

Progress in the Development of a High-Performance Heat Sink for Hybrid Electric Vehicle Inverters

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ABSTRACT

We have previously reported on the development of a novel active heat sink (AHS) for high-power electronic components offering unparalleled capacity in high-heat flux handling and temperature control. AHS employs convective heat transfer in a working fluid circulating in a miniature closed and sealed flow loop. High flow velocity, good flow attachment, and relatively high thermal conductivity of working fluid lead to ultra-low thermal resistance around 0.1 deg C/W. AHS appears very suitable for directly interfacing a hybrid electric vehicle (HEV) inverter to engine coolant loop. Alternatively, AHS may be used to interface inverter electronics to an air-cooled heat exchanger. As a result, the traditional dedicated liquid coolant loop for thermal management of the inverter can be eliminated, the inverter subsystem can be greatly simplified, and the power train electronics made much more compact.

Our previous work focused on AHS with working fluids based on liquid metals. This paper reports on AHS development testing with water-based working fluid, which are more suitable for automotive applications. Also presented are an AHS concept updated for high-volume, low-cost series production, and a concept for AHS integration into an automotive inverter.

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INTRODUCTION

Hybrid electric vehicles (HEV) and future plug-in hybrid electric vehicles (PHEV) require further advances in the areas of power electronics and electric machines to effectively meet anticipated benefits of reduced energy consumption and lower greenhouse gas emissions. The HEV/PHEV electric power train uses a solid-state electronics inverter to convert a direct current (DC) from a battery to a 3-phase alternating current (AC) to drive a propulsion motor, [Figure 1](#). Key semiconductor components in the inverter are insulated gate bipolar transistors (IGBT) and their associated shunt diodes. Silicon (Si)-based semiconductors are sensitive to temperature and must operate below 125°C (or very briefly up to 150°C) to maintain acceptable efficiency, reliability, and to avoid early degradation.

During vehicle acceleration, the inverter must generate tens of kilowatts (kW) of AC power on demand. Although HEV/PHEV power train electronics is ~96% efficient, at the very high power throughput even a small residual power loss translates to a heat load on the order of several kW, which is deposited into the inverter solid-state electronics. This heat must be removed from the semiconductor chips in real-time to prevent their overheating and failure. At peak power, the

projected thermal loads and fluxes to the semiconductor chips may approach 500 W and 450 W/cm², respectively, [Figure 2](#). High heat fluxes in IGBT /diodes, and resulting high temperatures decrease component lifetimes by accelerating failure mechanisms in materials, especially in electrical and mechanical connections.

The trades between technical choices and the associated economics are better understood considering that silicon chips represent about 50% of the inverter cost [1]. (For silicon carbide [SiC] chips, this fraction will likely be even higher.) The current trend is to reduce assembly cost and interconnection reliability by using as few IGBTs and diode chips as possible. With the increasing power per chip, the manufacturers are forced to use larger, more expensive dies to keep the resulting heat flux within limits. The resulting fewer but larger chip dies are also more susceptible to solder reliability due to a mismatch in coefficient of thermal expansion (CTE) with respect to the substrate. On the other hand, smaller dies are less costly, but they operate at higher heat flux, which requires heat sinks with very low thermal resistance.

The current approach for cooling HEV electric power inverters uses a separate cooling loop ([Figure 3](#)) with water-



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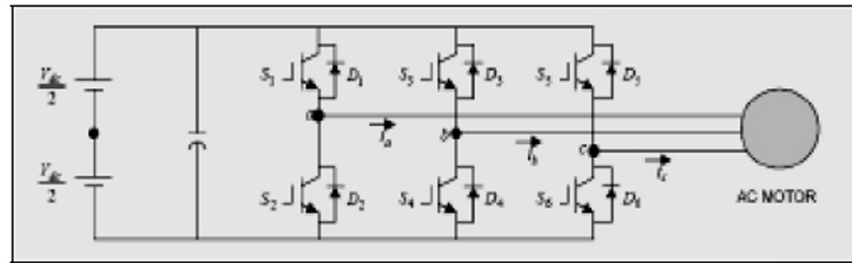


Figure 1. A 3-phase inverter feeding an AC motor from batteries

ethylene glycol coolant at about 70°C [1]. Such a dedicated cooling loop undesirably adds to system complexity, weight, volume, and cost.

