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White Paper

Overcoming the Challenges of Hybrid/Electric Vehicle Traction Motor Design

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Hybrid electric vehicles (HEVs) and electric vehicles (EVs) have been rapidly gaining traction in the global automobile market by providing high fuel efficiency and near-zero emissions at increasingly affordable prices. Many automobile original-equipment manufacturers (OEMs) are working on new HEV and EV designs; one of their greatest challenges is designing traction motors, which, in most cases, are interior permanent magnet (IPM) synchronous machines. Minimizing electrical and magnetic losses is critical to deliver maximum range and fuel efficiency to consumers. At the same time, engineers need to consider structural, thermal and electromagnetic issues that play a crucial role in vehicle performance, reliability and cost.

OEMs face the challenge of solving these issues quickly to squeeze through tight market windows in the rapidly evolving HEV and EV markets. Integrated multiphysics simulation technology helps to address these challenges by enabling engineers to rapidly evaluate — prior to physical prototyping — functionality, performance and cost of a wide range of design alternatives. This approach makes it possible to optimize traction motor design performance in a fraction of the time and cost required by traditional design methodology. By leveraging advanced state-of-the-art simulation, automotive organizations can gain a significant competitive advantage in the race to replace conventional powertrain technology.

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Background

Automotive OEMs are engaged in a global contest to build mass-market HEVs and EVs. A number of key technological advantages make these vehicles attractive to auto customers; these same factors are enabling manufacturers to resolve a variety of sometimes-competing demands, from government regulations to eco-friendliness to affordability — with the end result penetration in a wide range of automotive markets

First, electric motors are highly efficient; in HEVs and EVs, they convert 75 percent of the energy contained in their power sources — batteries, ultracapacitors and fuel cells — into tractive power for the wheels. In comparison, internal combustion engines (ICEs) convert only 20 percent of the energy stored in the gas tank into tractive power. The rest is lost in various mechanical and electrical losses.

Secondly, EVs emit no tailpipe pollutants. Moreover, renewable energy power plants that are targeted to provide the bulk of energy for EVs — such as nuclear, hydro, solar and wind-powered plants — do not generate significant pollutant emissions either.

Third, electric motors generally offer faster acceleration and quieter operation than similar-sized IC engines. EVs provide better handling and passenger comfort. Meanwhile, technological advancements in areas such as material science and nanotechnology are reducing vehicle cost and weight and increasing the life of batteries, thus making HEVs and EVs more affordable.

The basic design of the electric motor has not changed since it was invented almost two centuries ago. But EV and HEV traction motors have some special requirements that set them apart from conventional electric motors. For decades, automotive OEMs have invested relatively little to address these special requirements because the ICE was so widely used and accepted. Today, with the interest in new traction motor design there is a surge in R&D activities in this area.

"Maximizing efficiency is one of the most important challenges in motor design."

Design Challenges

The electric motor design determines how much electrical energy (which the battery provides) is transformed into physical energy used to turn the wheels of the vehicle. Therefore, maximizing efficiency is one of the most important challenges in motor design. Minimizing electrical magnetic losses is critical, since any loss leads directly to shortened battery run time. The loss also generates heat, which must be removed from critical components — possibly resulting in further energy losses, via fans and cooling flow modifications. Copper loss and lamination core losses must be determined at a wide range of operating conditions, such as speed and current.

The traction motor must also recharge the battery via regeneration braking. Motor efficiency is critical to this role as well. Any losses mean that energy captured from the decelerating vehicle is not fully absorbed into the battery.

Reliability is a crucial selling point for automobile customers; it is also a critical element in controlling warranty costs and the brand image. Traction motors must operate consistently under a number of extremes: hot and cold temperatures, severe vibrations, hard-duty cycles and rough road conditions. In an HEV, the traction motor is exposed to high temperatures produced under the hood. These and many other variables must be addressed during the motor design process.

