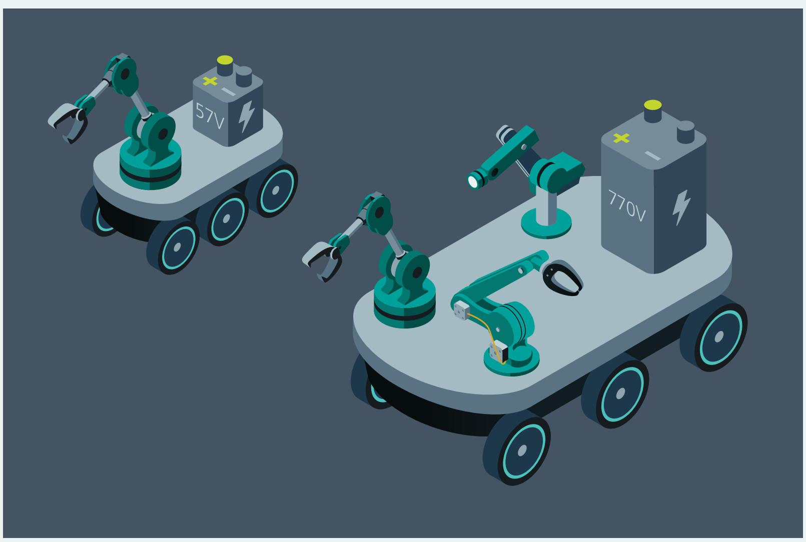


Figure 1: The two robotics platforms are vastly different sizes, but their power delivery networks have much in common. A modular approach offers flexibility in the initial designs and typically faster delivery of subsequent power systems design.

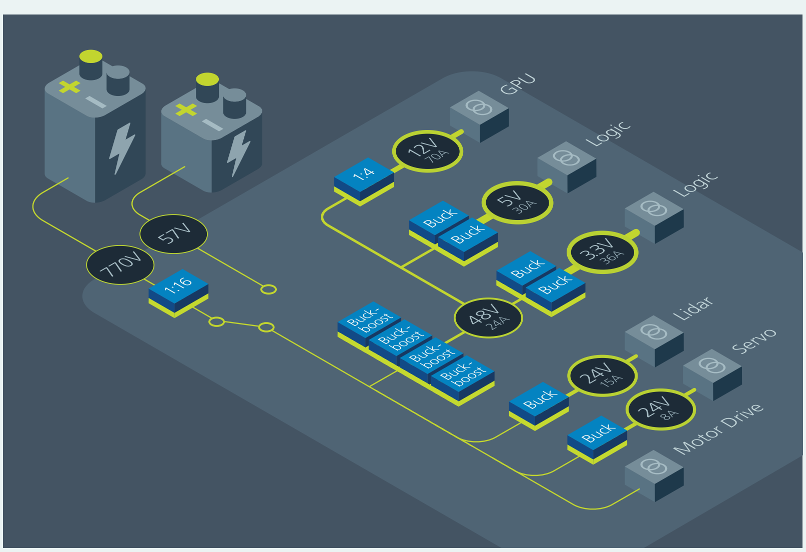


Figure 2: Power delivery network of a lower voltage supply powered by a $110V_{DC}$ SELV (Safety Extra-Low Voltage) battery or a larger vehicle's 770V battery transformed down to ~48V.

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

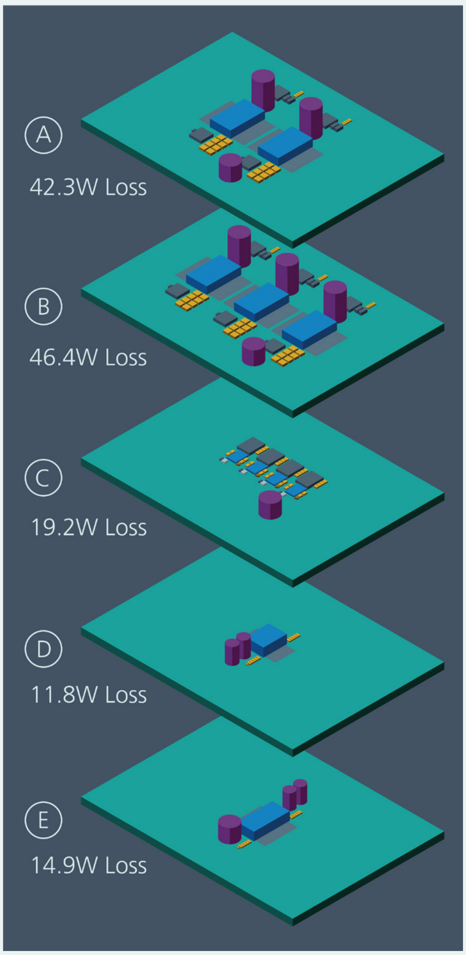


Figure 3: 600W, 48-to-12V solutions to scale, including required external components. (A) 36 – 75V, 320W isolated, regulated modules x2. (B) 43 – 154V, 240W wide-range isolated, regulated modules x3. (C) 30 – 60V, 216W, 18A buck converter x4. (D) 40 – 60V, 750W fixed-ratio converter x1. (E) 40 – 60V,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

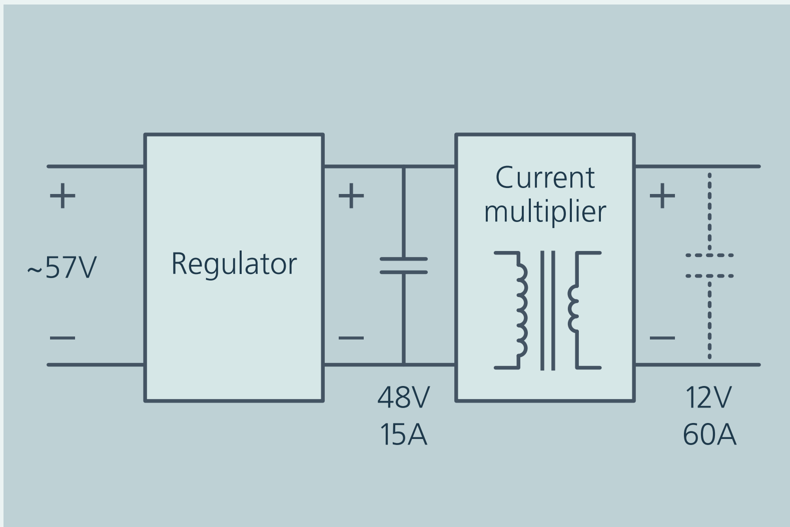


Figure 4: Diagram of a 720W (1kW peak) 48-to-12V buck converter, consisting of two conversion stages.

