

Emerging Solutions for Hybrid & Electric Vehicle DC-DC Converter Design and Test

Introduction

The global automotive DC-DC converter market is expected to hit USD 17 billion by 2026. This marks a compound annual growth rate of over 10% between the forecast period 2021-2026.¹

DC-DC converters are an essential part of the vehicle, converting voltages to power various onboard systems, such as increasingly sophisticated infotainment, and enhanced safety features using advanced driver assistance systems (ADAS).

The growing adoption of electric vehicles (EVs), both battery-powered and hybrid EVs (HEVs), is also boosting the demand for DC-DC converters.

Let's examine some of the industry trends and technology that are helping to support the development of more efficient DC-DC converters.



1. Automotive DC-DC Converter Market - Growth, Trends, Covid-19 Impact, and Forecasts (2022-2027); Mordor Intelligence

HEVs and EVs have multiple architectural variations. Figures 1 and 2 show simplified block diagrams of a couple of these architectures. For the strong (or parallel) hybrid and the pure EVs, a high voltage (HV) bus supplied by the large battery, drives the electric powertrain.

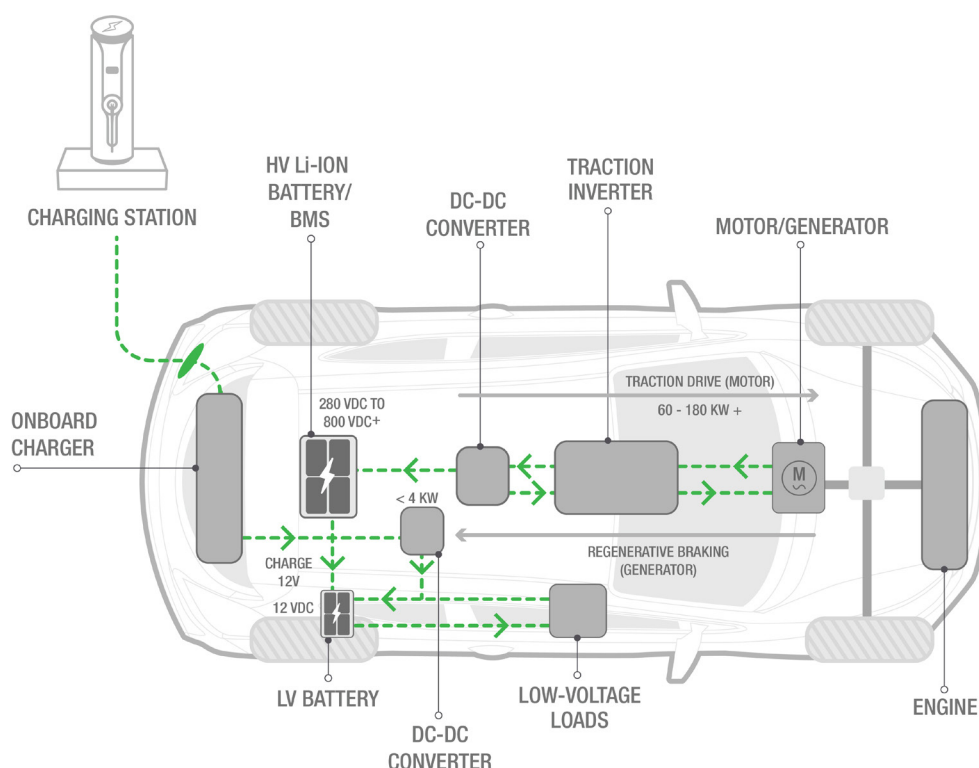


Figure 1. Simplified block diagram of a strong / full-hybrid EV

Power levels of the inverter and motor/generator range from about 60 kW up to and over 180 kW. Along with the large Li-ion battery, a significant investment is required to develop these architectures. Most of the components are bidirectional, allowing for power to go from the battery to the inverter, which turns the motor and moves the vehicle (traction drive). When decelerating, the momentum of the vehicle turns the generator, which drives power back through the inverter and charges the battery, in a process called regenerative braking.