At present, the majority of traction motors used in HEV/EV applications are IPM synchronous machines. A number of other machine types can be considered — induction machines (IMs) and switched-reluctance machines (SRMs), for example. Although these have been in use for many years, they must be redesigned to provide optimal performance in HEV and EV applications.

In a traditional motor development, such as three-phase induction machine or DC brush, new designs can be created simply by scaling existing designs up or down and using the same (or similar) controller and power electronics. But traction motor design is much more challenging because of the many unknowns, uncertainties and new procedures to consider:

- Should you use an IPM, IM or SRM design?
- If you choose an IPM design, where do you position the magnets, and how many do you need per pole?
- What design configuration will generate enough torque and speed but as little torque ripple as possible?
- How do you configure the motor to provide the best combination of PM torque and reluctance torque?
- Should the stator have a solid or stranded winding design?
- Should the windings be concentrated or distributed?
- Should you use single- or double-layer rotor magnet placement?

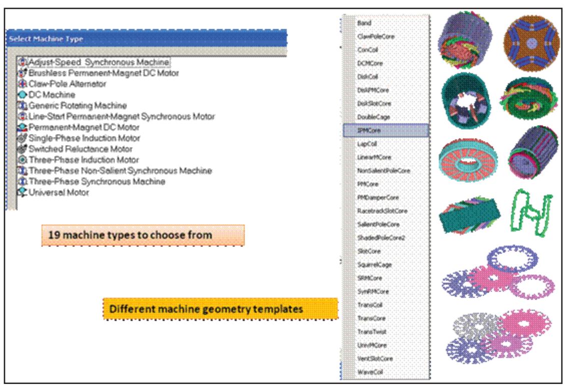

Figure 1. Types of electric machines. A magnetic circuit based motor design package from ANSYS called RMxprt provides a template for 19 different types of machines. This tool can quickly generate an initial design that can be imported to other higher fidelity simulation tools from ANSYS.

Examples of some of these design alternatives are shown in Figure 1

The IPM has both reluctance torque and permanent magnet (PM) torque. Therefore, the best individual IPM design and the best individual controller/power electronics design don't necessarily form an optimized system. For example, if an engineer plugs a Toyota-designed IPM into a GM-designed controller and power electronics, it is very likely that the system won't work. Even if it works, the combination will result in poor performance. In the HEV/EV world, a perfect combination of motor/controller/power electronics is absolutely essential for making a design competitive by achieving high performance targets.

In HEV/EV traction motor design, R&D teams must address structural and thermal considerations along with electromagnetic design constraints. For example, the small bridges used to contain rotor magnets must be structurally strong enough to hold the rotor together when spinning at high speeds. But from an electromagnetic perspective, the bridges must be as small as possible to minimize their effect on the magnetic field.

There are similar tradeoffs in thermal design. The power delivered to the wheels as well as the power needed to recharge the battery travels through the power electronics. Even the slightest power loss there creates a large amount of heat. The heat must be carefully managed and dissipated under a wide range of operating conditions, ranging from desert to subzero winter conditions, to avoid damage to the power electronics and nearby components. Therefore, engineers must accurately calculate electric losses and identify/design heat dissipation paths to ensure effective cooling.

Limitations of Conventional Design Methods

Obviously, design decisions involve a complex series of tradeoffs. Automotive development teams must consider an enormous number of alternatives to find the one that will succeed in the marketplace. To arrive at a highly optimum design today, leading HEV and EV OEMs typically study hundreds of thousands of design alternatives for motor magnetics. There are so many different options that OEMs have neither the time nor the money to build and test prototypes of even a fraction of them. In the past, R&D teams regularly spent 10 to 15 years developing a new ICE powertrain, but today's consumers and regulators are pushing the global automotive industry to develop HEVs and EVs within a much shorter timeframe.