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:

- An input-side switching stage that converts the DC input into a sinusoid.
- An ideal transformer stage that scales the ac voltage/current by the ratio of the turns between the input and output side.
- 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.

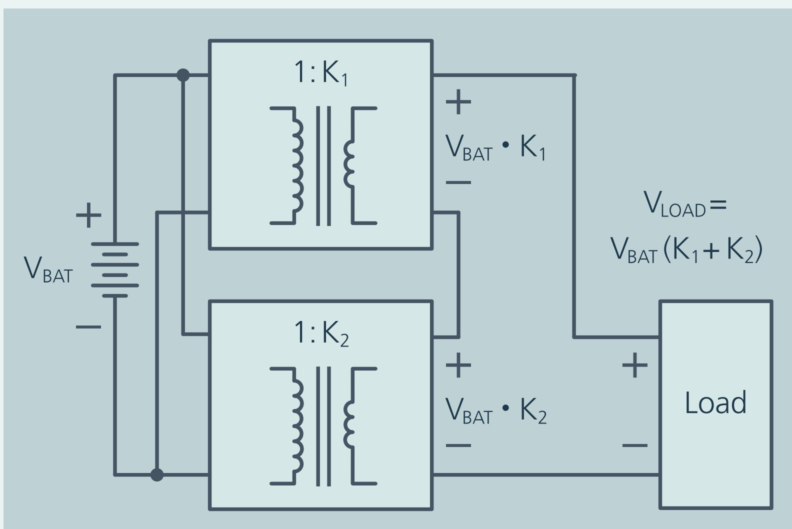


Figure 5: Input parallel, series output connection of isolated, fixed-ratio converters which can sum their output voltages.

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.

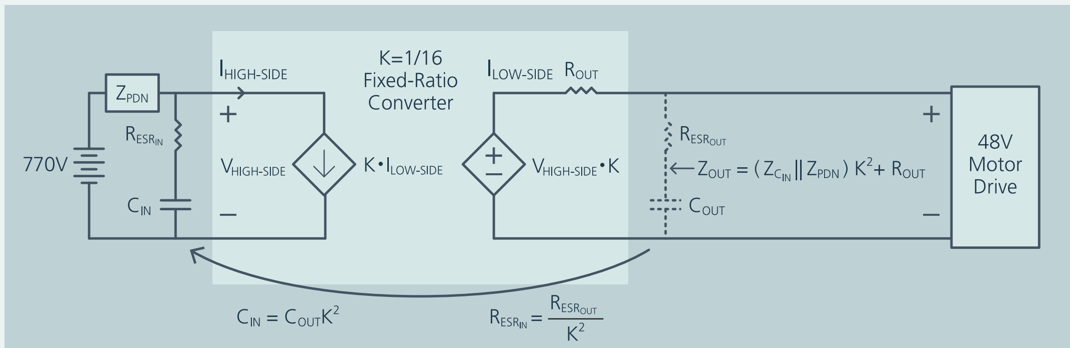


Figure 6: Impedance reflection can reduce the effective source impedance—and therefore the needed capacitance—by a factor of K^2.

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.

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.

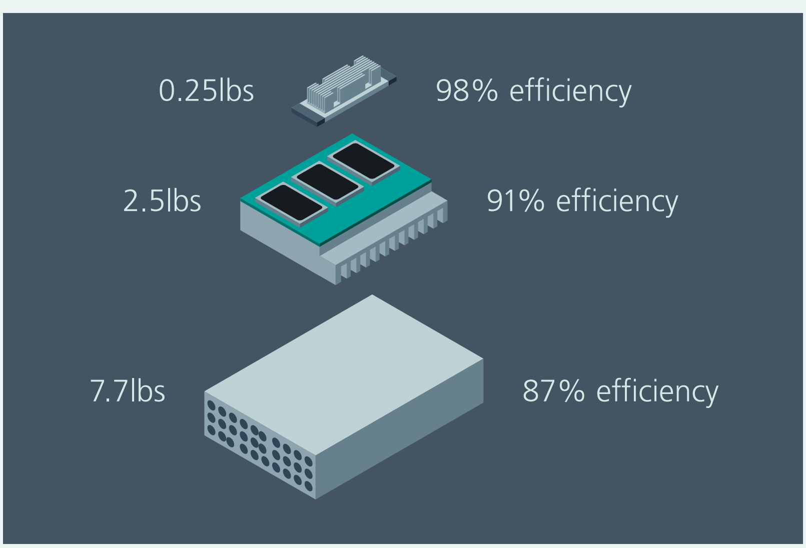


Figure 7: (from top to bottom) K = 1/16 fixed-ratio converter with heat sink, a commercially available regulated DC-DC converter array with heat sink, and a generator-driven AC-DC converter (fan-cooled).

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.