In the Mild Hybrid (MH), the motor/generator, inverter and battery are also bidirectional. They are not large enough to drive the vehicle by themselves (as in the HEV or EV), but instead are used to supplement the engine power during acceleration and recharge the battery during deceleration. The voltage level for MHs is typically 48 V, keeping the bus structure under the 60 V safety rating for HV, but also providing 4 times the potential power of the 12 V bus with the same current rating.

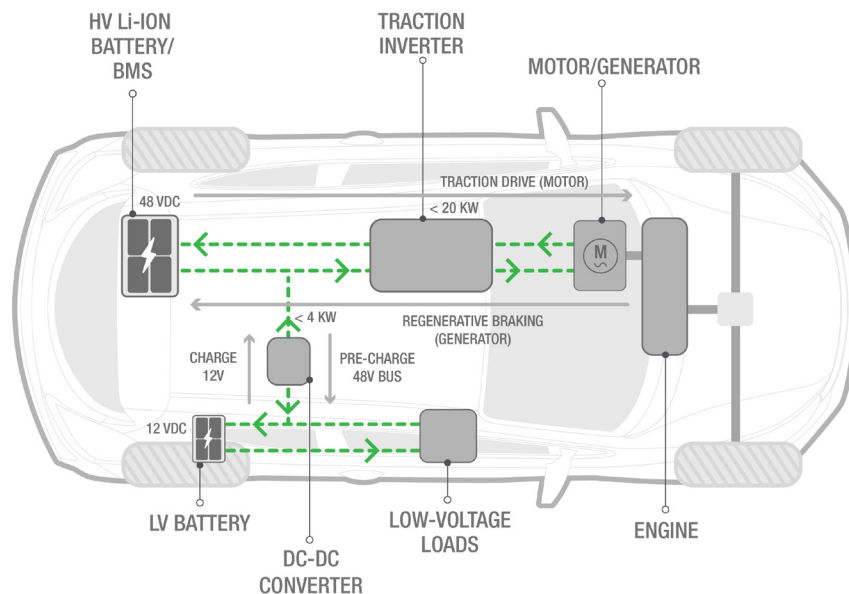


Figure 2. Simplified block diagram of mild hybrid EV

The DC-DC converter is a key component in both architectures, converting the higher voltage bus (MH - 48 V or EV / HEV - 100s of V) to the traditional 12 V power bus, from where most electrical loads are powered. The simulation, design, debugging, validation, and manufacturing test of this DC-DC converter is the focus of our discussion.

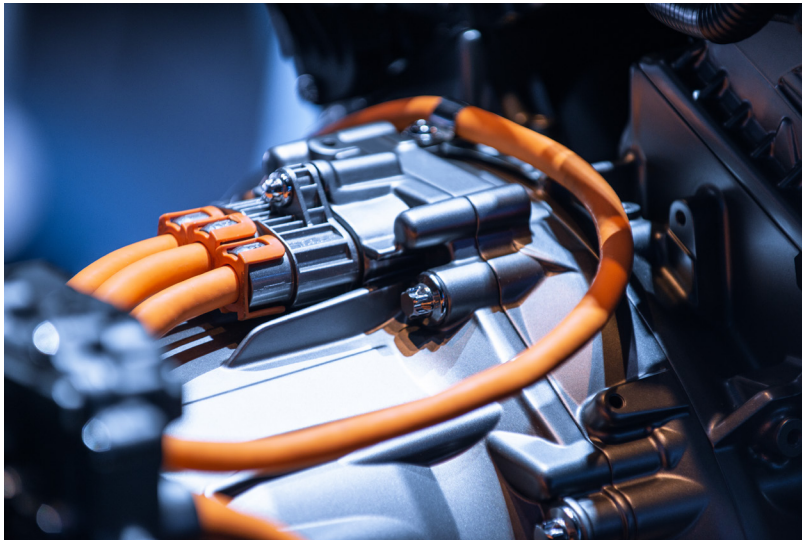
In the strong HEV or EV application, the DC-DC converter is used to convert power from the HV bus to the 12 V to charge the 12 V battery. There is currently no application for the 12 V bus to ‘boost’ power to the higher voltage bus and therefore many DC-DC converters are unidirectional for these architectures. However, in the MH architecture the DC-DC converter, in addition to charging the 12 V battery from the 48 V bus, also needs to convert power from the 12 V bus to the 48 V bus. The main application is to pre-charge the 48 V bus (i.e. input capacitance of the inverter), before contactors connect the 48 V battery to this bus. The pre-charge equalizes the voltage of the battery and the input to the inverter, minimizing arcing across the contactor.

