TECHNICAL WHITE PAPER

Chargers Integral to PHEV Success

1. Abstract

Reliability of the PHEV charging system is vitally important to the gains in fuel economy, reductions in emissions, and greater convenience (fewer fill-ups) that are critical to the viability of the PHEV concept. Understanding both the on-vehicle environment and the AC supply infrastructure is critical to the development of the ideal PHEV charger. Delta-Q's experience as an OEM supplier of onboard chargers for industrial vehicles has enabled us to develop a considerable depth of knowledge of both the on-vehicle and AC input requirements. This presentation will explore some of the challenges and development goals for a PHEV charger for use around the world, while fully integrated in a variety of vehicles and mobile industrial equipment. A variety of factors will be discussed as will design solutions to address the competing requirements.

2. Plug-In Hybrids Defined

Plug-in Hybrid Electric Vehicles (PHEVs) deliver the benefits of Battery Electric Vehicles (BEVs) without the range limitations. Like a Hybrid (HEV), PHEVs combine an internal combustion engine (ICE) with an electric motor, but with a charger and additional, or larger, battery pack. Charging a PHEV from a common household AC power outlet allows electric drive miles to displace ICE miles, resulting in lower cost and zero emissions.

Delta-Q has been actively involved in research, development, standards definition and early-stage commercialization efforts for PHEVs, believing that this technology enhances fuel efficiency, reduces greenhouse gas emissions, and eliminates the prevalent criticism of the pure BEV – limited range. In typical daily use, it is projected that PHEVs will have the ability to travel anywhere from 35 – 60 miles (60-100 km) on a single charge using only the electric drive train, depending on the size and capacity of the battery pack. With the ability to charge the PHEV while at work, this range is extended. In the instances where long trips are required, once the available electric range has been expended, the PHEV will operate exactly as a production HEV does today.

3. Plug-In Hybrids Gain Momentum

With recent and rapidly accelerating advancements in battery technologies, and the rapid acceptance of HEVs, automakers are starting to embrace the PHEV concept.

While production PHEVs are not yet available, after-market integrators have been converting HEVs into PHEVs. The costs for the early conversions are high, but the concept is being proven, using chargers from Delta-Q.

4. Early Delta-Q Support for PHEV Development

Interest in PHEVs at the grass roots level was building by 2002. Delta-Q made a strategic decision to investigate PHEVs as a concept and support PHEV integration efforts in 2003. Early PHEVs using Delta-Q charger technology had very basic charger communication using only "fast," "slow," and "stop" commands, which was limited by the QuiQTM charger, the only Delta-Q charger option available at that time.

The QuiQ charger has an excellent feature-set for the industrial BEV market that it was designed for, but PHEV applications required additional features, functionality, and communication. QuiQ chargers were modified as required to meet the needs of integrators and OEMs for charging high voltage advanced batteries found in HEVs. This early engineering support formed part of the required market investigation leading to the more complete set of requirements for today's PHEV chargers.

A variety of sophisticated charging options were available to PHEV integrators, but the small size, light weight, low cost and ruggedized construction quickly made the modified QuiQ popular amongst vehicle converters. The core technology in the QuiQ charger is very suitable for PHEV applications, and this proven technology is the foundation for the first generation of purpose-built PHEV chargers developed by Delta-Q.

5. Plug-In Hybrid Charger Design Considerations

Battery chargers for Plug-In Hybrid Electric Vehicles can be based on proven high frequency charger technologies available today – this is the approach taken by Delta-Q to date. However, there are a number of additional design considerations that must be taken into account in providing chargers for the high volume automotive OEM market.

Designers must consider all electrical grid, safety, and automotive personal protection regulations that may impact system design. The following list of standards and agencies is typical of North America, and offered here as a basic illustrative list of the types of standards that will need to be considered in other jurisdictions.

The Society of Automotive Engineers (SAE) is currently reviewing SAE standard J1772 to update charger cord set requirements. Other SAE standards may also be applicable such as those relating to electric vehicles, electric drive, communications, electric/electronic components, etc. Some SAE standards make reference to other external standards (i.e. UL), which by association must also be adhered to.

Part of the automotive specific requirements may include compatibility with onboard diagnostics (OBD) rules. The OBD rules exist to control vehicle emissions, which are reduced with the PHEV through reduced fuel consumption.