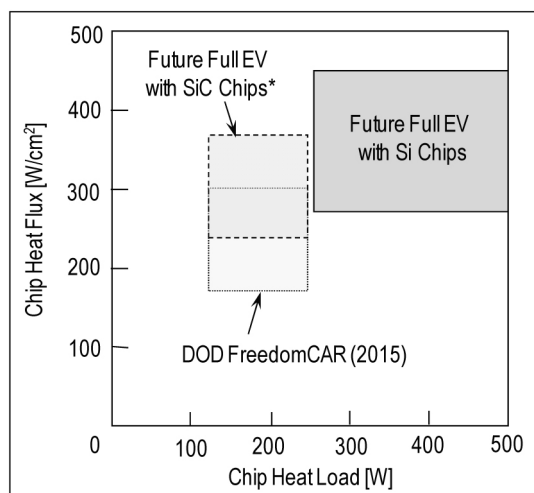


Figure 2. Heat loads to power semiconductor chips at maximum electric output (based on [2])

A preferred approach is to avoid the dedicated cooling loops and use the existing loop from the engine running through the radiator to cool the inverter, Figure 4. In this scenario, the coolant may reach temperatures as high as 105°C at the inverter inlet. Removing 200-500 W of waste heat at heat fluxes around 250 W/cm² from today's chips and nearly 450 W/cm² from future chips with only 20°C temperature gradient is extremely challenging because it requires heat sink with thermal resistance on the order of 0.1°C/W. Using air for cooling inverter electronics is an attractive option because it eliminates the need for plumbing to the engine cooling loop and provides the designer with more freedom in locating inverter hardware. However, cooling by air is considered even more technically challenging than liquid cooling by engine loop.

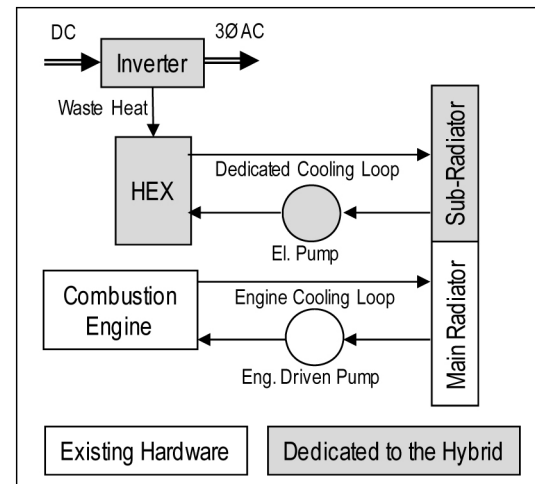


Figure 3. Current approach for cooling HEV electric power inverters uses a dedicated cooling loop

While future trench IGBTs and possible silicon-carbide (SiC) or gallium nitride (GaN) devices have more relaxed temperature limits, the ultimate temperature limit may be set by the thermomechanical stresses and fatigue failure in the chip dies as well as the in electrical and mechanical interfaces. Already today, the deep temperature cycling of inverter chips has been responsible for their limited reliability and shortened lifetime. Considering the very high cost of the inverter, the inverter manufacturers today design the hardware to specifically allow for inverter chip replacement [3], which complicates the design.

According to some estimates, a present day inverter represents about a quarter of the electric power train cost, not counting its dedicated cooling loop [4]. Packaging the required inverter electronics in a compact, lightweight, and inexpensive unit has been a very challenging technical problem. There is a strong need for technologies offering to make HEV/PHEV more cost effective to consumers. In particular, eliminating the dedicated cooling loop requires an ultra-low thermal resistance means for interfacing the high-wattage, high-heat flux load of the inverter chips to engine coolant or ambient air.