As the market for both architectures develop, new loads will be added to the HV busses. Loads on the HV bus are often more efficient than when powered by the lower voltage bus. In addition, electronic control of and energizing electric loads only when needed (e.g. pumps) can be significantly more efficient than mechanically operated loads that are always connected to the mechanical drive train. With more and more loads transitioning to the HV bus, there may be additional needs to have the 12 V bus boost power to the HV bus. For example, Li-Ion batteries don’t perform well in cold temperatures. So, when the starter for the engine is powered by the HV bus, it may be helpful to have the 12 V Lead acid battery, which has good cold start capability, supply power back through the DC-DC converter to the HV bus to help the starter turn over the engine.

So How Do the Industry Trends Affect EV Design and EV Test for DC-DC Converters?

There is extreme downward cost pressure on design and test, across the DC-DC converter development life cycle. With silicon (Si) based power converter designs, most DC-DC converters are water cooled. The additional cooling design cost for the HEV / EV manufacturer is passed on to the design and test engineers, requiring reservoirs, pumps and hoses to cool the DC-DC converter during design and test.

So, manufacturers are minimizing the number of liquid cooled modules by integrating multiple power converter applications into a single module (e.g. DC-DC converter and onboard charger). In addition, designers are starting to adopt new power semiconductor technology by using wide bandgap (WBG) devices. There are two leading technologies, Silicon Carbide (SiC) and Gallium Nitride (GaN). WBG devices offer some significant advantage over Si:



Power efficiency

Because of the ability of WBG devices to switch much faster than Si, much of the power losses (i.e. switching losses) that occur during power conversion are minimized. Additionally, higher frequency means smaller magnetics components, supporting a less costly design.

High voltage operation

WBG devices handle much higher voltages (600 V and more) than Si-based devices. This enables a HV bus architecture to power HEV / EV components with less current (i.e. small diameter wires), reducing the weight of wire harnesses.

High temperature operation

The thermal conductivity and melting point of WBG devices enable it to operate at temperatures over 300°C. The ability to work at high temperatures provides a more reliable solution for HEV / EV applications which require high temperature operation.

Simulation of WBG design

The emergence of WBG devices in power converter design complicate the simulation and design of the DC-DC converter. Manufacturers of GaN and SiC devices are still getting their processes in control and therefore don't have extensive characterization of their devices. Users need to evaluate each device to determine if the WBG devices will work in their designs. Additionally, because of the fast-switching characteristics, conventional 'lumped analysis' simulators don't provide accurate simulations of WBG power converter designs (see Figure 3).

The conventional model/simulation shows a significant difference between simulated results (bold line) and measured results (faint line) when switching on and off the power transistor. The poor simulation creates costly design delays as designers iterate their designs hoping the next prototype will work as expected. Having reliable simulations will also help improve reliability of the DC-DC converter designs!

