

Automotive Power Electronics

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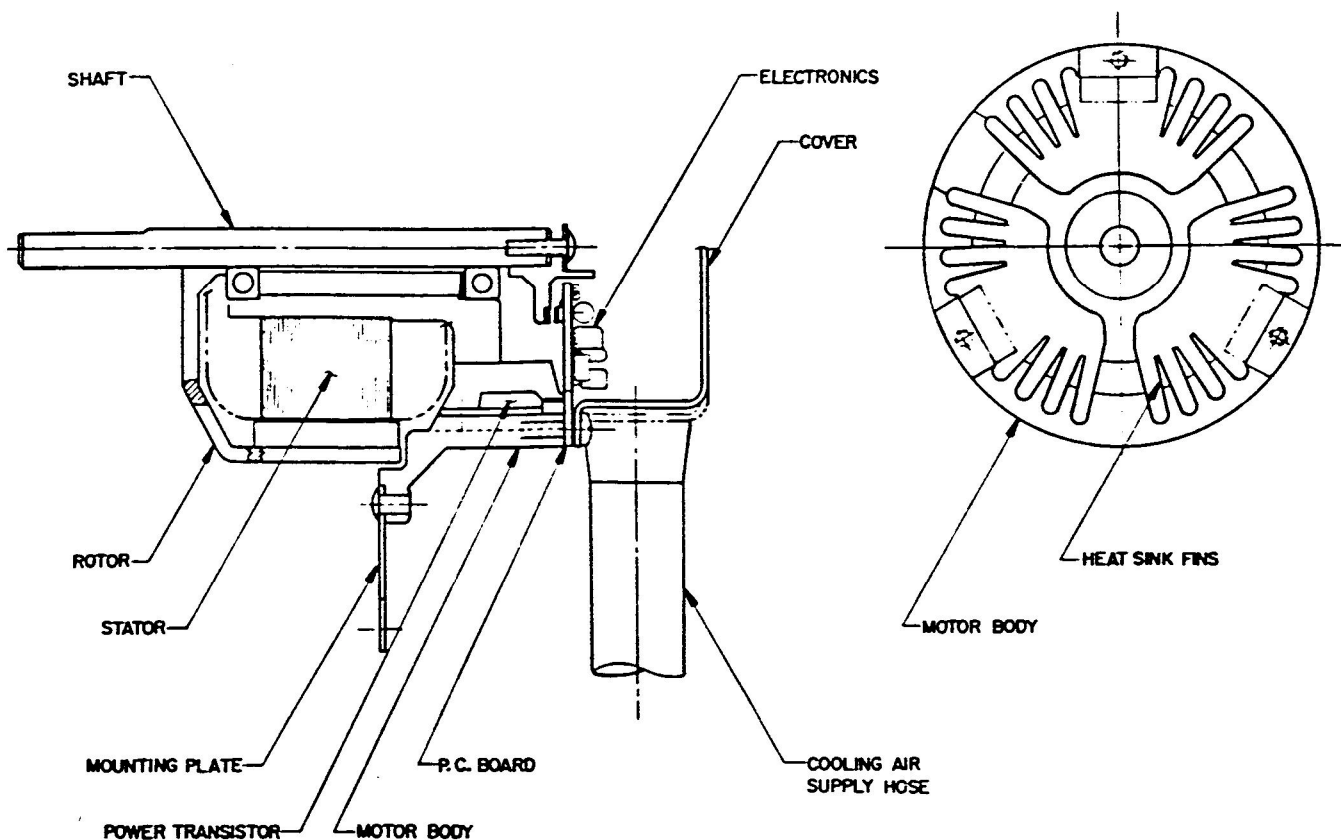
As power electronics matures it is becoming a major aspect of automotive design. As a design engineer, how would you approach some of the challenges those in the automotive industry face? This article covers some "driving" design issues, how they have been addressed, and the relative merits of electronic design trends in the industry.

Automotive design has been heading in a direction parallel to aircraft design, toward higher reliability, bussed interconnections, strong but lightweight frames, and streamlined airflow. The automotive sector of electronics is driven by the same enabling technologies as other sectors, but is interdisciplinary. This requires that automotive electronics engineers not only keep up with electronics advances but be able to combine them with the latest in drive train and body ideas to achieve an optimal overall design. One of the most dynamic areas in automotive electronics is power conversion and motion control, involving not only electrical-mechanical but also chemical-mechanical power conversion.

