Facing the Challenges

OF THE CURRENT HYBRID ELECTRIC DRIVETRAIN

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Introduction

Presented is a high-phase, order-induction motor drive for use in a series hybrid architecture. This solution overcomes numerous compromises in current hybrid powertrain designs. Notably, it allows for a vehicle that is competitive in terms of performance and cost. (Editor's Note: More information is available at *www.ChorusCars.com* and *www.ChorusMotors.com*.)

To arrive at a motor and drive solution for a cost-competitive hybrid drivetrain, we started by selecting the preferred hybrid architecture and used United States DOT road data to define real-world requirements for drivetrain capabilities. With these two pieces, we have designed a drive that should provide excellent performance without the cost premium that hinders market acceptance of hybrid vehicles today.

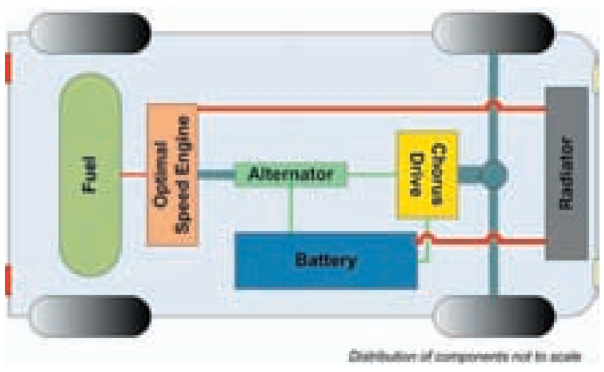

Figure 1—The series hybrid permits the internal combustion engine to operate at optimal speed for any given power requirement.

Selecting the Ideal Powertrain Architecture

The hybrid-electric drivetrain uses an electric motor to enhance the efficiency and performance of an internal combustion engine-powered vehicle. The size of an unassisted combustion engine is typically set by short duration performance requirements; thus the "base load" efficiency of the engine suffers because it is oversized for its average operating power requirements, which are quite low. However, using a smaller engine improves efficiency at the cost of performance. The hybrid approach restores performance while using a small, efficient engine operated at near-full power.

The simplest hybrid electric approach is the series hybrid—essentially a fully electric car combined with a fuel-powered generator. This is the same approach currently used in diesel electric trains and modern ships. The series hybrid approach requires the electric motor/inverter to meet both the continuous and peak operating requirements. All power from the engine is converted into electricity and then back into mechanical power.

Slightly more complex is the parallel hybrid, in which both the internal combustion engine and the electric motor supply mechanical power directly to the wheels. A single electrical machine may serve as both motor and generator, and, for continuous loading, the mechanical power may be supplied directly to the wheels without conversion losses. A significant downside of the parallel hybrid is that the internal combustion engine speed must match (via gear ratios) the wheel speed.

Current production hybrids take the complexity level and "kick it up a notch," using complex gearing and clutch arrangements to create a "series/parallel" hybrid. This offers the benefit of direct, mechanical drive—from engine to the wheels—and the ability to decouple the engine from the

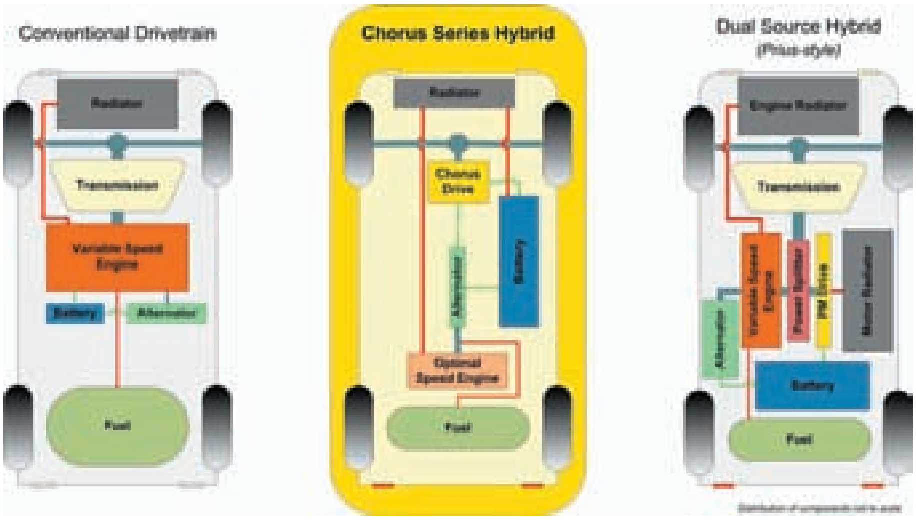

Figure 2—A comparison of a conventional drivetrain with series and parallel hybrids.

