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New Developments in Power Electronics

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Abstract

For hybrid and electric drive passenger cars to reach mass market adoption, their cost must be reduced so that they are nearer parity with gasoline and diesel powered vehicles. Delphi's research and development is focused on reducing the cost of inverters, DC-DC converters, and on-board chargers to meet the U.S. government cost targets. Technical innovations are being developed to increase the inverter temperature capability, which will enable the use of engine coolant for inverter cooling, eliminating the need for the secondary cooling loop. This is being accomplished by a novel power semiconductor packaging technique known as double sided cooling, allowing the cooling system to be in direct contact with both the bottom and the top side of the power semiconductor package. Work on new power switch packaging, wide bandgap power devices and high temperature bulk capacitors shows promise of performance improvements and cost reduction. Couple these activities with attention to common high volume manufacturing processes and lower cost power electronics are just a few years away.

Keywords: inverter, converter, semi-conductor, electric drive, market

1 Introduction

For hybrid and electric drive passenger cars to reach mass market adoption, their cost must be reduced so it is closer to cost parity with that of gasoline and diesel powered vehicles. Delphi's research and development has been focused on reducing the cost of power electronics for traction inverters, DC-DC converters, and on-board chargers. The U.S. Department of Energy (DOE) has established cost targets for a baseline hybrid propulsion system in volume production. The timeframe for adoption of these targets is aggressive, but the introduction of the 2017 – 2025 light duty fuel economy and emission standards in the U.S. is expected to increase the need for hybrid and electric vehicles. Key technical innovations are required to lower the cost of power electronics.

2 Regulations Drive Technology

In December 2011 the US Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) issued a Notice of Proposed Rulemaking (NPRM) for fuel economy and greenhouse gas emission standards for model year 2017 to 2025 light duty vehicles [1]. By 2025 the proposed standard is a fleet average of 54.5 miles per gallon and 163 grams per mile of CO_2, or approximately 4% per year improvement from 2016 standards. The NPRM estimates that strong hybrids, plug-in hybrids and all-electric vehicles could make up 15% of new car sales in 2025, approximately 2.6 million electric drive vehicles. Electric vehicles, plug-in hybrid electric vehicles, and fuel cell vehicles in model years 2017 to 2021 will be given incentives in the form of a multiplier meaning that each vehicle will count as more than one vehicle in the fleet calculation.

In January 2012 the California Air Resources Board approved new rules which require that one in seven of new cars sold in 2025 be an electric or other zero-emission vehicle (ZEV), representing a 34% cut in greenhouse gas emissions from 2016 levels. The classification includes battery electric vehicles, plug-in hybrid electric vehicles, and hydrogen fuel cell vehicles. Fig. 1 shows the numbers of ZEVs expected for compliance reaching 15.4% of sales in 2025 and totalling 1.4 million on the road by that year.

A variety of vehicle architectures exist to meet the various levels of CAFE standards. Even the lowest resulting fuel economy requires significant increases in U.S. vehicle electrification. Fig. 1 illustrates the impact regulatory changes have on the model mix of zero emission and plug in hybrid vehicles.