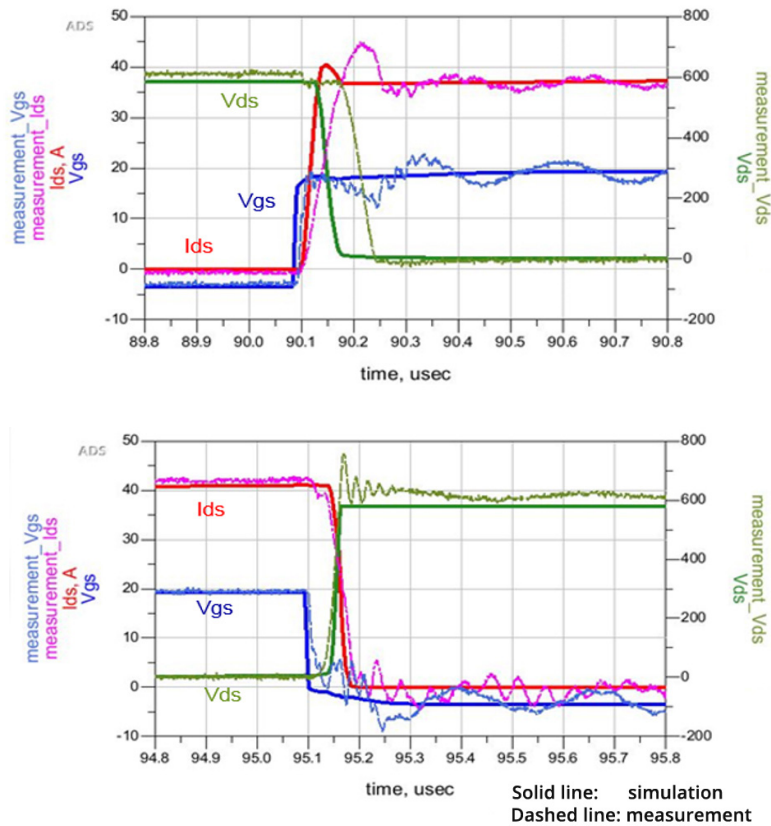


Figure 3. Conventional model/simulation results – Source: Rohm Semiconductor

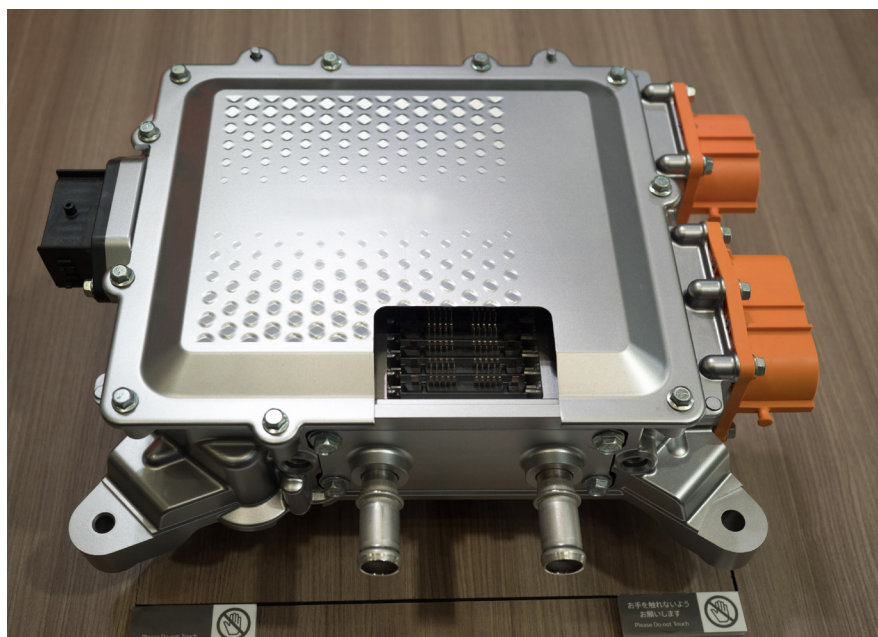
Bi-directional test

As more and more DC-DC converters become bidirectional, testing both directions of power flow require test equipment that is capable of sourcing and sinking power to the DC-DC converter. This is traditionally accomplished by connecting a power supply and an electronic load in parallel. However, external circuitry (i.e. diode to stop current flow into the power supply) and cumbersome 'two instrument' programming typically doesn't allow for smooth signal transitions between sourcing and sinking power, reflecting an inaccurate simulation of the operating conditions.

Electronic loads typically dissipate the power transferred to them from the DC-DC converter. But this dissipated power (heat) can start to add up, especially for test applications where multiple DC-DC converters are testing in parallel. Because of the need to remove the heat from the electronic loads, they are often large with significant forced air (via fans) or potentially even water cooling.