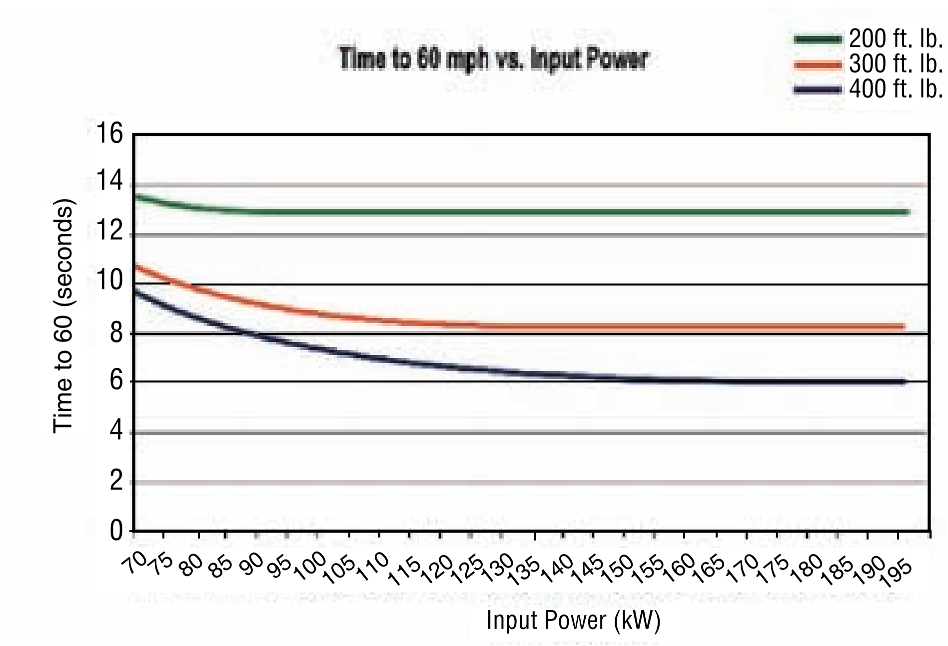

Figure 3—Peak acceleration of the vehicle as a function of the available input power; it illustrates the importance of the motor peak torque for 0–60 mph performance.

wheel. Performance is improved, compared to a parallel hybrid, but at the price of more complexity and cost.

Chorus has been exploring simple-series and parallel-hybrid approaches in an attempt to simplify the entire system. We believe that the series hybrid approach offers the opportunity to significantly improve efficiency while keeping the system simple. This will reduce costs and still provide the required performance. Figure 2 shows a comparison of a conventional drivetrain with series and parallel hybrids.

Performance Challenges

The first challenge faced in a pure-series hybrid is that the electric motor must be able to supply the full mechanical power requirements of the vehicle at all times. Customer performance expectations dominate this requirement. In particular, customers expect healthy acceleration, and even a sluggish 0–60 mph time requires roughly twice the tractive effort delivered to the wheels of a steady climb up the steepest slope on American roads. A "peppy" vehicle requires even more tractive effort delivered to the wheels. These high overload requirements last for seconds at a time—long enough to control power electronics sizing and short enough that motor heating is not an issue.

Peak acceleration of the vehicle as a function of the available input power is shown in Figure 3; it illustrates the importance of the motor peak torque for 0-60 mph performance. Higher peak torques yield significantly better performance, even with limited power. Depending on available power and customer requirements, Chorus would aim to maximize the peak torque of the motor drive to achieve optimal perfor-

continued

mance. The graph assumes the torque is capped at 200, 300 and 400 ft.–lb., respectively.

Stamina. A review of roads within the United States shows real-world requirements for a drive system. Specifically, the requirements are shown in Table 1.

In order to go from these requirements to a system design, the gearing must be determined.

