Abstract

Adaptive cell topologies embodied in Zero-Voltage Switching (DC/ZVS) DC-DC converters raise the bar for EV/HEV DC-DC converter performance. Vicor technology offers solutions to challenges associated with EV and HEV power conversion. These include:

- High power density
- High efficiency
- Low EMI
- Thermal management flexibility
- Modular scalability
- Fault tolerance
- Low cost.

Internal combustion engines (ICEs) have long been the keystone of an automaker’s technology portfolio. With the EV/HEV potential to provide significantly reduced, or petroleum-free, propulsion, power electronics is one of the emerging technologies that will enable future product differentiation. While the ICE may never be fully replaced, electric propulsion systems – from micro to mild to full hybrid as well as plug-in hybrid and extended range vehicles (ERVs) – make power electronics a core competency for future vehicles.

DC-DC conversion is an integral part of power electronics in any vehicle with a higher battery voltage than traditional vehicles. However, high-voltage/high-power conversion in vehicles is in its infancy. Many technical and economic challenges must be solved for EVs and HEVs to succeed. Vicor has been an innovative leader in power for decades and currently has technologies — power conversion engines — directly impacting DC-DC power conversion in EVs/HEVs.

Power Conversion for EVs/HEVs

In EVs and HEVs, applications for DC-DC converters start at the high-voltage (HV) battery. Although battery voltages are still typically in the range of 300 to 350 Vdc, some exceed 450 Vdc. The most basic requirement for DC-DC conversion is to power the traditional 12 V “hotel” loads. This DC-DC converter charges the 12 V battery from the HV bus eliminating the 14 V alternator. A bi-directional DC-DC converter is required where the 12 V battery may be used to supply the HV system.

In some vehicles, such as General Motors’ Dual-Mode hybrids, the 300 Vdc battery has an additional DC-DC converter to provide 42 Vdc for electric power steering (EPS).
In larger vehicles, the power steering requirements dictate increasing this voltage to avoid excessive current levels. In GM’s system, this DC-DC converter is not bi-directional. An unregulated, fixed ratio, bus converter may provide a more efficient, light weight and cost effective alternative.

Hard switching converters have been used for EV/HEV DC-DC converters. However, early adoption of low-frequency soft-switching converters has yielded initial improvements in efficiency and lower noise performance. For example, Honda increased the efficiency over a wide load range by changing from a 70 kHz hard-switching system in its 2000 model to a 90/115 kHz soft-switching system (90 kHz at light loads, 115 kHz at high loads) in its 2006 model. With a view to potential benefits, other manufacturers are pursuing advanced power conversion technology.

Boost converters are also used in HEVs. Toyota steps up the HV battery voltage to provide a higher voltage for the traction motors in its hybrids. The Prius THSII initially used a DC-DC boost converter to provide 500 Vdc for the motors. With the Lexus ES400h, a DC-DC converter steps up the 288 Vdc battery voltage to 650 Vdc. As with GM’s large SUVs, the ES400h uses a 42 Vdc EPS system. A buck converter is also used to step down the HV battery voltage for the EPS system.

Mild hybrids that use a system voltage such as 42 Vdc or higher, also require DC-DC conversion for the traditional 12 Vdc loads. Mild hybrids include belt alternator starter (BAS) and stop-start systems. Plug-in hybrids such as the Chevrolet Volt (GM’s extended-range vehicle) have similar power conversion requirements as EVs and HEVs as well as the need for 120 Vac and 240 Vac charging systems.

Other vehicle loads for which power conversion needs to be considered include the HV AC compressor, electric water pump, variable speed fan for battery cooling, electric oil pump, high-power audio system, high-intensity discharge (HID) lighting, and more. Even power conversion within 12 Vdc electronic modules is a candidate for upgrading from linear to switch-mode converters for low-voltage, e.g., 5 V or 3.3 V, requirements.

Systems in production today represent pioneering developments. Future growth and success will depend on technological breakthroughs and innovations enabling vehicles that provide consumers with the expected economic and environmental values.

**DC-DC Conversion Architectures & Technical Challenges**

Technical challenges in today’s electric vehicles – EV, HEV, PHEV, etc. – include: size, weight, efficiency, electromagnetic compatibility / electromagnetic interference (EMC/EMI), high-voltage isolation, heat removal / thermal management, and, of course, cost. Many of these challenges are interrelated. In some cases, ongoing research for new materials and new power switching devices (for example SiC or GaN) may provide improvement over today’s products and further reduce conduction and switching losses. Practical realization of such breakthroughs is confronted by
uncertainties. While many initiatives have potential for improving performance, 
technologies that can enable rapid realization of substantial gains represent opportunity.

**Vicor Power Technologies Hold Promise for EV/HEV DC-DC Converter Challenges**

Vicor has been an innovative leader in power electronics for decades (see sidebar) and has developed technologies — DC-DC power conversion engines in its portfolio — that promise advanced solutions for EVs/HEVs. They include:

1. Zero-Voltage Switching (DC/ZVS) DC-DC converters with 95% efficiency at 1 kW/in³ power density;
2. ZVS Buck-Boost regulators with > 97% efficiency at 1 kW/in³; and
3. Sine Amplitude Converter™ High Voltage (SAC HV) bus converters with 97% efficiency at 1 kW/in³.