Untested reliability and safety concerns

With new power semiconductor technology in many of the DC-DC converter designs, additional design validation and reliability testing is required to ensure a reliable product will last over time with harsh automotive operating conditions. Of course, the additional cost for the validation and reliability testing is necessary, even though these costs make the HEV / EV less competitive. The risk is high for skimping on test, if for some reason there was a quality problem with the DC-DC converters in the production of HEV / EVs.



With the power and voltages levels used with DC-DC converters, designers, technicians, and operators need to be careful when testing a converter. The input of the HEV / EV DC-DC converters are all over the 60 V safety limit, requiring special safety mechanisms (e.g. NFPA 79) in manufacturing. These safety standards require a redundant system, where one failure of the test system would not expose the high voltage to an operator. The redundant safety systems are often custom designed, using PLC logic to operate independently from the test system. This adds additional design, cost, and complexity to the manufacturing test systems.

Maximize efficiency

And finally, the designer is challenged to maximize the efficiency of their converters. Efficiency is dependent on many factors, including temperature, operating voltage, % of rated power and other environmental conditions. Because of the many influences on efficiency, it is difficult for the

designer to simulate all the combinations of conditions to characterize their design. Additionally, designers are trying to measure 0.1% changes in efficiency at 95% efficiency or greater. This requires a measurement instrument with high dynamic range, typically 16 bits of resolution or better. Combined with the need for accurate current transducers and well synchronized current and voltage waveforms, the measurement challenges are complex.

The 'whole system' operation of the electric powertrain should also be included in this effort to maximize efficiency. As more efficient control algorithms are developed for different combinations of ICE powered and motor-powered propulsion and regeneration, the DC-DC converter will play a part in routing power. To validate the firmware in the DC-DC converters, as well as validate the control algorithms spread across the power train components, power hardware-in-the-loop (PHIL) testing is critical for 'real world' testing of the whole system efficiency.

Emerging solutions for EV design and EV test of DC-DC converters

To address some of these design and test challenges, new, innovative approaches are being developed.

High frequency enabled models/simulations

Because of the higher frequency content of WBG switching waveforms (rise and fall times < 10 ns), high frequency or electromagnetic-enabled models and simulators are needed to accurately simulate power semiconductor behaviors. EMI simulation is needed to understand the DC-DC converter's contribution to radiated and conducted interference. Physical positioning of the parts in layout of the converter, characterizing semiconductor package parasitics, and PCB effects also need to be considered. Finally, with the significant impact of temperature in DC-DC converter designs, thermal simulation and analysis is critical to understand cooling requirements.

Rohm Semiconductor uses an empirical/mathematical model, which includes high frequency characteristics (S parameters measurements for 'zero bias' and on-state for the switching transistor model) and Keysight's PathWave Advanced Design System (ADS) electronic design automation software, to simulate their devices in converter designs. They were able to achieve significant improvement in matching simulated data with measured data using this technique (see Figure 4).