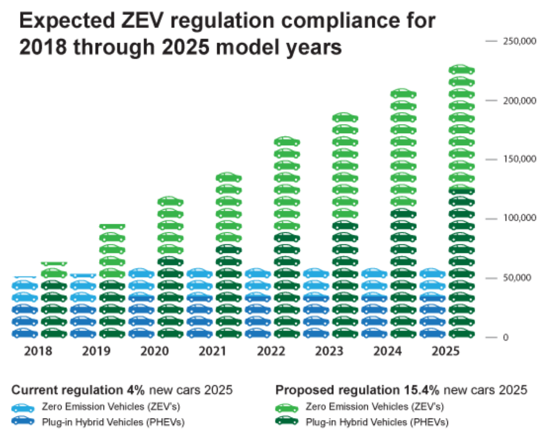
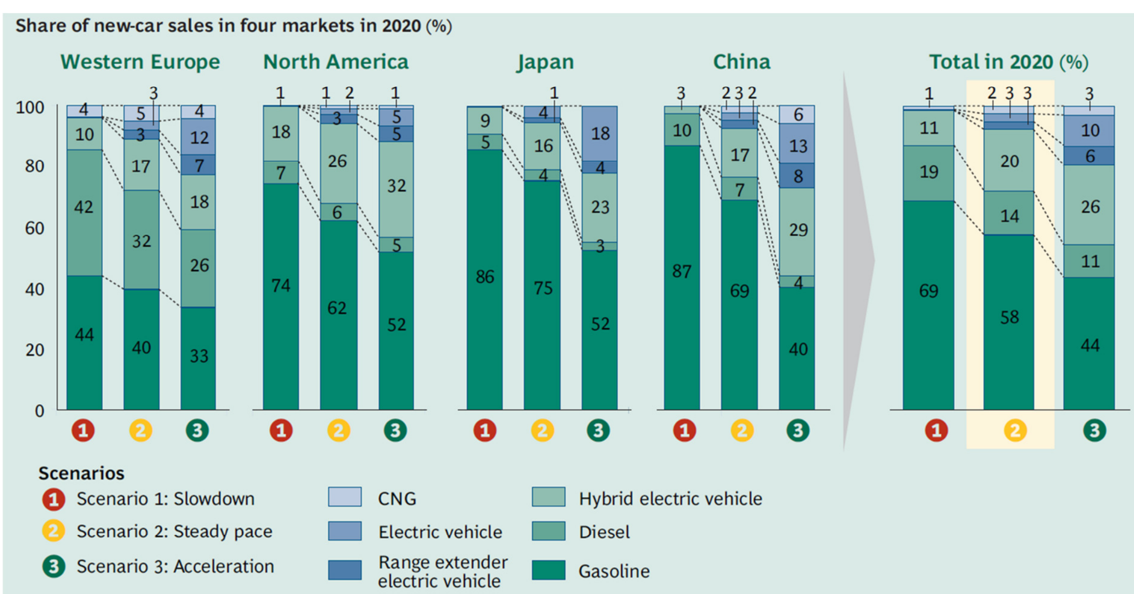


Figure 1. California ZEV Compliance [2]

Similar to the U.S. outlook, global adoption of electrified vehicles is predicted to increase dramatically. As summarized in Fig. 2, a study by The Boston Consulting Group estimates the global sales of electrified vehicles based on three scenarios of market push from governments and market pull from consumers. In these scenarios, the degree of global electrified vehicle adoption in 2020 ranges from approximately 12% to 45% of new car sales.

Figure 2: Boston Consulting Group View of Three Vehicle Electrification Adoption Scenarios [3]



3 Target Costs

The total cost of a modern hybrid vehicle electrification system breaks down into several significant components. As shown in Fig. 3, these components include the traction drive system (electric motor and inverter), DC-DC converter, the supervisory controller, and the battery pack system (battery cells plus the rest of the battery energy storage system, such as the controller and the structure to protect the cells).

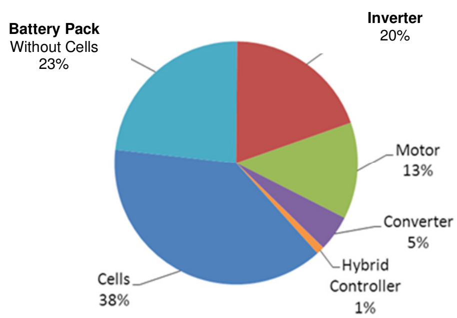


Figure 3: Percentage Cost Breakdown of Typical HEV Electrification Components

The DOE has established technical and cost targets for the various components within a modern electrified powertrain. While much focus is rightfully placed on the battery costs (cells and system), significant cost reduction is required in the traction drive system (motor and inverter) as well, as summarized in Table 1.

Table 1: U.S. Department of Energy Cost Targets

Traction Drive System Cost Targets

55 kW peak, 30 kW continuous

Year	Power Electronics ($/kW)	Motors ($/kW)
2010	7.9	11.1
2015	5.0	7.0
2020	3.3	4.7

4 Power Electronics Cost Breakdown

The power inverter is a complex system of controls, power switches, and heat transfer mechanisms. The percentage cost breakdown of a typical traction inverter system is shown in Fig. 4.