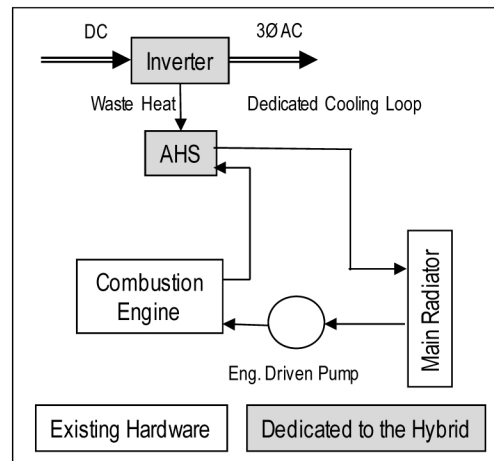


Figure 4. Inverter cooled by engine coolant loop

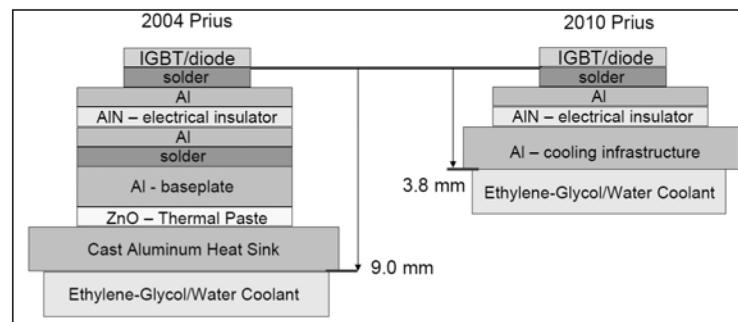


Figure 5. Thermal resistance stack-up for the IGBT and its associated diode in Toyota Prius [5]

LIMITATIONS OF CURRENT INVERTER COOLING TECHNOLOGIES

Three things affect the junction temperature of inverter semiconductors: motor drive current, thermal path, and coolant temperature. The first one is the cause of the heat load. The second one accounts for everything between the semiconductor material and the coolant. Figure 5 shows the different layers constituting a conventional IGBT package in an inverter. Each layer increases the thermal resistance from junctions to coolant. In the 2010 Toyota Prius, the stack-up was reduced to 3.8 mm. While this allowed Prius to increase the electrical output, it did not eliminate the dedicated cooling loop. A variety of techniques has been considered to reduce the junction-to-coolant thermal resistance, thus reducing the chip temperature, increasing the chip output, or both:

Passive Heat Spreaders use materials with very high thermal conductivity to “spread” high-flux heat load over a larger area, thereby reducing the heat flux to downstream components. Traditional heat spreading materials have insufficient performance. A variety of novel materials with non-isotropic thermal conductivity approaching 1,000 W/m²K are now being developed for military electronics,

including diamond film, carbon fibers, and metal-carbon composites. Novel carbon-based materials with thermal conductivity in excess of 10,000 W/m²K are also being forecast. Even when mature, the high price of these materials and the lack of joining methods may keep them out of reach for the automotive market.

Two-Sided Active Cooling applied to an inverter chip provides a second thermal path, thus theoretically reducing chip temperature rise over the heat sink by as much as a factor of four. One of the most advanced active two-sided cooling is now employed in the Lexus 300 HEV, Figure 6. The IGBTs and diodes are placed on vertical cards, which are contacted via thermal grease to flat cooling tubes running between supply manifolds. While this approach delivers 55 kW of electric power to Lexus traction motor, it does not eliminate the need for the dedicated cooling loop. The drawbacks of double-sided cooling include complexity, increased risk of coolant leaks (more connections), and impeded access for servicing to replace failed chips. In particular, to facilitate chip replacement, the cold shoes used to draw heat from the chips are not soldered but contacted via thermal grease, resulting in a significant thermal resistance.