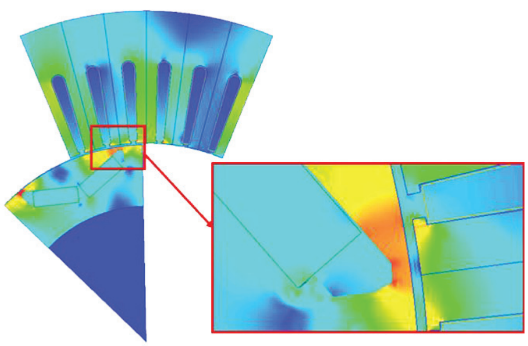

Figure 2. Finite element analysis accurately accounts for details such as nonlinearity and local saturation of a rotor and stator. ANSYS Maxwell electromagnetics field simulation software uses the finite element method to solve static, frequency-domain and time-varying electromagnetic and electric fields. A key benefit of Maxwell is its automated solution process where users are only required to specify geometry, material properties and the desired output. From this point, Maxwell will automatically generate an appropriate mesh for solving the problem.

Traditionally, engineers widely used textbook-based linear equations for electric machine design. But this approach is not suitable for IPM concepts. IPMs have high saturation, especially in the bridge area on the rotor, as shown in Figure 2. A three-dimensional simulation such as finite element analysis (FEA) is required to capture nonlinear effects of such high saturation. The analysis must be accurate, since HEV/EV traction motors need to utilize the limited energy in the battery pack as efficiently as possible. Simple linear equations do not provide the required level of accuracy.

Multiphysics simulation software solves this problem via virtual prototypes that enable engineers to understand how a design will perform — without the need for physical hardware. Real-life scenarios can be accurately simulated, including the effects of and interactions between fluids, structural mechanics, thermal physics, electrochemistry and electromagnetic forces. Engineers can then easily adjust the design based on the simulation results. With such a process, design alternatives can be generated faster and systems can be optimized upfront in the cycle, avoiding surprises and problems that might occur in the later stages of product development.

Multiphysics Simulation: Electromagnetic Effects Simulation

In developing the motor/generator, a design team first focuses on the electromagnetics of the electric machine. Initial CAD drawings and related engineering specifications of the assembly provide entry data for electronics design optimization software: defining the main elements of the motor/generator including magnet materials, coil configurations, number of turns, air gaps and more. Parasitic extraction tools can be used to compute the machine's electrical properties.

These outputs, in turn, provide data for electromagnetic field simulation software, which computes the torque profile of the machine — that is, how the torque ramps up over time for driving the vehicle in motor mode as well as the electrical resistance in stopping the vehicle in regenerative brake mode. Vehicle weight is brought into the analysis to determine acceleration as well as stopping time for various scenarios. Based on output results, the team modifies the design by changing any basic design parameters (magnet size, for example) to balance machine performance against its size, weight and cost.

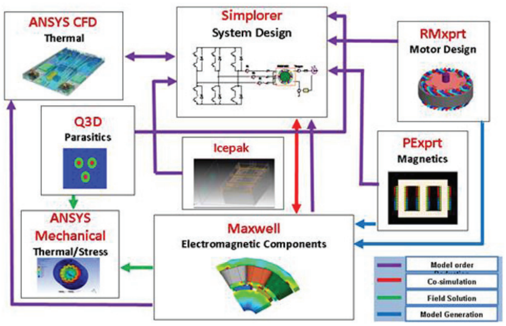

Figure 3. Systematic integrated simulation approach for motor and drives systems. ANSYS Simplorer is a multi-domain system simulation software program used for designing high-performance systems that include electrical, thermal, electromechanical, electromagnetic, controller designs, etc. Simplorer ties all these different physical analyses together to ultimately optimize the whole electric powertrain as one coherent system. This figure shows the resulting design flow.