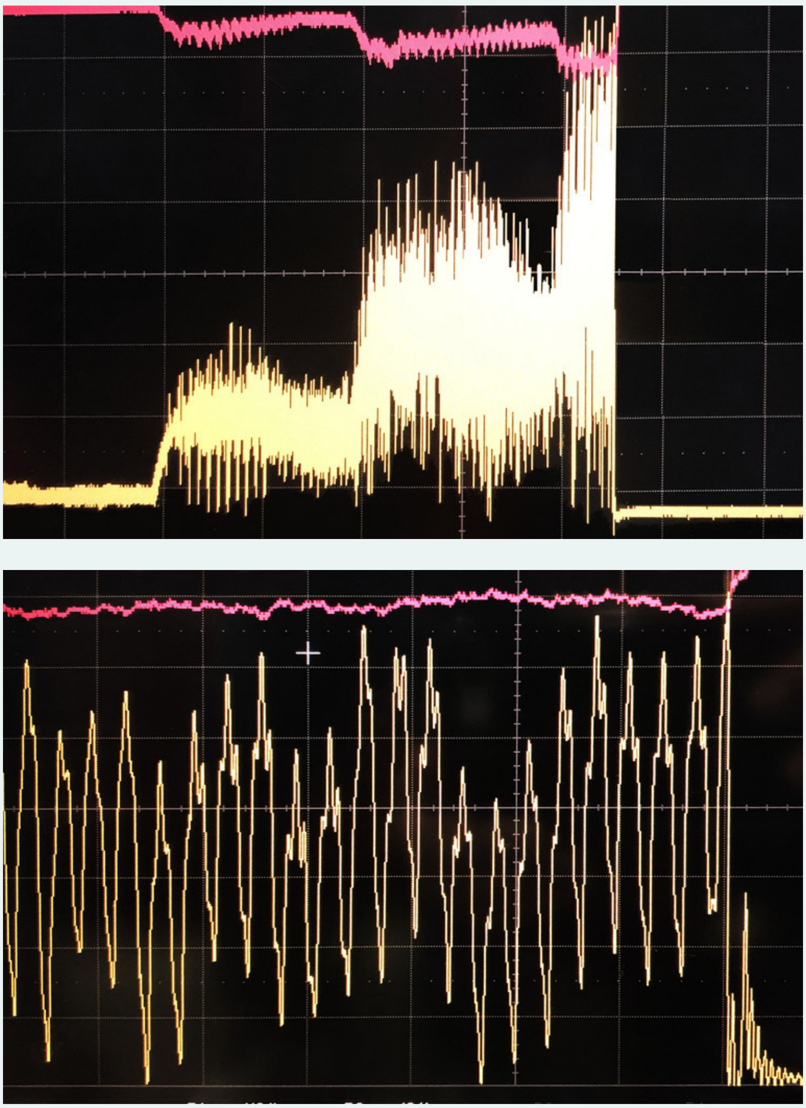


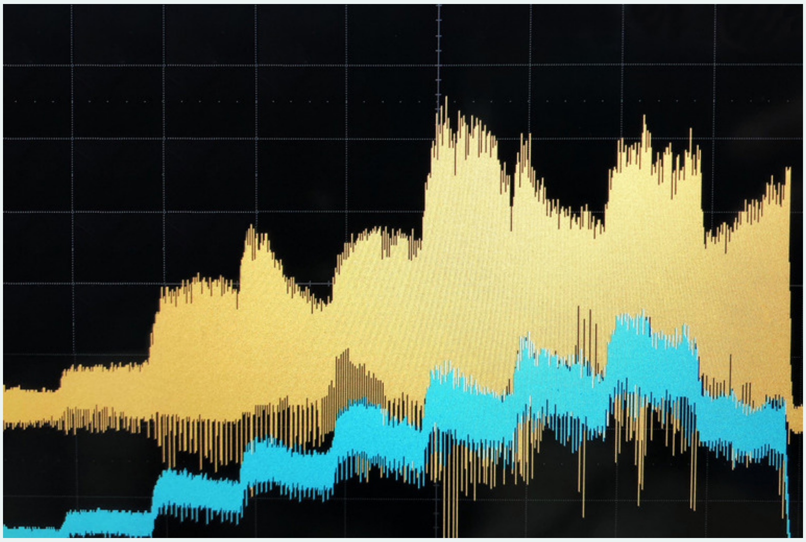
Figure 8: (top) Oscilloscope image at 20ms/div of the 770V input [red] at 100V/div and current [yellow] at 2A/div accelerating a 48V motor through a 6kW [8kW peak] fixed-ratio converter showing acceleration steps and PWM pulses, (bottom) peak detail at 100µs/div.

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.



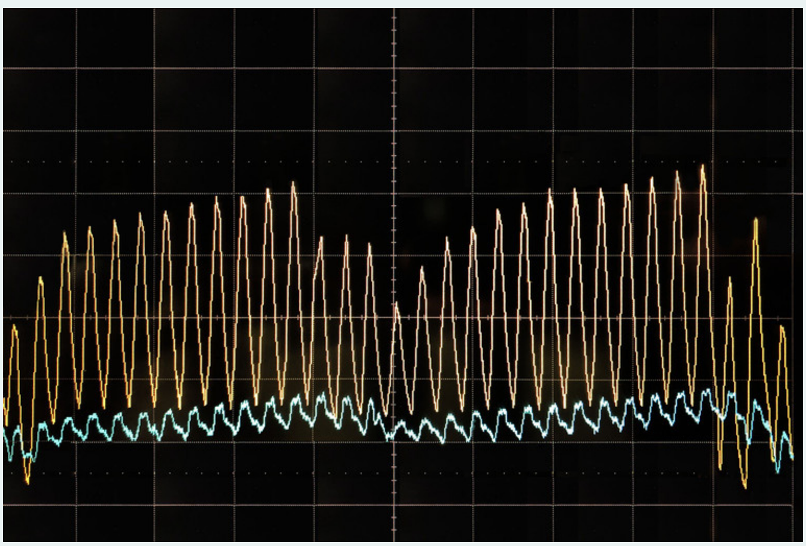


Figure 9: Converter output of 180A_{PK} (yellow) at 40A/div, input current (blue) at 2A/div. Ripple is reduced by capacitance placed a the input. (left) 20ms/div (bottom) 0.1ms/div.

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.