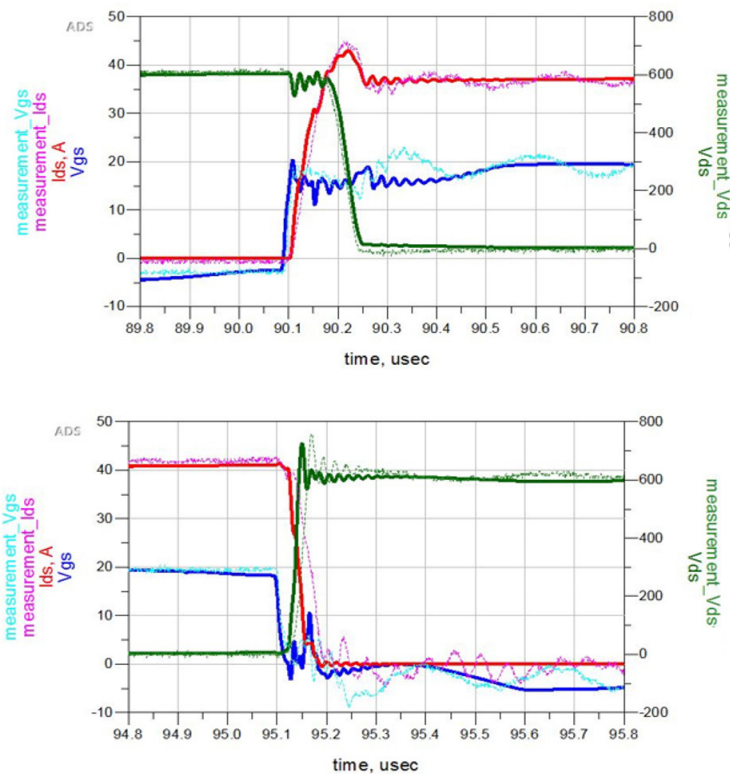


Figure 4. High frequency enabled model/simulation results – Source: Rohm Semiconductor

Integrated source/sink power system with regeneration

Multiple vendors are introducing integrated source/sink solutions in a single product. The products can seamlessly move from sourcing current (Quadrant I) to sinking current (Quadrant II) without external circuits or synchronized programming of a separate power supply and electronic load (see Figure 5). The integration enables a smooth output waveform that correctly simulates the bidirectional DC-DC converter's transition between opposite directions of power flow.

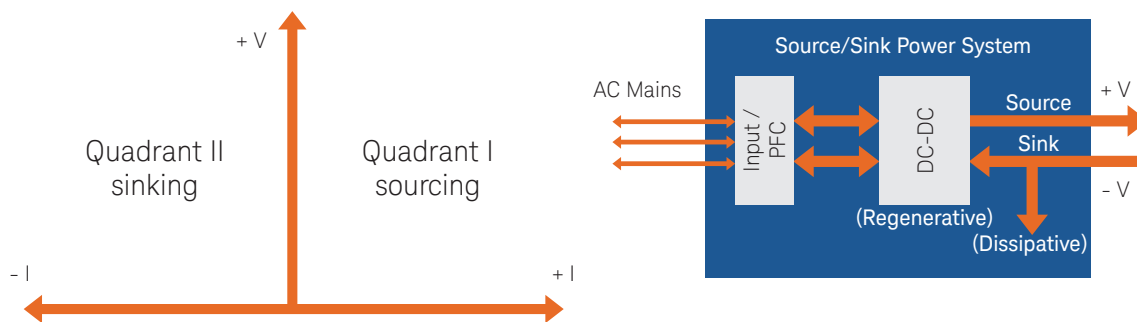


Figure 5. Source/sink power system

When the power system sources power to the DC-DC converter, most of the power (depending on the efficiency) is passed through the converter to the automotive load. When the power system sinks power from the DC-DC converter, the power must be absorbed by the power system. Most power systems (or electronic loads) dissipate this power in heat, requiring larger-size products with fans, for power levels of DC-DC converters of up to 4 kW. Therefore, it is necessary to increase test system size and HVAC requirements to remove the heat from the facility.

At the 5 kW power level and above, there are source / sink power systems and electronic loads that regenerate (or return) the power to the AC mains (see Figure 5). This technique is not 100% efficient, but most designs allow about 90% of the power to be delivered back to the grid. This leaves only 10% of the power (about 500 W in the case of a 5 kW product) to be dissipated as heat. The result is a dramatic reduction in size of the products and the HVAC cost to remove heat from the test system environment.

The important question to ask for regenerative solutions is, how clean is the power being returned to the AC mains?

If you work in manufacturing, any distortion in the power returned to the AC mains will be amplified by the number of test systems in the facility. ‘Dirty power’ can create intermittent problems in your facility, requiring isolation transformers for each test system to help mitigate the problem created by poor regeneration. It is best to check with the product vendor to confirm low distortion power is returned to the AC mains (see Figure 6).

