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IGBT Devices And Modules Evolve To Address Inverter Design Challenges In Electric And Hybrid-Electric Vehicles

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The mass adoption of electric vehicles (EVs) and hybrid electric vehicles (HEVs) depends on automakers achieving reductions in the cost, size and weight of electric power train systems, while simultaneously increasing their reliability. Table 1 lists some of the performance targets that the industry seeks to achieve for the power electronics in these vehicles. The industry struggles with these issues due to the relative immaturity of the existing power electronics systems. The low production volumes of these systems do not create the necessary economy of scale.

On the one hand, standardization is needed to lower the cost of these systems. But on the other hand, automotive OEMs and tier one and two suppliers are seeking differentiation and looking for new, better, more cost-effective solutions to be more competitive. Innovative solutions in the form of better semiconductor devices and modules are needed to overcome these conflicting goals.

This article will discuss the challenges faced in the design of traction inverters for EVs and HEVs, explain how these challenges necessitate changes and improvements in the applicable IGBT devices and modules, and discuss recent trends and advances in device and module development with a focus on International Rectifier's CooliR technology.

Table1. Status and approximate technical targets for traction power electronics in electric and hybrid electric vehicles.

	R&D Status	Targets	
	2010[a]	2015[b]	2020[b]
Cost, $/kW	<7.9	<5.0	<3.3
Cost, kW/$	>0.127	>0.200	>0.303
Specific power, kW/kg	>10.8	>12.0	>14.1
Power density, kW/L	>8.7	>12.0	>13.4

Notes:
a. Based on a maximum coolant temperature of 90°C.
b. Based on a maximum coolant temperature of 105°C.
Source: The United States Council for Automotive Research LLC (USCAR)—U.S. DRIVE Electrical & Electronics Tech Team (EETT).

Inverter Configurations And Construction

Existing EVs and HEVs are typically equipped with voltage-source inverters (VSI) using hard-switching three-phase bridges to develop variable-frequency sinusoidal voltages and currents by means of PWM modulation schemes. The inverters are typically bi-directional and can operate as motor drives in motor mode or rectifiers in generator mode.

Sometimes an additional bi-directional converter is used to adjust the dc link voltage according to battery state of charge and operating mode. Such dc-dc converters allow intelligent optimization of operating conditions depending on driving profile (including speed, torque or power requirements) and state of the batteries. Despite introducing additional power losses, the dc-dc converters can improve the efficiency of the entire power train system thus extending the driving range.

An alternative to the VSI is the current-source inverter (CSI). It doesn't need the bulky dc bus capacitors that are required by the VSI.

The "Z-source inverter" uses an impedance-matching network made of passive (L, C) components to connect the inverter to the battery. Such an arrangement also allows for elimination of the large dc capacitor needed for the VSI-type inverters, which leads to substantial reduction of inverter size, weight, and cost.

Regardless of the topology, the typical mechanical construction of the traction inverter includes the IGBT switches in the form of "power modules" mounted on a heat sink, a dc link capacitor connected with low-inductance dc bus, and a gate drive, protection and control board, typically mounted on top of the power modules. Such a construction method results in an inflexible, non-differentiating "shoe-box" form factor leaving little room for optimization.

The main reason for this inflexible mechanical arrangement is the packaging of the IGBT power modules, which typically come in 6-pack (six-switch) or half-bridge (two-switch) packages. The typical modules, sometimes called "bricks" for their form factor, do not allow for much innovation or for reduction in size, weight or cost. A different solution is needed.

Inverter Design Challenges

Typical inverter currents are in the 100-Arms to 450-Arms range for continuous operation and can be as much as two to three times higher for short-time (5- to 30-second) operation. The high peak-power-handling requirements result in the inverter semiconductor devices being sized for short-time peak power rather than the much-lower continuous rating.

One of the most critical challenges becomes heat management and maintaining the semiconductor switches' temperature in a safe range to guarantee reliable operation and robustness of the electric traction systems. The semiconductor devices must be able to handle higher heat flux densities to meet the increased power density goals. This demands reduction of the thermal resistance of the power module packages, improved thermal interface materials and more-efficient heat sinks. The state-of-the-art semiconductor devices also operate at higher current densities and are characterized by smaller die areas, which further contribute to the problem of high heat-flux density. As a result, there's a need for devices with higher operating junction temperature and packaging technologies that offer reduced thermal resistance.