Reliability Beyond Brush Motors

Ever since the Japanese auto makers posed a market threat to the Big Three car companies in Detroit, reliability has become a principal parameter of automotive component design. Not only has automobile reliability significantly improved, manufacturers have backed it up at their own risk by extending warranties to 100,000 miles or more. Working against positive gains in reliability has been the tendency -- once again, as in the days before the advent of the Volkswagen Beetle -- to add "bells and whistles" to cars, thereby increasing their complexity and cost, without directly contributing to the basic transportation function.

The chief category of unreliable electronic components are those that combine electrical and mechanical functions. Motors, connectors, cables, and electromechanics in general have been targeted for improvement.



One major item that kept warranties from being extended beyond 50,000 miles was the various brush motors scattered about a typical automobile: starter, windshield wiper, air blower, radiator fan, window, seat, and others. Brush motors are dc motors for which phase control, or commutation -- the switching of windings --- is done electromechanically, with brushes and commutator bars. These moving switches wear out shortly after the statistical 50,000 miles of operation. To extend warranties, brush motors have been replaced with permanent-magnet synchronous (PMS) motors, sometimes called "brushless dc" motors. Side and rear views of a radiator fan cooling motor prototype are shown above.

This particular design uses an outer-rotating rotor. The rotor is outside of the stator, inverted in construction from what is usually found in brush motors. The stator armature also doubles as a heat sink and the motor-drive electronics is contained within the motor enclosure.

The driving parameter for this application is reliability at the ambient temperature found in one of the hottest places in the engine compartment. The maximum junction temperature of the MOSFETs is not the biggest constraint (though that is a close second) but that of the electrolytic filter capacitor across the battery supply in the motor. To satisfy this constraint, air is piped in to cool the electronics. (This is an example of where a fault in the air supply could cause a fault in the motor electronics unless it has an over-temperature shutdown.) Once the radiator cooling fan quits, it would be advisable to inform the engine computer to shut down the engine. In complex systems, fault interaction becomes a design consideration, leading to the study of possible fault sequences.

Brushless motors require electronic phase control in place of mechanical switching, and each PMS motor has a motor-drive of some kind. The additional complexity of the electronics, however, is more than compensated by its greater reliability. In this case, greater complexity results in greater reliability.

Starter Motor and Alternator Combined

Fewer components usually improve reliability, and one way to reduce them is to make a component perform multiple functions. A prime example is the combination of starter motor and alternator. Starter motor use is perhaps 3 s of cranking out of an average 20 min drive (1200 s), or 0.25 %. For 99.75 % of the time a vehicle is used, the starter motor is merely added weight. Motors are bidirectional in their power conversion capabilities; every motor is also a generator (hence the more general name, electric machine). So why not use the starter motor to generate vehicle electric power too? One approach could be to leave the starter motor and its flywheel gearing intact and interface bidirectional power-converter electronics to the now dual-function "stalternator."

A refinement can also eliminate the gearing. By placing magnets on the flywheel or timing wheel, the motor radius is increased. Motor torque is proportional to radius, and a category of high-torque motors called ring motors are of large radius and short in length. They have been around for years. The starter-alternator, in essence, becomes a ring motor.

With such obvious advantage, why did starter-alternators not appear in cars long ago? I worked on a starter-alternator project in the mid-1980s but automotive engineers are characteristically slow to implement new concepts, not due to a lack of ability, sometimes due to politics (as in the real-life example in the movie *Tucker: The Man and His Dream*), but always in observance of caution. A design fault copied millions of times can induce panic in otherwise confident engineers. The driving parameter was instead the development of power electronics, followed by cheap, high-temperature magnets. With highly-reliable, high-power MOSFETs now available at low pricing, the starter-alternator is now feasible for more than concept cars. Would you choose an inner or outer rotor for your design?