About the Authors

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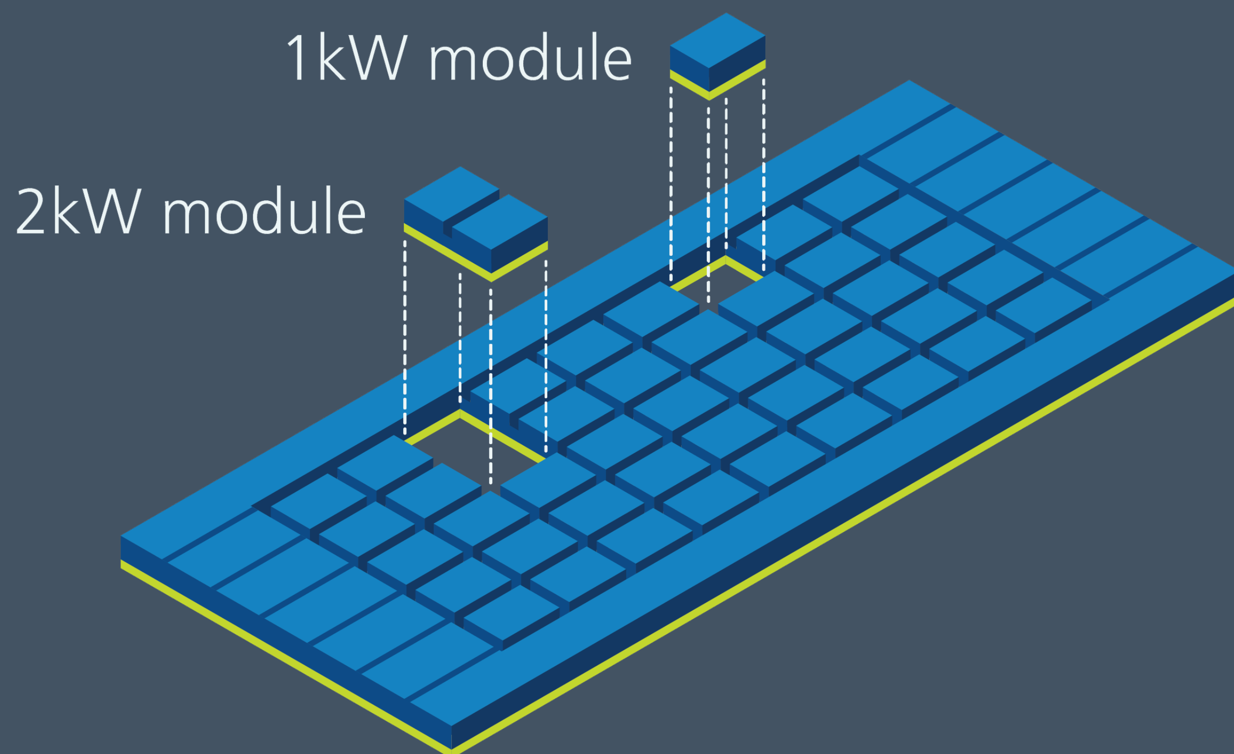


White Paper by Phil Davies, Corporate Vice President

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

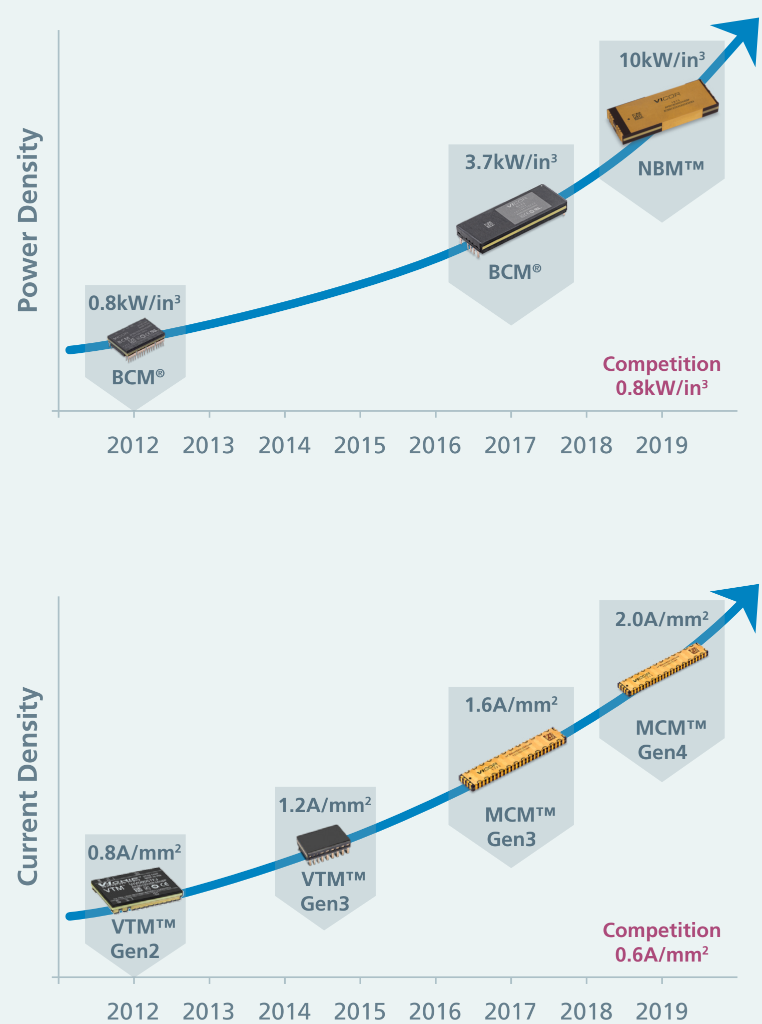


Figure 1: Continual advancements in the four pillars of innovation have reduced power losses by 25% every 2.5 years enabling significant power- and current-density improvements

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.

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.

"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."

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.