A reduction of power dissipation in the semiconductor switches is also needed. Both the conduction and switching losses must be reduced. However, higher switching speeds and shorter switching times lead to EMC issues and put additional constraints on inverter construction, demanding reductions in parasitic inductances as well as improved shielding and filtering. Semiconductor power devices with conduction and switching performance optimized for automotive traction inverters are needed. Additionally, there is a need for power modules with reduced parasitic inductance in order to reduce the voltage stress on the devices and enable higher switching speeds. Otherwise, the inverter designers cannot fully utilize the fast switching devices and are forced to deliberately limit their performance.

Increasing power demands lead to higher dc link voltages required to minimize the motor currents as well as the size and weight of wiring. Lithium-ion battery voltage varies widely depending on the state of charge. Operating the inverter with high battery voltage leaves little room for voltage overshoots due to switching transients. Many automotive inverter applications would benefit from power modules with optimized voltage ratings between the industrial 600-V and 1200-V standards.

However, the most important challenge is meeting automotive reliability expectations. The requirements of the automotive environment include extreme temperatures (ranging from -55°C to +150°C or higher), mechanical shock and vibration, and robustness to abnormal, extreme electrical, thermal or mechanical conditions. Standard power modules based on wirebonding interconnection technology are inadequate in terms of meeting the long-life requirements. Wirebond fatigue and failure is typically the dominant factor limiting the number of power cycles the power module can withstand.

The ability to meet the automotive industry's requirement for smaller, more-compact and less-expensive traction inverters is severely limited by the use of conventional, brick-type power modules. Such modules provide no flexibility in terms of inverter package design and impose the heat sink dimensions, terminal layout, size, weight and form factor of the inverter. The conventional power modules were originally developed for industrial motor-drive applications. They were not optimized for use in automotive traction inverters.

The industry-standard brick-type power modules dictate the current and power capabilities of the inverters, leaving the OEMs very little room for optimization. The bricks result in all traction inverters looking and performing alike with very little chance for product differentiation or flexibility.

A new and literally “out of the shoe-box” solution is needed.

New Device And Power Module Solutions

Further improvements are needed in terms of size, weight, reliability, flexibility of system-level packaging, and cost of traction inverters.

Reduction of size and weight leads to higher power density. Further increase of power density is possible either by a reduction of power dissipation or an ability to operate the semiconductor devices at higher junction temperature (Tj) or improved thermal management. The requirements may seem contradictory but improvements in all three areas simultaneously are necessary to achieve maximum power density.

Recent developments in fast-switching IGBTs and diodes are helping to reduce the power dissipation due to conduction and switching losses. New devices with low voltage drop and high switching speed generate lower conduction and switching losses. However, there is an inherent trade-off between the low turn-on voltage drop and high switching speed. Both cannot be achieved simultaneously. Design of the devices must be optimized to achieve the best performance in an inverter application taking into account the switching frequency, current and voltage ratings.

System-level techniques such as the variable switching frequency strategy may come to the rescue and minimize the switching losses during brief overload events. Normally, the lowest acceptable inverter switching frequency is selected based on the ability to produce sinusoidal motor currents with acceptable ripple and distortion at the highest output frequency of the output voltage and current, which correspond to the highest motor speed.

Typically, maximum current needs to be delivered to the motor in order to produce maximum torque while the vehicle is moving very slowly or when the motor is stalled, for example during the so-called “hill or curb climbing” event. Such events are dictating the high, typically more than two times the nominal rating, output-current requirements for automotive inverters. Reducing the switching frequency during such events could greatly reduce the switching losses.

However, the lower switching frequencies result in higher motor ripple currents, leading to vibration or audible noise.

With their ability to switch at high speeds, some of the modern semiconductor devices seem to be the answer to lower power dissipation. But these devices don’t come without penalty. The increase in switching speed is often limited by EMC requirements and the parasitic inductances and capacitances imposed by the practical construction of the inverter. The inverter designers may not always be able to take full advantage of the fast-switching-speed devices. As a result, the ability to reduce power losses reaches a practical system-level limitation and power modules may still end up operating at higher junction temperatures.

Semiconductor devices operating at a high Tj (e.g. 175°C or higher) are needed to build more-compact, higher-power-density inverters. However, operating the semiconductor devices at higher junction temperatures requires packages operating at higher temperatures. The high operating temperature puts higher stress on the package itself and affects the reliability of the module and its lifetime.