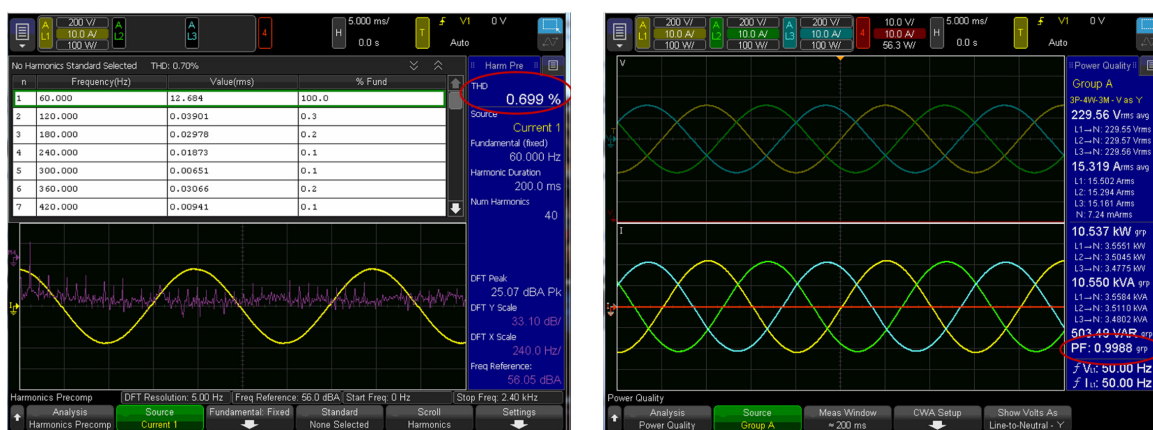


Figure 6. THD & PF measurements on power returned to AC mains from Keysight's RP7900 Regenerative Power System – measurements made with PA2203A InteraVision Power Analyzer

Safety

As mentioned above, safety disconnect systems are typically custom designed for each application. They often take up a lot of space and are hand wired. Because many of the functions are the same from application to application, purchasing a commercial-off-the-shelf safety disconnect product with 80% of the solution already integrated into a small package would save design time and cost.

The key characteristics of a safety disconnect system are:

- Redundant, galvanic disconnects (physical relays) to open the + and – outputs of the high voltage power supply in the test system.
- Independent sensing of the disconnect relay positions (e.g. mechanically coupled sense relays).
- Ability to sense Emergency Stop (E-Stop) switches to open disconnect relays in case of an emergency determined by the operator.
- Ability to sense test fixture cover position to ensure high voltage is not present for operators swapping DC-DC converters.
- Bleed resistors to discharge high voltage on external terminals of the DC-DC converter.
- Appropriate lamp indications of safe and unsafe states.

Additionally, the source/sink power system, power supply or electronic loads can contribute to a safer test system, if they include safety related features like:

- Over-voltage protection
- Over-current protection
- Over-temperature protection
- Open sense lead detection
- Solid-state disconnects ($< 5 \mu\text{s}$)
- Down programming ($< 2 \text{ ms}$)
- Watchdog timer

To take advantage of these safety features in the power product, it should be able to communicate with the safety disconnect system, if any power product ‘alarm’ state was detected. Keysight’s EV1003A Power Converter Test Solution combines a commercially available safety disconnect system integrated with a well-designed source/sink power system to keep your employees safe (see figure 7).



Figure 7. EV1003A Power Converter Test Solution with 2-quadrant, regenerative power system and integrated safety disconnect solution.

Summary

In summary, designing and testing DC-DC converters will continue to be a challenge as the functionality of these modules evolves with the market. As we've discussed, cost pressures are significant in this market and will continue to be as EV and HEV continue to come with a price premium. New technologies like higher capacity Li-Ion batteries and WBG power semiconductors are the enablers to help this market break through into the mainstream. What is needed is thoughtful adoption of new design and test technologies and approaches to enable the engineer to maintain quality and reliability of the DC-DC converter, while minimizing unnecessary costs.

Keysight Technologies provides many solutions for the HEV / EV market, including DC-DC converter design and test. Please visit our website at www.keysight.com/find/e-mobility to learn more about our broad offering of HEV / EV design and test solutions.

Keysight enables innovators to push the boundaries of engineering by quickly solving design, emulation, and test challenges to create the best product experiences. Start your innovation journey at www.keysight.com.