- The Federal Communications Commission (FCC) and Special International Committee on Radio Interference (CISPR) dictate the types and level of emissions that a device may emit and accept through normal use. As the PHEV is likely to plug in to a residential outlet, the residential standard [1] will likely apply. The requirements for residential emissions and susceptibility are stringent and typically quite challenging, especially for power supplies of the higher power level desired for future PHEVs.

- Electrical regulations such as US National Electrical Code (NEC), along with standards such as UL, CSA, IEC, etc. The standards and agencies responsible for electrical safety and the grid-side of the PHEV are possibly the greatest challenge for the PHEV charger. The NEC specifies continuous electrical loads must draw no more than 80% of a maximum rated current. For the common 15A North American household circuit, this 80% results in maximum input power of 1440W at 120VAC (1900W for a 20A outlet). As larger and larger PHEV battery packs are contemplated, higher power and shorter recharge time becomes more important. With the higher power comes

[1] FCC Part 15 Class B

more complex and expensive electrical infrastructure (to support the PHEV outlet), and increased charger cost.

Beyond regulatory requirements, there are a large number of electrical design considerations that must be considered.

- System design must also consider nuisance tripping (caused by other loads plugged in to the same circuit) and shock hazard. Ground Fault Circuit Interrupter (GFCI) outlets and breakers may also be installed where PHEVs will plug in. GFCIs can be sensitive to high frequency power supply topologies, which are required to meet size and weight targets for onboard chargers.

- Compatibility with utility load management is becoming increasingly important, yet the standards have not yet been universally adopted. A stationary load such as an air conditioner or electric water heater can be easily equipped with a control system using a communications standard unique to the utility providing the power. Owing to the PHEV being a mobile load, it is likely that vehicles will plug into outlets other than at the owner's home, possibly outside the original owner's home utility region. With the utilities free to adopt the control and communications system they prefer, a patchwork of communications schemes has resulted. As important as time of use and single subscriber billing is deemed to be, there is yet to be a common system. The means of communication has not even been standardized – options being considered include low power wireless, power-line carrier (PLC) and even auto OEM type systems currently used for emergency communications. Vehicle to Grid (V2G) power transfer[2] could complicate the grid connection even further. V2G requires robust communications for safety and control. UL has recently updated the standard pertaining to V2G power transfer, but fast-tracked PHEV development programs and competing communications schemes make this a significant challenge.

- High efficiency is particularly important for a PHEV charger since losses during power conversion do not charge the battery, but are instead wasted as heat. More efficient power conversion designs use less input power to deliver the same output, reducing the operating cost of the vehicle, although increased efficiency typically costs more to build. Higher efficiency will ensure more charging power is delivered to the battery pack for a reduced charge time. Highly efficient products are more suited to being fully sealed to maximize resistance to water and contaminants, and allow for very flexible on-board mounting options.

- The PHEV charger must be compatible with various cooling methods including passive (convection), forced air, conduction, and liquid cooling. The simplest cooling methods are conduction or convection cooling, since there is no need for active cooling systems; however, the vehicle design must have the air or conductive surfaces to handle the heat load. Air cooling is suitable for chargers at the lower end of the power range, around 1.5 kW; liquid cooling could be used at any level but is particularly appropriate when a significant amount of heat must be moved. Improvements in efficiency may be achieved if power does not have to be diverted to run a fan or circulating pump. Selection of charger location on the vehicle must be carefully considered to balance the requirements of the charger with environmental and weight requirements. Examples of different cooling methods are shown in Figure 1.

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[2] V2G is a system where the vehicle communicates with, and/or feeds power back into, the grid or utility.

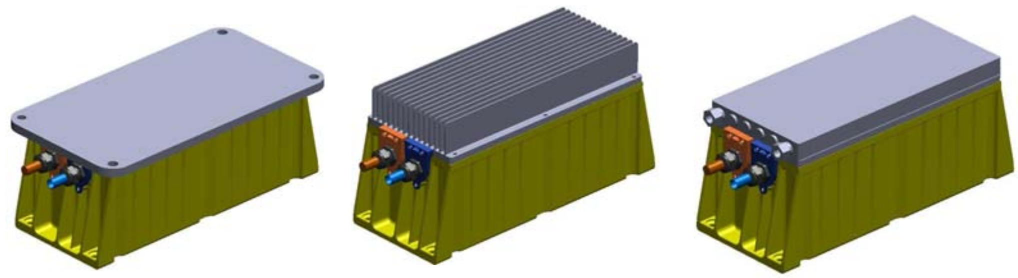

Figure 1 – Cooling Configurations: Conduction, Convection/Air, and Liquid

- Power Factor Correction (an important consideration in Europe where the electrical grid is running at near capacity) is extremely important in a PHEV charger to maximize charge power, and minimize charge time, charge cost, and nuisance tripping of branch circuit breakers. Auto manufacturers are particularly sensitive to the effects of poor power factor.