The obvious solution to the high operating temperature is improved thermal management and reduced thermal resistance from device to coolant.

Only by applying all of these solutions simultaneously will designers achieve the highest-power-density inverter.

Meanwhile, improvements in reliability must also be pursued. The reliability of a power module is typically measured in terms of the module’s ability to withstand temperature cycling or temperature shock (e.g. typically a number of -40°C to +125°C cycles) and power cycling (the number of cycles as a function of ΔTj.)

The most typical failure modes for these modules are: wirebond failure, die-attach failure and baseplate-attach failure. The wirebond failure is the Achilles heel of all conventional power modules and is the most critical factor limiting temperature and power cycling capability of the modules. All three failure modes are related to the power module’s physical construction.

Some of the new inverter power modules are attempting to advance the packaging technology and their reliability by replacing wirebonds with direct lead bonded (DLB) die-attach techniques. The wirebond failure mechanism is eliminated. However, the reliability of direct die attachment to a relatively thick copper leadframe is still a challenge.

Meanwhile, designers of modules that still use wirebonds are trying to improve the reliability by resorting to copper wirebonds, which require copper metallization or some sort of copper layer attached to the die surface (e.g. by sintering) to create an interface for copper wire bonds. All these measures are increasing the cost of power modules.

Recently, another packaging trend has become apparent. A few module vendors are moving away from the traditional gell-filled, wirebonded bricks by offering a new module style in the form of transfer molded packages. With their reduced size and weight, these modules are definitely a move in the right direction that will help to reach the weight and volume targets set for automotive inverters. Table 2 compares some of the new IGBT power modules that are now available.

Table 2. Comparison of different generations of IGBT power modules.

Gen	**Module type**	**Ratings**	**Dimensions (mm)**	**Volume (l)**	**Weight (g)**
1	Wirebonded and gel filled 1 (note 1)	650 V, 400 A	72 x 140 x 13.5 (w/o terminals)	0.136	485
1	Wirebonded and gel filled 2 (w/pin-fin base plate) (note 1)	650 V, 800 A	100 x 216 x 19.5 (w/terminals, w/o pin-fins)	0.421	1250 (w/pin-fin base plate)
2	Transfer molded and wirebond-less (note 1)	600 V, 300 A	56 x 64 x 7.5 (w/o terminals)	0.027	100
2/3	CooliR^{2}Bridge 1 (note 2)	650 V, 300 A	45.4 x 50 x 9 (w/o terminals)	0.020	35
2/3	CooliR^{2}Bridge 2 (note 2)	650 V, 480 A	58.7 x 59.8 x 7.5 (w/o terminals)	0.026	approx. 80

Notes:

1. Source: other manufacturers' datasheets.
2. Source: IR CooliR^{2}Bridge datasheets; volume and weight specifications are for Gen 2 type modules. CooliR^2 technology enables implementation of Gen 3 solutions with the potential to reduce the volume further by a factor of 2 to 3.

The new-style modules are definitely helping to break away from the Generation 1, shoe-box type inverters and create a new, Generation 2 of more-compact inverters with lower weight and improved reliability. The future however, needs a Generation 3 with its higher level of integration, where the inverter and electric motor are combined into one assembly and where the inverter "disappears" inside of the motor housing (Fig. 1.) Only then will drastic reduction of size, weight and cost be realized.

Such an approach requires revolutionary, game-changing solutions to address all the challenges posed by modern automotive inverters and advance the technology to the era of "mechatronics"—seamless integration of mechanical systems with the associated electronics.

Fig 1. Mitsubishi Electric Inc. integrated inverter and motor (source: www.sae.org).

Fortunately, such solutions already exist and are being prepared for the market. An example is the recently announced CooliR^2 platform of high-power semiconductor devices and modules from International Rectifier. The CooliR^2 platform consists of advanced high-power IGBT and matching diode devices to be offered in a variety of forms and packaging options (Fig. 2.)