Gearing tradeoffs are complex: a gear is desirable to maximize the value of the motor, but a variable speed gear adds complexity, weight and cost. For this design, we settled on a gear ratio of 4:1 as a suitable compromise. This is a fixed gear to reduce complexity and cost. There is no need for the traditional mechanical transmission or clutch.

With this gear—and conservative assumptions (Mass = 1,500 kg [3,307 lb]; C_{rr} = 0.015; C_d = 0.28; Cross-Sectional Area = 2.16 m^2 [23.3 ft^2]; Wheel [with tire] diameter = 0.635 m [25"])—the power and torque requirements for maintaining constant speed (without accelerating) are shown in Table 2.

Cooling. A motor's losses will increase as power output increases, very roughly proportional to the square of output torque. Better cooling can allow for a smaller motor or better performance from a given motor. Cooling is effected using either air or liquid.

Air cooling is generally less effective, which is why it cannot be used in this environment for thermally sensitive motors such as DC brushless machines. But it is considerably simpler than liquid cooling, which requires more hardware, complexity and moving parts.

Component temperature compatibility is the other side of the cooling equation. The hotter the motor, the more heat will dissipate to the same amount of coolant. Motor temperature is limited by winding insulation system limits, bearing lubricant limits and coolant limits, and critically limited by magnet temperature limits. On the other side of the coin, motors become less efficient as temperature increases. As the motor temperature increases, the conductivity of copper goes down and permanent magnets get weaker.

Table 1—Real-world requirements for a drive system.

Requirement	Duration
Steepest Interstate: 7% grade at 60 mph	19 minutes
Steepest Highway: 10% grade at 40 mph	2.3 minutes
Steepest Local Road: 12% grade at 25 mph	20 minutes
98 mph (kW-limited)	19 minutes
Level 85 mph cruise	Continuous

For a given mass of iron and copper, permanent-magnet machines of this scale tend to be more efficient than electromagnetic (induction) machines; however, induction machines tend to have a wider range of temperature compatibility. These machines may reasonably be 'pushed' to peak winding temperatures of 200°C, with higher rotor temperatures permitted. Brushless DC machines are restricted to lower temperatures because of weakening in the magnets as temperatures rise.

For this design, we have selected a motor with passive air cooling. This is in line with the desire to have a simple and inexpensive system without the extra complexities of fans, radiators, pumps and fluid lines.

Materials availability. Electric motors require electrical conductors, soft magnetic materials, insulating materials and magnetic field sources. At the present time, all but one of these items have many sources of supply. High-energy product permanent magnets depend upon the availability of rare earth metals, in particular neodymium. Not all customers are comfortable with the risks associated with relying on neodymium, the supply of which is controlled by China (Refs. 1–2).

For temperature sensitivity, ruggedness and cost reasons, our design is an AC induction solution.

Sensors and control. Virtually all motors being considered for hybrid applications are electronically commutated, and switching events must be timed appropriately. In the case of brushless DC and switched reluctance motors, this means accurate rotor position sensing—either directly or inferred. In the case of induction motors, rotor speed sensing is desirable, but again this can be inferred from drive current measurements. Induction motors offer the benefit of operating asynchronously from the drive, which relaxes sensor requirements.

Power electronic switching elements must be sized to carry peak overload current to meet acceleration requirements. Semiconductor thermal mass is low, limiting overload capability, but heat sink mass is often significant. It is generally possible to design a 30-second overload, suitable to meet automotive acceleration requirements.

Proposed Design Solution

Chorus has approached these challenges with the following design:

- We have selected an induction motor using standard copper windings, standard silicon steel laminations, standard insulation materials and

Table 2—Power and torque requirements for maintaining constant speed (without accelerating).

Requirement	Duration	Torque	Power
Steepest Interstate: 7% grade at 60 mph	19 minutes	88.3 ft-lb.	40.5 kW
Steepest Highway: 10% grade at 40 mph	2.3 minutes	105 ft-lb.	32.2 kW
Steepest Local Road: 12% grade at 25 mph	20 minutes	118 ft-lb.	22.6 kW
98 mph (kW-limited)	19 minutes	53.7 ft-lb.	40.2 kW
Level 85 mph cruise	Continuous	43.6 ft-lb.	28.3 kW

standard bearings.