- In an automotive environment with advanced batteries, communications between the charger and battery or other vehicle systems is critical to the seamless integration of the PHEV system.

- Automotive designers must consider current and potential battery chemistries when designing new vehicles. Ideally, a PHEV charger will be adaptable to new batteries and Battery Management Systems through sophisticated software control. These onboard chargers must also support reprogramming using existing OEM programming tools.

- The PHEV is a new concept, yet there is a great deal of interest and even competition amongst OEMs to respond to the market demand. There is no set standard across the OEMs for battery capacity and therefore no common recharge requirements. A clean sheet automotive module development program can take years to complete, which further challenges the PHEV introduction timeline. Some OEMs even see a requirement for different charger power levels. This further complicates the approval process, as well as increasing development cost (for multiple modules).

- Space and environmental considerations play a large role in charger design. The variety of vehicles and mounting schemes across the different OEMs make a universal PHEV charger a challenging goal. With space at a premium, PHEV chargers have the potential to be mounted virtually anywhere on the vehicle. Figure 2 shows different charger configurations to accommodate space and form requirements. Higher power chargers using multiple modules of different orientations could use a similar building block design.

Beyond the long list of external requirements, OEM specific requirements must also be considered. Each auto manufacturer will require component suppliers to meet their own requirements governing safety, environmental, communications, weight, size, efficiency, etc.

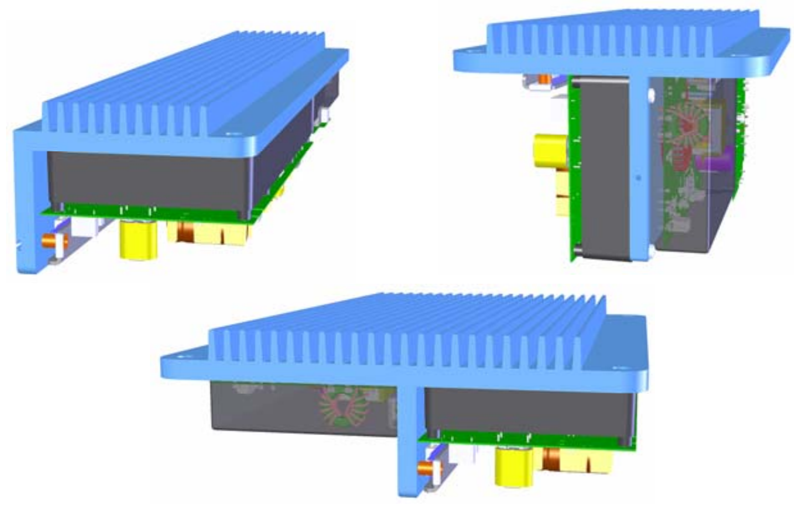

Figure 2 – Various Charger Configurations Shown for Flexible Mounting

6. Delta-Q – a leader in Plug-In Hybrid Charging

Delta-Q has fielded PHEV chargers through various integrators and OEMs as a first step in the commercialization of Plug-In Hybrid technology. Delta-Q's PHEV charger is based on the proven QuiQ charger platform, with over 100,000 units shipped worldwide. Owing to battery, cell management, and cooling schemes not being standard across the different OEMs and component providers, the Delta-Q charger will be adaptable to meet many of the applications currently being considered.

In addition to being compliant with all applicable standards and regulatory requirements, Delta-Q's new family of PHEV and EV chargers are in development and testing to support a variety of OEM PHEV programs. The basic 1.4kW PHEV charger is the first model to be released, with higher power chargers following close behind. Delta-Q's approach to the demand for a variety of power levels is to standardize on a universal power module of approximately 1.5kW and gang the modules to achieve a scalable platform. The available power levels include 3.3, 5, and 6.6kW. By using universal power modules, very flexible packaging is possible. The rectangular modules can be configured side-by-side for either a square section or very low profile; end-to-end mounting results in a long and thin form factor, as shown in figure 2. In addition to the different orientations and form factors, and considering the variety of cooling schemes, the new 1.4kW PHEV charger can be adapted to a wide variety of vehicle platforms.