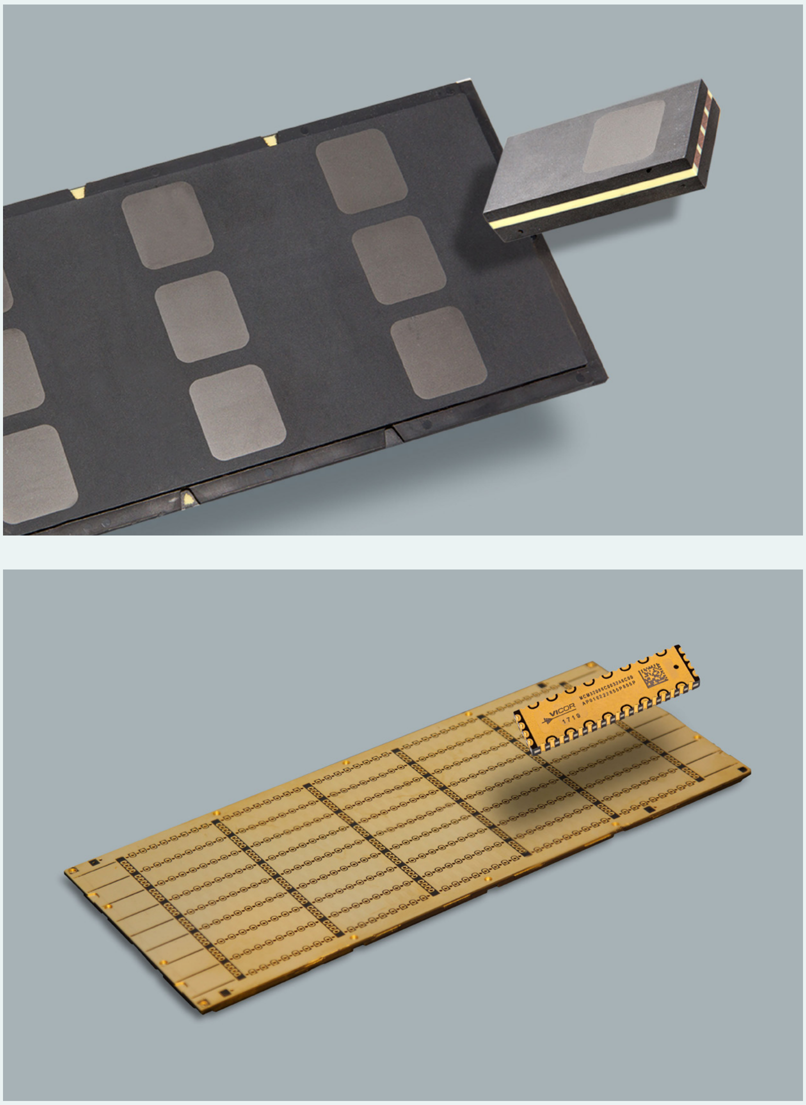
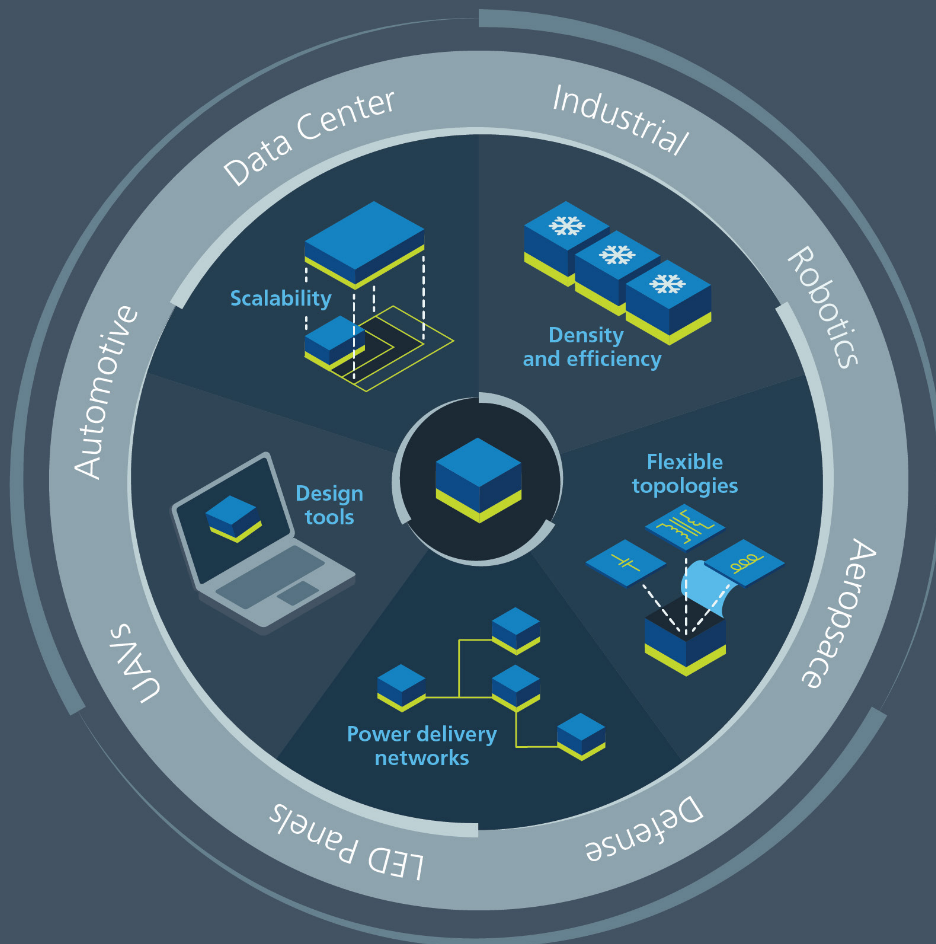


Figure 2: The new panel manufacturing process was another innovation for the power industry. ChiPs are all cut from the same size panel, enabling an automated high-volume manufacturing process.

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.



Article by Robert Gendron, VP Product Marketing

Power of the module

VICOR

Eliminate intermediate energy storage in EV power architectures

Introduction

Vicor has established a power module capability spanning product design, manufacturing, simulation and selection tools. This capability allows Vicor to enable power systems designers to quickly and easily deploy high-performance power delivery networks (PDNs) from the power source to the point-of-load (PoL) for end systems extending across many different industries such as automotive, AI/data center, defense and aerospace, LED lighting, etc.

This modular power component approach signifies a new standard within the power industry, addressing the increasing power needs of modern, high-performance end systems with a methodology that also provides other power system benefits such as reduced power system footprint, high efficiency and faster time-to-market.

The need for power modules

Power delivery networks are rapidly changing within many end systems across many industries today. The power requirements for these different systems vary widely from each other and require a wide portfolio of modules to enable the maximum flexibility for a modular power component methodology to be employed. The range of modular power solutions Vicor provides include:

- AC-DC and DC-DC modules
- Power levels from 50W to over 50kW
- Currents from a few amps to 1,000A+
- Voltages from sub-1V to over 1,000V
- Isolated and non-isolated converters and regulators
- Regulated and fixed-ratio converters
- Board-mount, chassis-mount and surface-mount power module packages

> "Utilizing power modules follows the practice and benefits of a mass customization capability."