- Current densities have been selected to permit a totally enclosed machine, and overload capability was selected to provide a "peppy" car with plenty of acceleration.
- We depart from the conventional induction solution by using Chorus' high-phase-order approach coupled with a "toroidal" winding geometry.

The selection of toroidal winding permits better slot fill and larger pole area without excessive losses to end turns. Additionally, toroidal windings are most suited to large-diameter "pancake"' machines, and are better matches for automotive torque/speed requirements. The toroidal winding also provides better access to core copper for cooling. Large pole areas are an optimization pushed by the use of an electromagnet machine. Finally, the selection of a toroidal winding relaxes winding symmetry restrictions and permits the use of the "harmonic mesh effect," while operating as a variable pole machine.

The selected design is intended to power a 3,300-pound sedan, as a "pure"-series hybrid. For this paper, we have not considered battery pack mass or other balance-of-system issues. The mass of the active materials is about 135 pounds; we have estimated the total motor mass at about 310 pounds. This includes considerable material used to handle mechanical forces and potential shocks in operation. While our design may be overly conservative, the same frame capabilities would be required for any motor solution; a lighter frame could be adapted for this motor design. This leads to both a motor and inverter design as found in the specifications in Tables 3 and 4.

Anticipated 0-60 time is about 9 seconds. Anticipated acceleration at zero speed—3.5m/s^2 (1/3G).

Conclusion

While the design presented is sure to be modified to fit the specific requirements of a given application, it shows that a motor drivetrain for a hybrid car can at once be light, mechanically simple and inexpensive. When incorporated within a series hybrid sedan, a standard sedan can be developed that provides excellent performance and superb mileage without a cost premium.

(Authors' Note: Although this paper has not examined the overall energy flows, the Chevy Volt and Chrysler's recent announcements have been for series hybrid vehicles that promise 45-50 mpg when using the engine—and that is with hundreds of pounds of batteries to allow for pure electric "plug-in" operation. Our design reduces vehicular weight, and so should further improve fuel efficiency.

Diesels are more efficient: Volkswagen's new Golf BlueMotion diesel is listed at 62 U.S. mpg. The Golf TDI diesel hybrid is listed at 83 mpg (Euro), which AutoBlogGreen places at 69 U.S. mpg. A series hybrid approach with diesel should yield even better results, and at a competitive cost.)

References

1. *http://www.magnetweb.com/Col04.htm*
2. *http://www.lynascorp.com/page.asp?category_id=1&page_id=2*

Table 3—Motor design.

Dimensions	14.5" x 16" (plus 2" shaft extension)
Mass of Active Materials	135 pounds
Total Motor Mass (no cooling required)	310 pounds
Peak (30-second) Torque	295 ft-lb.
Continuous Torque	118 ft-lb.
Maximum Speed	5,000 rpm
Base Speed	2,400 rpm
Peak Power From Generator/Energy Storage	104 kW
Power Factor at Peak Torque at Rated Speed	65%

Table 4—Inverter design.

DC Bus	300 V
Inverter	160 kVA (30 seconds)
Inverter	110 kVA (continuous)
Inverter Phase Count	18 phases
Inverter Current per Phase	105 A

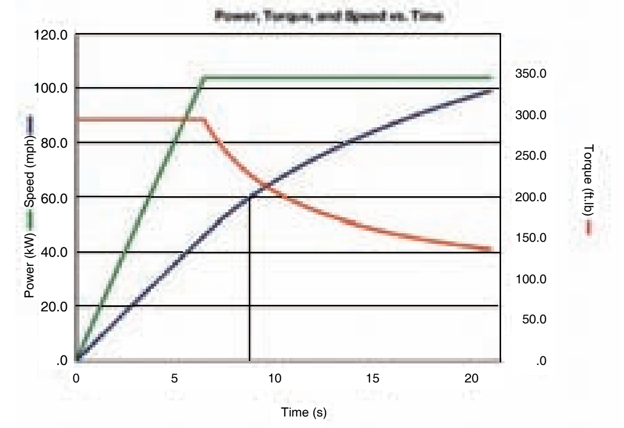

Figure 4—Anticipated 0–60 time is about 9 seconds; anticipated acceleration at zero speed—3.5 m/s^2 (1/3 G).