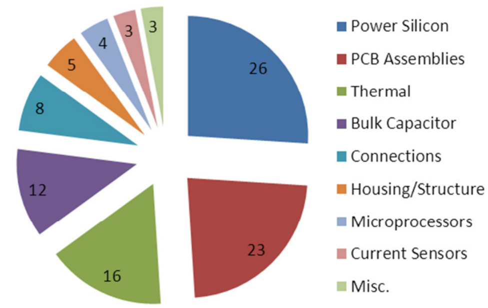


Figure 4: Percentage Breakdown of Inverter Cost Elements

Research and development is focused on cost reduction in each of these categories, while maintaining or improving performance and reliability. With co-funding support from the DOE, Delphi's focus has been particularly on the development of power devices, thermal design, bulk capacitors, and manufacturing processes that will minimize production costs when produced in typical automotive volumes, by maximizing the economies of scale. Major cost reductions are possible by optimizing these components for standardized, volume production, and are being achieved in each of these primary contributors to the overall inverter system cost.

5 Overall Thermal Capability Improvement

Savings in vehicle cost can be realized when the secondary cooling system is eliminated, and when the power electronics can operate with engine coolant at 105°C. In the DOE's Advanced Power Electronics and Electrical Machines (APEEM) program, Delphi is developing a high temperature inverter to meet this goal, by employing new developments in power semiconductors, capacitors, and thermal design.

The secondary cooling loop for the power electronics can increase vehicle cost. By using the engine's higher temperature (105°C) cooling loop and eliminating the secondary cooling loop, some cost could be added to the power electronics, while achieving lower overall system cost.

Two major components limit the thermal capability of an inverter. These are: (1) the

Insulated Gate Bipolar Transistor (IGBT) power device and its packaging, and (2) the bulk capacitors.

5.1 IGBT Double Sided Cooling

Traditional power electronics typically actively cool only one side of the IGBT power switch, since wire bonds are used to connect to the non-direct cooled side of the device. This loss of cooling area, due to the wire bonds, is significant.

Delphi has developed novel component packages for power semiconductor devices eliminating wire bonds for the electrical interconnection. The new packages provide low electrical and thermal impedances, can be tested individually, and also provide the capability for double sided cooling. Due to their unique design, these packages enable higher and more uniform current densities. Combined with matching coefficient of thermal expansion, this design provides for a highly reliable component that can also be easily manufactured using standard low-cost, high-volume manufacturing processes. The diagram in Fig. 5 shows a cross section of the unique package with double sided cooling.

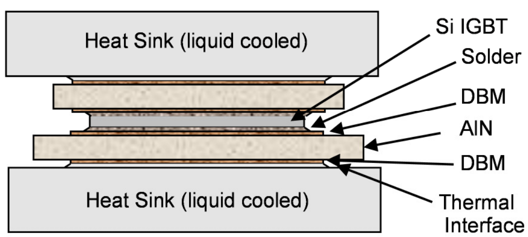


Figure 5: Example of Double Sided Cooling of IGBT

Such an IGBT package, coupled with appropriate liquid-cooled heat sink technology, can achieve thermal resistance values of R_{th} = 0.15°C/W when double sided cooled and R_{th} = 0.3°C/W when single side cooled. With this improved thermal performance, the inverter can be designed to handle higher phase currents for the same amount of active silicon or, alternatively, be designed to operate at the same phase currents at a higher operating temperature.

Design flexibility is even further improved with the ability to utilize lower cost heat sink material (such as aluminum vs. copper) in design tradeoffs, particularly when using double sided cooling.

5.2 Design Example at 70°C Coolant

In this example where a secondary coolant loop is available in the vehicle, it is shown in Figs. 6 and 7 that a single side cooled single switch with an aluminum heat rail is capable of supplying 100 Arms, while the double sided cooled system could provide 180 Arms. By changing the heat rail material to copper and providing a more aggressive fin structure in the copper heat rail, the double sided cooled power device could provide 280 Arms or 2.8X more current than the baseline single side cooled system, significantly reducing system cost.