Vehicle Power Conversion

The 12-V battery-based electrical distribution system in cars is now becoming obsolete due to higher electric power demands. At more than 1-kW demand, which is where automobiles are nowadays, that corresponds to over 83 A, with correspondingly large wire sizes. Just as control cabling has gotten out of hand, so has power cabling. The obvious solution is to go to a higher voltage and the 42-V battery bus has been chosen for future designs, at three times the nominal 14-V system. Wire area is reduced by a nominal three times. The voltage chosen is a good one as the maximum of its range is at the limit of human safety, around 50 V. It used to be that 42.5 V was the standard threshold voltage for human safety, but that number has been moved up to 50 V. (Are humans acclimating to electricity? Or, instead, is the threshold rather fuzzy? In medical instrument applications, for catheterized patients the threshold is much lower.)

Another advantage of a higher supply voltage for electronics design is that the electrical noise riding on the battery bus is a smaller fraction of the bus voltage for comparable loads. This can reduce the amount of EMI filtering needed for a subsystem, though across-bus components will require higher voltage breakdown. MOSFET on-resistance increases roughly by the 2.5 power of breakdown voltage, resulting in a net increase in on-resistance for the same die area, despite the $\frac{1}{3}^2$ reduction in ohmic power loss from current. In the late 1980s, when MOSFET breakdown voltages were no lower than 50 V, the excess margin for 12 V systems was wasted. Now that 20-V MOSFETs are available, thereby optimizing 12-V systems, the battery voltage is moving up -- a new application of Murphy's Law.

Higher voltage will require more lead-acid cells in series. Variations among cells contributes to charging and life problems. To charge all cells, some become overcharged, shortening cell life. Advances in battery charging become more important, and optimal charging algorithms of greater value. Gary Bergstrom g.bergstrom@ieee.org and King Heiple of Cleveland, OH have developed a charging method that seeks the current corresponding to the minimum dynamic resistance of the battery, and charges at that dc current. Tests have shown that their patented algorithm produces less battery gas than previous charging methods.

Time-Shared Wiring

As more functions (needed or not) are added to cars, their interconnection becomes a major criterion of design optimization. Wire cabling has increased to the point where cost and weight, no less reliability, are problematic. In aircraft weight restrictions led long ago to "fly by wire" and signal multiplexing. The automotive industry developed the CAN bus; power and a multiplexed signal are provided by means of a simple, low-weight, low-cost cable to the various devices requiring electric power and control. Even headlights are networked onto the bus with their own CAN interface, which receives a node address and an on-off command that switches the light with electronics. With this approach, as in highly integrated circuits, the interconnections become the limiting factor, and it is better to add a bus interface at every node than to run separate wires. Silicon is both cheaper than copper and cheaper to support in the system. All these networked devices depend upon the reliable operation of the bus and, like telecom connections, must be designed to localize node failures so that no single node can bring down the bus.

Because each CAN node requires electronics, the design appeal is to expand node functional capabilities. From on/off headlights, a designer might imagine dimming them with a lighting controller, thereby combining bright-dim and fog lighting into a single function. By adding a reflective sensor, the controller could adjust brightness to maximize fog or rain penetration of the beam. It is understandable how an excessive growth of vehicle features can be encouraged by system-level changes. The rapid increase in power density of switching devices allows them to be placed in cramped spaces, and the CAN-bus concept

has become optimal relative to the wiring harness. But consider: as Americans go broke, one might imagine another "Volkswagen Beetle" to appeal to the masses, with so few bus nodes that the wiring harness again becomes the optimal approach. Could it happen?

Chemical "EMI"

Another driving parameter, exhaust emissions, impacts the key non-electronic device, the engine, in a way that involves power electronics. Better engine control is required to keep the burn optimal under all operating conditions, especially at zero scale (idle). Just as the control circuitry in a dc-dc converter controls the power-converter circuit, the engine controller correspondingly controls the power-converter function, which happens to be thermodynamic instead. (Actually, two conversions occur; combustion converts chemical energy to heat, followed by thermal to mechanical conversion due to gas expansion against the pistons.) For both electrical and thermodynamic converters, the more refined the control the higher the efficiency and the lower the emissions, whether as EMI or chemical "EMI" in the form of exhaust products from a suboptimal burn. With low-cost microcontrollers, control refinement increases without increasing electronics reliability or cost. However, control improvement is yielding diminishing returns as fundamental heat-engine limitations are reached. A new mechanical power converter is due to replace the century-old engine.