These power conversion engines can support efficient high-voltage electric power distribution within vehicles and provide key advantages to the power system designer, including small size, low weight, high power density, high efficiency, design flexibility, and fast response to changing electrical demands.

**DC/ZVS DC-DC Converters**

Adaptive cell topologies embodied in DC/ZVS DC-DC converters raise the bar for EV/HEV DC-DC converter performance. For example, Figure 1 shows the relative size of a contemporary EV/HEV DC-DC converter and a DC/ZVS DC-DC converter with comparable power processing capability. The DC/ZVS DC-DC converter is capable of the same power throughput in one-tenth the volume – or capable of much higher throughput in the same volume.

![Figure 1](image_url)
Adaptive cell power systems involve a multiplicity of converters (Figure 2) that are configured in an array to provide wide-range, high-voltage, high-frequency power processing. A converter block typically utilizes two magnetically coupled converter cells that are selectively configured in series or parallel. In either configuration, common-mode noise is essentially cancelled, eliminating a major filtering challenge for EVs and HEVs.

Adaptive cell topologies may include Sine Amplitude Converter (“SAC”) cells. Vicor proprietary SAC engines utilize zero-voltage/zero-current switching to eliminate switching losses. By eliminating switching loss, the SAC can be operated efficiently at relatively high frequencies, typically in the MHz range, resulting in smaller product size. High operating frequency allows for miniaturization of many components, increasing overall converter power density. Soft switching converters operating at high frequency also minimize electromagnetic interference (EMI) and the filtering components required by hard-switching converters operating at low frequency.

The SAC engine is typically used to provide fixed voltage ratio bus conversion with HV isolation. The DC/ZVS engine is typically used to provide DC-DC conversion with regulation and isolation. Figures 3 and 4 show efficiency and output ripple performance for DC/ZVS converters configured in a multi-kW array.
ZVS Buck-Boost Regulators

ZVS buck-boost regulators (Figure 5) provide a regulated output from an unregulated input source. ZVS buck-boost regulators may be used standalone, as non-isolated voltage regulators, or combined with SAC current multipliers to create isolated DC-DC converters. The regulator may be “factorized” away from SAC current multipliers to provide increased density at the point of load while supporting efficient power distribution and savings in conductor weight and cost. In combination, these engines enable DC-DC converter systems with significantly higher density, flexibility, and efficiency than conventional converters.

ZVS buck-boost regulator capabilities include:

- Input and output voltages up to 650 Vdc
- Up to 5:1 input voltage range
- Up to 5:1 voltage step-up / step-down ratio
- Conversion efficiency up to 98%
- Scalable from hundreds of Watts to kilo-Watts

A unique soft switching topology and ZVS control architecture enable efficient HV operation at 1 MHz. Regulators may be paralleled to achieve increased output power. A feature of the regulator control architecture is that its switching sequence does not change in either buck or boost mode — only the relative duration of phases within each operating cycle are controlled to effect voltage step up or step down.
SAC HV Bus Converters

SAC HV bus converter capabilities include:

- Input and output voltages up to 650 Vdc
- Up to 5:1 input voltage range
- Current multiplication up to 200X
- Conversion efficiency up to 98%
- Scalable from hundreds of Watts to kilo-Watts

Unique ZVS/ZCS Sine Amplitude Converter topologies with a low Q power train support efficient high frequency power processing with a fixed frequency oscillator having a high spectral purity and common-mode symmetry, resulting in essentially noise-free operation. The control architecture locks the operating frequency to the power train resonant frequency, optimizing efficiency and minimizing output impedance. By effectively canceling reactive components, output impedance, Zout, can be relatively low. To further reduce Zout, or for greater power capability, bus converters can be paralleled with accurate current sharing. Quiet and powerful, SAC bus converters provide essentially linear voltage/current conversion with flat output impedance up to about 1 MHz.

In combination, Vicor power technologies promise superior solutions to the technical challenges associated with EVs and HEVs including small size, low weight, very high efficiency, low EMI, high-voltage isolation, heat management, modularity, design flexibility, scalability, fault tolerance and cost.

Conclusion

DC-DC converters for future EVs and HEVs require density, efficiency and scalability that cannot be cost-effectively supported by low frequency, bulk converter designs. While a 2 kW DC-DC converter may be a common design target, high-end vehicles require more power, whereas smaller DC-DC converters with lower power ratings would provide lower cost for entry level EVs and HEVs. To cope with this breadth of power needs, a flexible, scalable power system methodology using high-density, modular converters capable of efficient bus conversion, isolation and voltage regulation will enable greater performance and faster time-to-market, cost-effectively.

Sidebar: Vicor Milestones in DC-DC Power Conversion

1981 Developed zero-current / zero-voltage switching high-frequency power conversion topologies

1984 Introduced the first full-brick power component at 100 W, 25 W/in³, using 1 MHz zero-current switching and active clamp technologies.

1988 Introduced first half brick at 50 W/in³.

1996 Introduced the first quarter brick at 150 W, 91 W/in³.

2003 Introduced 1000 W/in³ SAC current multiplier and ZVS buck boost regulator modules in IC-style packages enabling a novel Factorized Power Architecture.