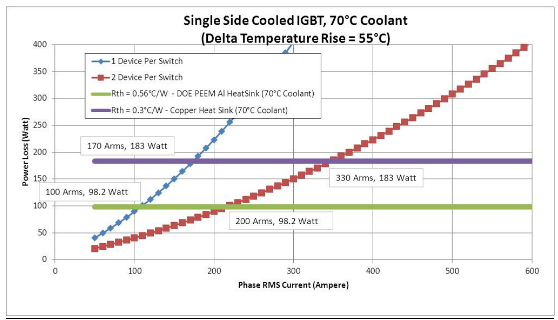


Figure 6: Single Side Cooled with Inlet at 70°C

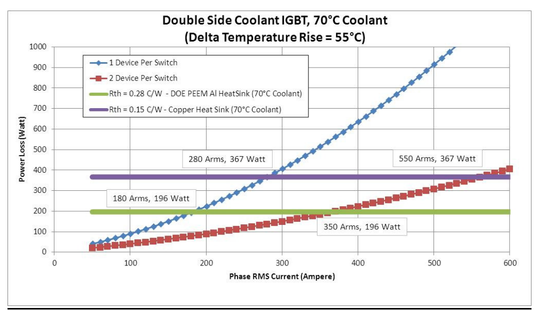


Figure 7: Double Sided Cooled with Inlet at 70°C

5.3 Design Example at 105°C Cooling

The advantages of double sided cooled power devices can be illustrated with the following example where the required current for the application is 80 Arms with an inlet coolant temperature of 105°C. As shown in Figs. 8 and 9, the amount of current that the system is capable of supplying, with an aluminum heat rail, a single side cooled power switch, 105°C inlet coolant and maximum junction temperature of 125°C, is 50 Amps. Under the same conditions, using the same power package, and same silicon, but adding a second heat rail to extract heat from both sides of the power switch, the available current is increased to 80 Arms, adding minimal cost to the inverter

To meet the application requirements, the single side cooled application could double the amount of silicon and silicon cost. Or the single side cooled system could lower the inlet temperature to the power device requiring a separate cooling loop for the vehicle. We have estimated this separate cooling loop to add $60 to the vehicle. With double sided cooled power packaging the OEM could save the separate cooling loop cost while meeting the application requirements.

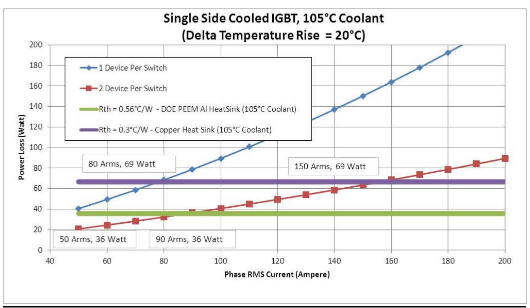


Figure 8: Single Side Cooled with Inlet at 105°C

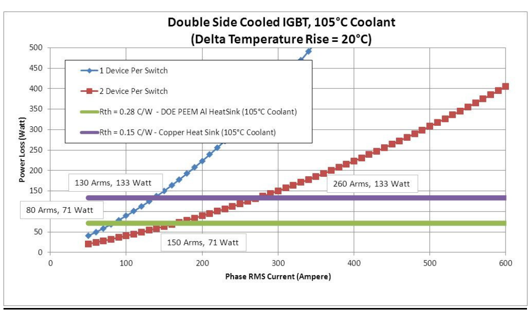


Figure 9: Double Sided Cooled with Inlet at 105°C

6 Power Semiconductors and Packaging

Delphi and its semiconductor suppliers/partners are developing advanced silicon and wide bandgap devices, and their associated packaging for use in inverters, DC-DC converters and on-board chargers. Technologies being evaluated include advanced silicon, silicon carbide (SiC), gallium nitride on silicon (GaN-on-Si) and sintered packaging. Evaluations will allow the best technology and cost/performance for the needed application to be selected.

6.1 GaN-on-Silicon

One very promising power device technology appears to be GaN-on-Si. This technology offers a strong potential for achieving improved performance vs. cost, specifically by lowering specific on-resistance at operating voltages of 600V and higher, as summarized in Fig. 10.

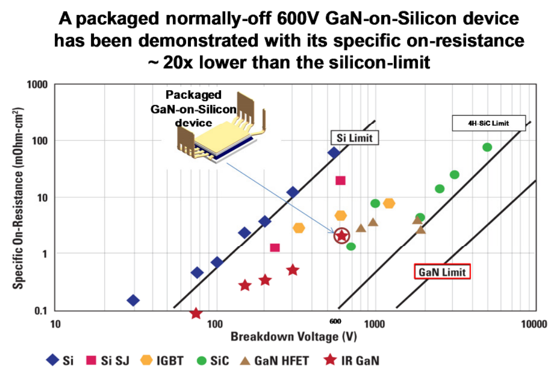


Figure 10: Power Switch Technology Comparisons illustrating the benefits of GaN on Silicon

6.2 Sintered Packaging

Power switch performance is not a function of only the chip itself. The package effects must also be accounted for. Delphi has applied its double sided cooled package to GaN-on-Si.