Electric Engines

While better power electronics advances use of PMS motors and actuators in cars, a strategic innovation is now in the new-product stage that could replace the heat engine with a direct chemical-to-electrical conversion device: the fuel cell. For some time, leading companies such as Ballard Power Systems in Vancouver, BC <http://www.ballard.com> have been developing proton exchange membrane (PEM) fuel cells, based on hydrogen as a fuel. Hydrogen can be dangerous, though not to the extent popularly believed, but it is hard to store. The small molecules leak through metal tanks, and also liquefy near 0°K, making high-density storage a formidable cryogenics problem. A more practical approach for cars is to use adsorption onto high-surface-area material, not unlike that found in high-density electrolytic capacitors. Another major constraint on PEM fuel cells is that the hydrogen must be free of contaminants -- such as sulfur compounds -- that readily foul the converter stack. One of the goals of automotive designers is to use gasoline as a fuel. This requires a pre-conversion process for separating hydrogen from hydrocarbons, and is a limiting factor in the commercialization of fuel-cell cars.

As PEM technology has advanced, direct alcohol fuel cell (DAFC) development was stuck on a problem that made it less promising. Then in the early 2000s, the problem was solved, and now the DAFC is a leading contender for automotive (and also residential) applications. This is good news, for ethanol (or methanol) can be stored in ordinary gas tanks, DAFCs are not as subject to stack fouling, and ethanol is emerging as an alternative biofuel. (Gas in Brazil contains 20% ethanol by law.) This will also give agriculture an alternative market for grain and sugar production, thereby linking the economics of food and energy. Additionally, enzymes have been developed <http://www.bio.org> for producing ethanol from waste organic matter, such as municipal solid waste, corn stalks and husks, wheat straw, or bagasse, left over from sugar cane production.

Fuel cell chemistry is not unlike battery electrochemistry, except that the reactants and products flow through rather than reside in the conversion device. Electric power conversion brings more power electronics into cars, in the form of electric drive motors. With one motor per wheel, direct mechanical drive using ring motors, and motor-drive electronics to effect "electronic gearing," mechanical components such as drive shafts, couplings, differential gears, and even transmissions disappear. A 60-hp "drive train" will have 15 hp or about 12 kW at each wheel. At this power, the efficient drive switches are IGBTs, causing the optimal

motor voltage to be over 200 V, and probably around 500 V. This results in high-impedance (high-voltage, low-current) drive motors, with many winding turns of smaller wire. Insulation is cheaper than copper, and low-current connectors are cheaper too. Wheel rims become filled with neodymium-iron-boron magnets of many-pole, large-radius PMS motors.

With electric machines at each wheel, regenerative braking converts mechanical power into charging power for the onboard batteries, which now are only needed for starting the fuel-cell pump and for transient energy storage. Electrochemical capacitors, in time, might replace most of them. The engine controller will need to manage power flows, and throttle back the fuel cell as power returns from wheels. As each wheel is PWModulated to provide anti-skid braking, varying amounts of power from each wheel must dynamically be stored and later combined with fuel-cell output for motoring. The electric car will have as much power electronics as mechanics.

The best single website I have found on fuel-cell technology is that of Ben Wiens, formerly of Ballard:
<http://www.benwiens.com>

Some other fuel-cell or hydrogen-fuel websites of note are:

<http://www.fuelcells.org/biblio.html>

<http://www.fuelcell-magazine.com>

<http://www.fuelcelltoday.com/index>

<http://www.epri.com>

<http://www.nrel.gov>

<http://hydpark.ca.sandia.gov/splash.html>

<http://www.icaen.uiowa.edu/~chemeng/datta.html>

<http://www.fuelcellscanada.ca/index2.html>

<http://www.ercc.com/homeframe.html>

<http://www.nferc.uci.edu>

<http://www.usfcc.com>

<http://www.h2eco.org>

<http://www.ergenics.com>

<http://www.metallipower.com/index.htm>

Closure

Automotive power electronics nowadays looks both exciting and challenging. It is growing, as cars become increasingly electric, thereby presenting design challenges for automotive EEs -- who optimally are wider in their engineering skills than electronics alone. As land-based vehicles become more electric, and less mechanical, automotive is emerging as a leading application area for power electronics.