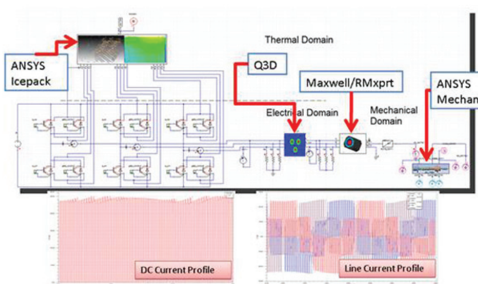

Figure 4. Multidomain simulation example in which the traction motor is one component of a larger system. Here, the traction motor, insulated-gate bipolar transistor (IGBT) inverter, cable/busbar and mechanical load are all modeled in a single integrated simulation conducted with the system level software ANSYS Simplorer and other integrated software tools integrated with it such as ANSYS Icepak for electronics cooling, Q3D for parasitics, Maxwell and RMXprt for electromagnetics, and ANSYS mechanical for structural analysis.

Multiphysics Simulation: Thermal, Structural, and Fluid Effects

The computed torque output is used further in a structural mechanics solver for computing mechanical stresses, loads, deformations and vibrations of the physical parts of the powertrain including the driveshaft and gearing. Vibration analysis is important because traction motors can be a prominent source of noise in EVs. Further, a fluid dynamics solver is used for studying thermal management issues, mapping energy losses, and determining heat distributions in the motor/generator assembly.

Multidomain Simulation

Putting two or more individually optimized components together does not make an optimized system. This is particularly evident in HEV and EV traction motor design where it is crucially important to design and optimize the motor as a part of a larger system comprising of the power electronics, controller, and other components. A multi-domain system simulation software program is essential for designing such high-performance systems that include electrical, thermal, electromechanical, electromagnetic, controller designs, etc. It has to tie all these different physical analyses together to ultimately optimize the whole electric powertrain as one coherent system. Figure 3 shows the design flow that can be achieved with such a multi-domain system simulation program.

Figure 4 shows an example where the traction motor, insulated-gate bipolar transistor (IGBT) inverter, cable/busbar and mechanical load are all modeled in a single integrated simulation. In this example, using electronic thermal current tools, engineers specify the geometry of the major heat sources in the powertrain system such as (the IGBTs) and current-carrying parts of the motor/generator. Each heat source is applied individually at major points of interest in the system with air circulation and conducted thermal energy taken into consideration. The software then processes this data and generates a thermal model that determines overall temperature profiles of each IGBT. The software also provides temperature-dependent performance variables, such as energy drained from the batteries to ensure that heat levels do not exceed specified limits to adversely affect IGBT performance.

From this temperature profile, engineers can utilize the thermal–structural analysis capabilities of FEA-based structural solver to determine the resulting thermal stresses. Electronic design analysis tools are applied to calculate electromagnetic forces acting on motor/generator components to determine deformations and mechanical stress distributions on the structure. Engineers can then modify the structure to eliminate stress concentrations and excessive deformation, or conversely, to lighten regions that may have been overdesigned.

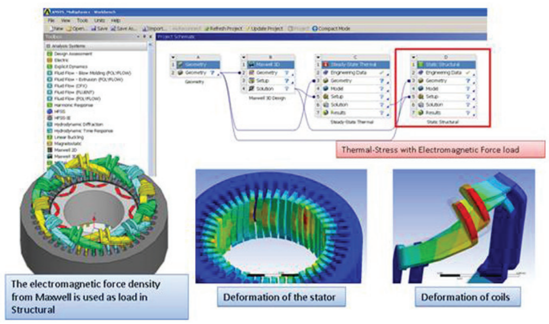

Figure 5. - A schematic showing the common simulation platform ANSYS Workbench being used to simulate a typical multiphysics problem in traction motor design. ANSYS is the only simulation technology provider that has industry leading tools for all physics required for traction motor design: electromagnetics (ANSYS Maxwell), electrical circuit (ANSYS Simplorer), structural mechanics (ANSYS Mechanical) and computational fluid dynamics (ANSYS CFD). All these tools work together seamlessly under ANSYS Workbench which is a single unified environment that hosts all these tools and provides smooth sharing of data between them. As a control dashboard, ANSYS Workbench provides a project schematic view that ties together the entire simulation process, guiding the user with ease through the high-end, tightly interconnected multiphysics analyses. The platform also provides bi-directional CAD connectivity, automated meshing, a project-level update mechanism, pervasive parameter management and integrated optimization tools.