As shown in Fig. 11, the measured on-resistances of the packaged devices are very close to the values predicted by the chip level device model. This indicates that only a very low amount of resistance (less than 4%) is being added by the package.

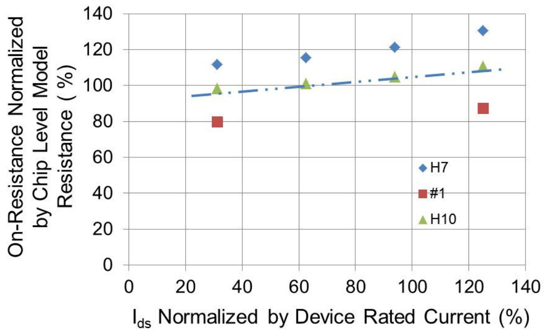


Figure 11: GaN-on-Si packaged performance

In the development of the GaN-on-Si packaging, Delphi investigated eliminating the device solder joints. Reviews of the technologies led to use of a sintering process to package the GaN-on-Si chip in a double sided cooled package. Measured thermal resistance data of sintering versus soldering showed more than a 200% improvement in thermal resistivity for sintering when compared to use of a solder/copper joint. We were able to achieve 0.0030 to 0.0062 cm^2-°K/W. Fig. 12 shows flash diffusivity measurements of thermal resistivity of silver sinter bonded direct bond copper and aluminum nitride substrates.

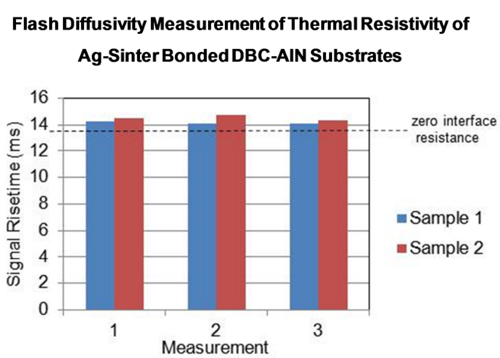


Figure 12: Thermal Resistance Measurements of Sinter Bonded Substrates

Bond strength in the package was greatly improved over solder. Sintered joints provided nearly double the shear strength of soldered joints. By eliminating solder fatigue stress failures, we expect improved device reliability.

A performance figure-of-merit (FOM) containing the energy loss information of the transistor during conduction and switching is defined as:

$$FOM = V_{ds} \times (E_{on} + E_{off}) \qquad (1)$$

V_{ds} is the voltage drop across the transistor when the transistor is in the "on" state. E_{on} and E_{off} are the energy losses of the transistor during switching "on" and "off", respectively.

Overall, packaged performance for a GaN-on-Si device in our sintered double sided cooled package could provide performance with an FOM that is better than conventional silcon IGBT in a power module by a factor of 5 times.

6.3 Packaging Benefits

By combining the advancements in semiconductor devices with advancements being made in semiconductor packaging, higher performing and lower cost devices are possible. For example, the 600V GaN-on-Si power device being developed, combined with sintered interconnects and double sided cooling, is expected to reduce energy losses and cost by at least 50% over equivalent Silicon IGBT devices. As shown in Fig. 13, increased performance of power semiconductor devices, coupled with new packaging and double sided cooling, gives an increase in current density.

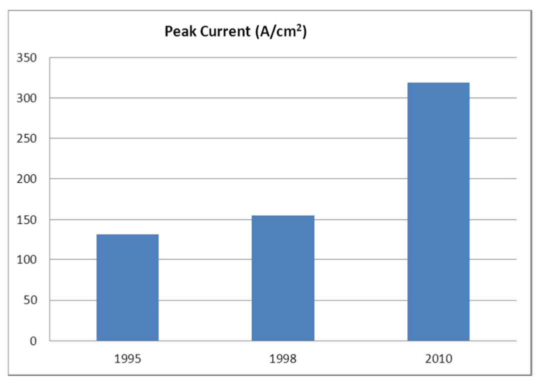


Figure 13: Trend for Power Inverter Current Density

Additional improvements in power switch packaging, such as sintering and the introduction of new wide bandgap power devices, will further advance this trend.