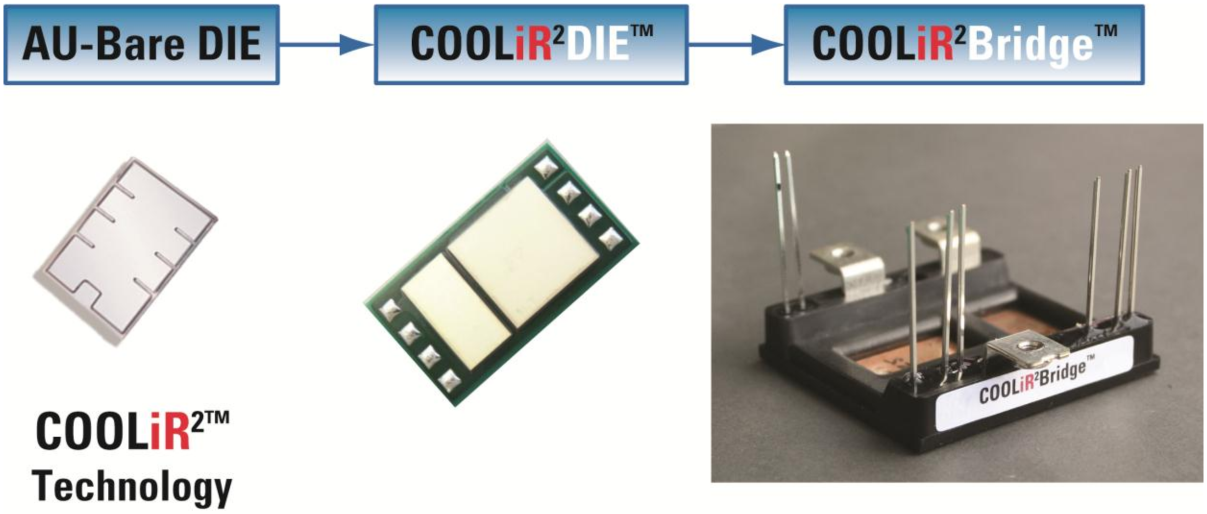

Fig 2. International Rectifier's CooliR^2 Platform of IGBTs and matching diodes.

The platform is based on purposely designed and optimized, low-voltage-drop and low-switching-loss IGBTs and soft-switching diodes, both rated for operation at a maximum junction temperature of 175°C. The devices offer solderable front metal (SFM), which allows soldered or sintered die attachment on both sides of the die. This, in turn, enables wirebond-less packaging techniques. As a consequence, modules can be built with the capability for dual-sided cooling.

Dual-sided cooling can theoretically reduce the thermal resistance by half, allowing for double the power dissipation in the same module. Even when taking into account any practical limitations in achieving equally good thermal resistance on both sides of the package, up to 50% increase in current density can be expected with dual-sided cooling.

In addition, the devices come in a variety of physical packages, from bare die through discrete packages to the IGBT and matching diode die mounted on a DBC substrate (CooliR^{2}Die) as well as modules (e.g. CooliR^{2}Bridge.) The CooliR^2 platform is based on a building-block concept that implies flexibility coming from different form factors, packages and the ability to apply single- or double-sided cooling. The modules enable development of the Generation 2 inverters by offering smaller, transfer-molded packages with single- or double-sided cooling capability. At the same time, the CooliR^{2}Die assemblies are true enablers of the Generation 3 mechatronic solutions. These devices can be assembled like surface-mount devices onto substrates with different shapes and forms, which can then be directly fitted into motor enclosures.

The benefits of CooliR technology are numerous. The wirebonds are eliminated, thus the fundamental failure mode is also eliminated and the reliability is significantly increased. In addition, the parasitic inductance and package resistance of the module is decreased. The double-sided cooling capability increases power density. The low conduction and switching losses together with a maximum junction operating temperature of 175°C allow for higher power density and increased reliability as well. In addition, the packaging technology is extremely compact and flexible, with single- or double-sided cooling capability. CooliR^2 platform is an innovative and comprehensive solution addressing challenges faced by the designers of modern EV and HEV inverters today as well as those anticipated in the future.

About The Author

Jack Marcinkowski holds the position of senior technical marketing and applications manager in International Rectifier's Automotive Business Unit and is responsible for development of power modules with a focus on HEV and EV applications. Jack first joined IR in 2003 as an applications design manager working for the Automotive Business Unit for four years and re-joined IR in July of 2011. His professional experience includes many years of working as a marketing manager, engineering manager and power electronics design engineer in the area of industrial and automotive power electronics and in the semiconductor industry. Besides IR, Jack has worked for General Motors, Fairchild Semiconductor and National Semiconductor where he held multiple positions with increasing responsibilities. Jack holds an MSEE degree from Technical University in Warsaw, Poland as well as an MBA degree from UCLA in Los Angeles, California.

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