In addition to the above, there are also different control features such as telemetry, compensation and programability, plus any industry/safety certifications that can be required. To effectively support different PDNs in different industries with an optimized solution, a comprehensive power module approach in needed. Utilizing power modules follows the practice and benefits of a mass customization capability. Mass customization enables the ability to offer unique PDNs optimized for different end systems while benefiting from common design and manufacturing processes. Common, scalable design and manufacturing processes also offer advantages in faster time-to-market, reliability, technology risk and cost management. The key elements of this power module approach are:

Modular power component design methodology

The modular power component design methodology is the ability for the end designer to select, configure, optimize and source a unique power delivery network comprised of different power modules.

Power module design

The power modules themselves are assembled within a common manufacturing process and can easily be configured by utilizing:

- Flexible power switching topologies and control systems
- Configurable and scalable packaging

Modular power component design methodology

Multiple PDN designs are enabled by a large power module portfolio offering a range of functionality, scalability and performance. Selecting the optimized power modules for different power delivery architectures out of the portfolio and building the highest performing PDN is possible with the **Power System Designer** and **Whiteboard tools** (Figure 1). These tools provide an environment to analyze different architectures and modules optimized for overall performance, cost or size considerations. The modular power component design methodology—supported by a large power module portfolio and tools for selection and optimization — is the more visible element to the Vicor power module approach since customers use it to interface with Vicor daily. It is the second element of power modules, the power module design itself, that is not as visible to customers — but it is equally important to providing the benefits of mass customization.

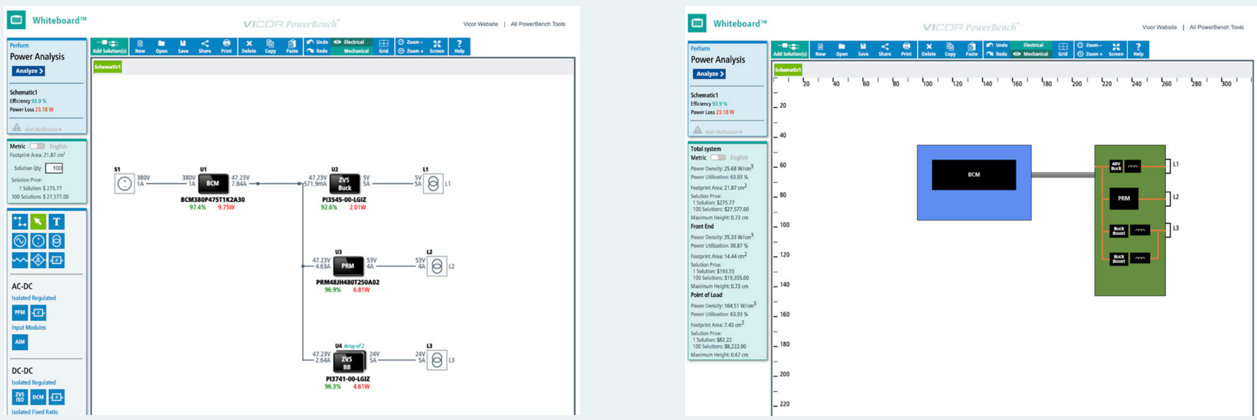


Figure 1: Example of a power delivery network designed and optimized using the Vicor Whiteboard tool

Flexible switching topologies

Vicor has innovated flexible switching topologies that can adapt to the various power conversion functions and needs. Topologies vary in their functionality, and one or more can be used within a power module. The Sine Amplitude Converter (SAC™) topology is one of the most common topologies and can be quickly configured to different power requirements, primarily by means of changes to the FETs and planer magnetics within the module design. The use of flexible switching topologies allows for quick development time and low risk for new power modules optimized to meet specific application needs.

Configurable and scalable packaging

Vicor developed the CM-ChiP™ common package technology to maximize power module density and thermal performance. The CM-ChiP package is a 3D package with an internal mid-plane substrate that enables component placement on both the top and bottom sides. Package thermal impedance is equal