7 Capacitors

Today's inverters for automotive power electronics use DC link capacitors in their designs. These devices account for about 12% of the cost of a power inverter. The present capacitor technology requires the inverter designer to use a larger capacity capacitor than preferred, to compensate for the capacitor's life characteristics, which adds to the capacitor's cost as well its size.

Over the past several years, under the DOE APEEM program, Delphi has been working with GE, film suppliers, and capacitor manufacturers to develop extrudable polyetherimide (PEI) and polycarbonate (PC) films, new materials that show strong promise of both a very high dielectric constant and higher temperature capability, compared with today's standard polypropylene (PP) capacitor.

In addition, Delphi has been collaborating with Argonne National Laboratory on Argonne's Lead-Lanthanum-Zirconate-Titanate (PLZT) dielectric material. This material has also shown strong promise of a very high dielectric constant approximately 25 times higher than today's film capacitors, as well as high temperature capability.

To evaluate the potential for cost reduction in film capacitors utilizing the extrudable high dielectric constant PEI and PC materials, for comparison purposes, it is assumed that the processing cost per unit volume of capacitor module can be very close to the same as that for today's PP capacitors.

The cost to make the high-dielectric constant (Dk) polycarbonate polymer commercially was estimated based on the information presently available, but will ultimately depend on a number of key parameters, including the cost to make the monomer required to build the polycarbonate molecule, the amount of this monomer needed in the final formulation, and the volume of resin produced.

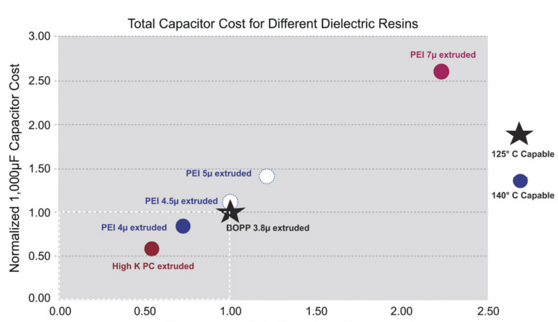


Figure 14: Capacitor Roadmap for Higher Dk Materials

Fig. 14 illustrates the roadmap for achieving both size and cost reductions for the bulk capacitor by using either PEI or high-Dk PC extruded with the same film thickness of polypropylene (PP). In addition, the temperature capability of the PEI and high-Dk PC capacitors is also improved.

Work continues on a 5 µm extruded PEI capacitor to demonstrate its high temperature capability operating in an electric drive inverter with a 140°C ambient environment and 105°C coolant for the power electronics.

8 Manufacturing Processes

Products planned for low-cost, high-volume production are designed to utilize manufacturing processes that are common with other high-volume, highly reliable automotive electronics products, and compatible with standard worldwide manufacturing processes, such as surface mount lines. Fig. 15 shows the use of friction stir welding to simplify the manufacture and assembly of the housing and cooling chamber. Friction stir welding provides a highly reliable method to seal the cooling chamber liquid passage versus conventional seals and fasteners. The use of other advanced processes can improve reliability as well as reduce production costs. Common test platforms also minimize the required up-front investment and provide flexibility of rapid changeover for producing a wide range of different products.

Figure 15: Friction Stir Weld Process Sealing Heat Exchanger on Power Electronics Box [4]

Significant reductions in product cost should also result from product standardization by the vehicle OEMs, particularly as standardization occurs both nationally and globally. Such standardization will avoid substantial up-front engineering costs that presently raise the cost for each special variant for each OEM platform. Likewise, special variants also lead to higher production unit costs, due to less productive utilization of up-front investment required for the production equipment, personnel and support systems.

9 Summary

- The path to increased powertrain electrification is through cost-effective technical innovation.
- Powertrain electrification solutions support the U.S. 2017 – 2025 fuel economy and emissions standards.
- The needed lower-cost power electronics fit the high volume production and supply base strengths of Tier 1 suppliers.
- Standardization of requirements across multiple OEM customers will lower costs by accelerating volume production.
- Optimizing component designs for both performance and volume production will substantially reduce the cost and increase the competitiveness of electric drive systems, when compared with either traditional or with other alternative powertrain systems.

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