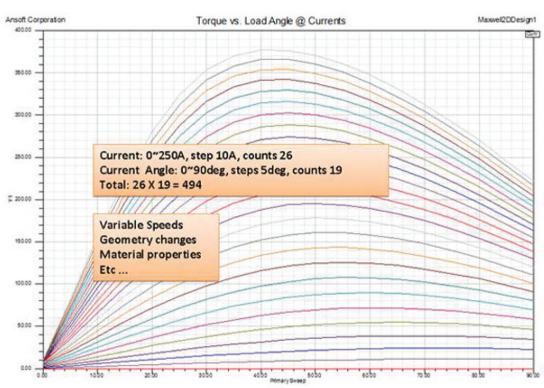

Figure 6. A plot of IPM torque output vs. load angles and currents, used to maximize Maximizing output torque at different load angles and currents.

A common simulation environment

Throughout the electromagnetics and mechanical development processes, a common simulation platform needs to coordinate the action and exchanges of data between the various physical simulations in the many computations performed for different load scenarios and in comparing various design alternatives.

Figure 5 shows a schematic of a common simulation platform that is being used to simulate a typical multiphysics problem in traction motor design. The end goal of this simulation is to find out the stress/deformation on stator lamination and coils as input for vibration/acoustic noise or fatigue analysis. Common geometry is used for both structural and thermal analysis. The magnetic solver computes both electromagnetic losses and magnetic force. Losses from the magnetic solver are automatically mapped into the thermal solver as thermal loads on an element-to-element basis to compute the temperature profile. This temperature profile is then automatically mapped into the structural solver to compute thermal–mechanical stress.

At the same time the magnetic component of the force is mapped from the electromagnetic to the structural solver. The engineer can also apply any additional force directly in the structural solver. The final simulation simultaneously takes into account all the loads that would act on the motor under real operating conditions thereby simulate the motor's performance with real-life accuracy. Once one such is simulation is completed, the common simulation platform allows engineers to change the geometry and update all simulations in different physics in a highly automated way without having to setup each simulation again.

Figure 6 shows a plot of IPM torque output vs. load angles and currents. For each current output torque peaks at one particular load angle. To optimize the motor and drive design, this load angle and current should be used to drive the motor to achieve maximum torque within a given geometry. To derive this type of curve, at least 494 combinations need to be simulated. This doesn't even include potential changes in geometry, motor speeds and material properties at different operating temperatures. This example shows that hundreds of thousands of designs need to be simulated to optimize a typical IPM design. Figure 7 shows how the simulations of thousands of such design variations can be sped up drastically by employing High Performance Computing (HPC) with a DSO (Distributed Solve Option).

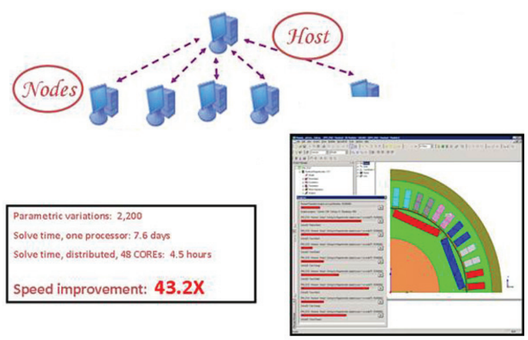

Figure 7. Distributed solve technology reduces time-to-market. Thousands of design variationss can be simulated using ANSYS Optimetrics and DSO (Distributed Solve Option) technology using multi-core clusters. ANSYS Optimetrics and DSO perform parallel processing by creating and managing numerous simultaneous simulations, each conducted on a separate set of computer cores, to drastically reduce the total simulation runtime. In this example, a speedup factor of 43.2 is achieved by using 48 cores to solve 2,200 variations in parallel

Conclusion

Automotive engineers face the challenge of designing extraordinarily complex next-generation electric powertrains within demanding timeframes that cannot be met using the trial-and-error prototype testing methods. Multiphysics-based simulation-driven development makes it possible to rapidly evaluate hundreds of alternatives within multiple domains, conduct what-if studies, predict vehicle behavior in real-life driving scenarios, and optimize final designs. Today, engineers at leading HEV and EV manufacturers are using these tools to build strong competitive advantage by designing high-performing traction motors and integrating them tightly with other vehicle systems.