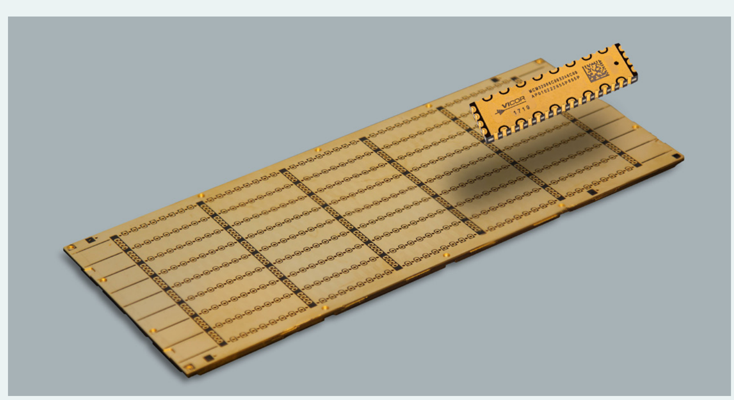


Figure 2: Panel fabrication process enabling configurable CM-ChiP packaging

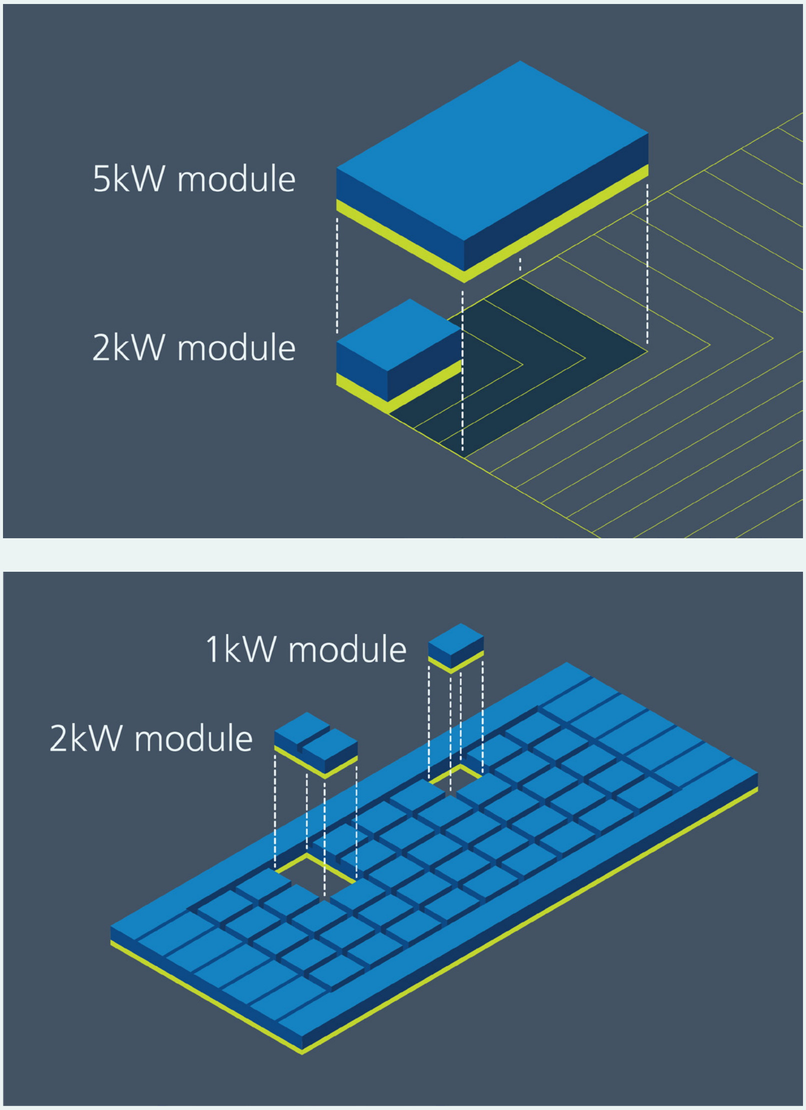


Figure 3: Scaling approaches with the panel fabrication process: linear scaling (top) and integer scaling (bottom)

from the top and bottom sides of the package, allowing for dual-sided cooling if desired. Exterior plating options provide flexibility for shielding options and terminal connections, which include surface-mount, pinned and chassis-mount terminations. No tooling is required for different form factors or terminal connections. By using the CM-ChiP common package technology, a faster time-to-market and a higher level of performance predictability can be achieved in new power module designs.

The CM-ChiP is fabricated within a panel fabrication process, which is similar to a wafer fabrication process (Figure 2). Both processes enable multiple modules or devices to be fabricated from a single panel or wafer, standardized on a fabrication line. The panel can accommodate various module form factors with the largest possible module utilizing the full panel. A critical element to mass customization, the panel fabrication process shifts the manufacturing focus away from conventional fragmented, single-component package support and yield-enhancement efforts towards panel-level efforts that encompass all products.

Flexibility within the PDN architecture and design includes the ability to parallel most power modules for increasing system power demands. In addition, Vicor can increase module power delivery by scaling the power module itself to a larger size. Scaling can be accomplished by module linear scaling, increasing the power capability by modifying the core module design to a higher power level. Another scaling option is integer scaling where 2x, 3x, 4x power capability is possible by singularization of more than one base module from the panel (Figure 3).

Advanced modular power delivery network examples

When artificial intelligence (AI) processor power system designers wanted to maximize their processor performance on an AI accelerator card, they turned to Vicor. Power performance requirements for the processor called for the delivery of 500A+ at a sub-1V level (Figure 4). In addition, the power delivery network needed to fit within the industry-standard Open Compute Platform OAM card, pushing the power density limits of conventional multiphase buck regulators.

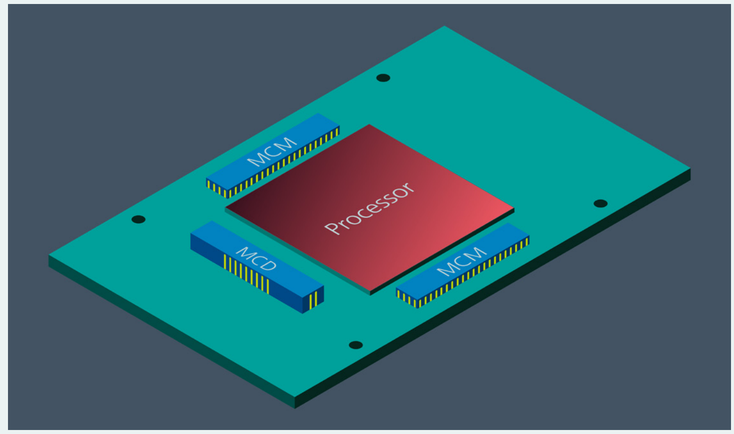


Figure 4: Power delivery network for advanced AI processors delivering 500A+ at sub-1V

Vicor configured a SAC-topology-based module, the MCM4609 with a K factor of 1/48, to fit within the north and south sides of the AI processor with dimensions of 46 x 9 x 3.2mm (Figure 5). Each MCM4609 provides 325A, or 650A continuous in total at sub-1V levels to the processor. The MCM4609s receive a drive signal from the MCD4609 module completing the power delivery network. The AI PDN provides unparalleled density and proximity to the processor minimizing PCB losses.

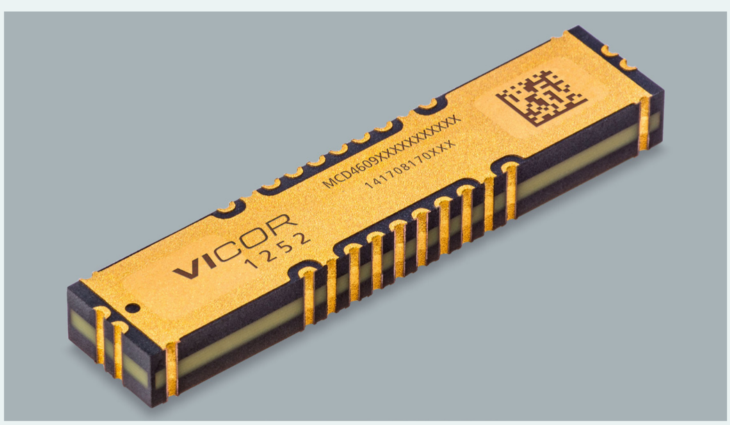


Figure 5: MCM4609 power module for AI processor power delivery

Similar to the AI processor need, when approached to develop a high-density electric vehicle (EV) battery PDN, Vicor was able to quickly configure a SAC-topology-based module to meet those needs (Figure 6). EVs require a 48V rail to support non-motor loads within the vehicle from the primary battery in addition to requiring a chassis-mounted package. Conventional solutions to provide 48V from the 800V battery in an efficient and lightweight manner were limited.