For OEMs and suppliers to succeed in the fast-changing HEV and EV market, they need a simulation solution with the required breadth and depth of multiphysics technologies that all work together in an integrated environment.

ANSYS is the only simulation software provider with industry-standard mechanical, fluid dynamics, magnetics and electrical tools for complete multiphysics simulation. Tools integrated on the ANSYS® Workbench™ platform that are used extensively in HEV powertrain development include:

Simplorer™ multidomain system simulation software for design, modeling, analysis and optimization of high-performance systems that include electrical, thermal, mechanical, electromechanical, electromagnetic and hydraulic designs

Q3D Extractor® computational field solver for the calculation of frequency-dependent resistance, inductance, capacitance and conductance parameters of electrical current-carrying structures for engineers designing printed circuit boards, electronic packaging and power electronic equipment

HFSS™, a full wave solver for 3-D full-wave electromagnetic field simulation, providing electric and magnetic fields, currents, scattering parameters and near- and far-radiated field results. From specified geometry, material properties, and output type, the tool automatically generates an appropriate, efficient and accurate mesh for solving the problem using the finite-element method.

Maxwell®, a low-frequency electromagnetic field simulation tool that uses the finite element method to calculate static, frequency domain and time-varying electromagnetic and electric fields for designing and analyzing electromechanical and electromagnetic devices such as motors, actuators, transformers, sensors and coils

RMxprt™, which speeds the design and optimization of rotating electric machines such as motors and generators. Templates for specific machines enable users to easily create models, assign materials, calculate machine performance, make initial sizing decisions and perform hundreds of what-if analyses in a matter of seconds.

ANSYS® Icepak®, computational fluid dynamics software for thermal management of electronics systems that predicts heat flow and thermal transfer at the component, board or system level. Simulations include fluid flow and all modes of heat transfer (conduction, convection and radiation) for both steady-state and transient thermal flow.

SIwave™, which analyzes entire PCBs and IC packages for performing complete signal- and power-integrity analysis from DC to beyond 10 Gb/s. The tool extracts frequency-dependent circuit models of signal and power-distribution networks directly from electrical CAD layouts.

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ANSYS® Mechanical™, a comprehensive solution for structural linear, nonlinear and dynamics analysis including stress, deflection and vibration. A complete set of element behaviors, material models and equation solvers are provided for a wide range of engineering problems as well as thermal analysis and coupled-physics capabilities involving acoustics, piezoelectric, thermal–structural and thermal–electric analysis.

ANSYS CFD, a product suite that offers a wide range of general-purpose and application-specific modeling and fluid flow analysis capabilities. Modeling capabilities are included to represent fluid flow, turbulence, heat transfer, laminar-to-turbulent modeling, incompressible-to-fully-compressible, and isothermal analysis for stationary and rotating devices.

ANSYS® Multiphysics™, a wide-ranging set of engineering analysis tools for simulation of complex coupled-physics behavior. Solver technology addresses a wide range of physics disciplines including structural mechanics, heat transfer, fluid flow and electromagnetics within the open and adaptive ANSYS Workbench framework.

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ANSYS is dedicated exclusively to developing engineering simulation software that fosters rapid and innovative product design. Our technology enables you to predict with confidence that your product will thrive in the real world. For more than 40 years, customers in the most demanding markets have trusted our solutions to help ensure the integrity of their products and drive business success through innovation.