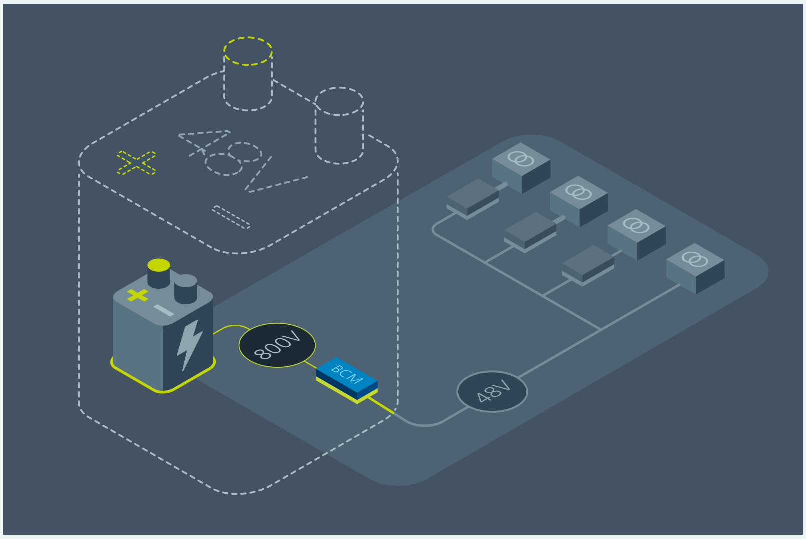


Figure 6: Power delivery network for 800V EV battery power conversion

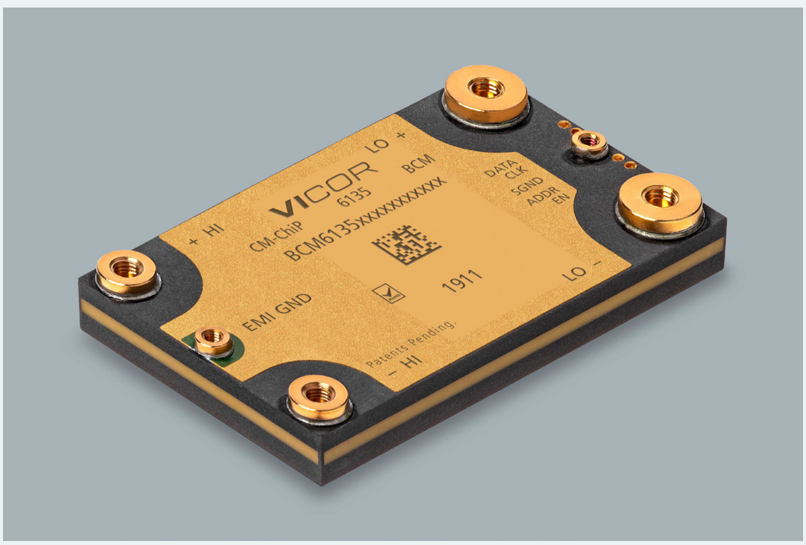


Figure 7: BCM6135 power module for EV battery voltage conversion

Vicor therefore developed a SAC-topology-based module with a 1/16 K factor within a larger CM-ChiP (compared to the AI MCM4609) to accommodate higher power and chassis mounting. The power module, BCM6135, provides $800V_{IN}$ to $48V_{OUT}$ at 80A (or 3.8kW of output power) conversion at over 97% efficiency in a 61 x 35 x 7.4mm CM-ChiP package (Figure 7). Additional power modules downstream of the BCM6135 support regulated 12V and 48V rails to complete the PDN. The high-density and high-efficiency attributes of the BCM6135 and downstream power modules enable a reduced weight and higher-performing EV battery conversion.

Application notes

This section provides information on select Vicor products used in robotics and links to their online application notes for key implementation details and considerations to note when designing a power delivery network.

Single DCM

- A DCM DC-DC Converter Module contains isolation, regulation, thermal management, and fault monitoring all in one single module. The DCM is applicable to a variety of industries and military applications due to its wide input voltage range, high output power, high density, and high efficiency. This single DCM has two available packages: Converter housed in Package (ChiP) and Vicor Integrated Adapter (VIA) package.

Paralleling DCM

- When an application calls for more power than can be delivered by a single DCM, parallel DCMs can be utilized. Paralleling DCMs is rather straightforward, since the operation of each DCM in an array is nearly identical to that of a single DCM circuit. In a parallel circuit, each DCM operates on its own load line, depending on its share of the load. Because of this, having parallel DCMs allows for the same load line to be remapped over a higher current range, with no derating.

Reverse-mode SAC

- Sine Amplitude Converters (SACS) are symmetrical power processing systems which function as a close approximation to an ideal power converter. When a SAC is placed in reverse mode, the source is applied to the SAC secondary power port. The SAC delivers a voltage boosted according to the K factor associated with the particular module, which it presents to a load connected across its primary power port.

Filtering considerations

- An Intermediate Bus Converter (IBC) is a very efficient, low profile, isolated, fixed-ratio DC-DC converter based on the Vicor patented Sine Amplitude Converter (SAC). The IBC exhibits low levels of noise and has a very wide bandwidth with high efficiency. To guarantee optimal performance of the IBC, a filter can be applied. Here you can learn about filter considerations and approaches to best fit your IBC.

Thermal management

- Proper thermal management is important for Vicor VIA and ChiP package converters because it provides improved module and system MTBFs, smaller size, and lower product life-cycle costs. Vicor provides guidelines for achieving effective thermal management.

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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