To achieve the goals set earlier, ANSYS developed tools to automate the design process of an electric machine. A set of user-defined solutions were scripted using Python and completely integrated into ANSYS® Maxwell® desktop (Figure 1). This facilitates further complex post-processing analyses. The following properties are in the developed UDO scripts:

- Generalized
- Automated
- Accurate
- Efficient
- Ease of use
- Extendible

The electric machine design toolkit consists of advanced solutions for the following:

- Efficiency map computation
- Efficiency map displayer
- Torque speed curve computation

Calculating torque-speed curves and efficiency maps is very challenging in finite element analysis (FEA). The toolkit not only runs the simulation, but it also (and most importantly) finds the optimal operation points.
Efficiency Map – Method of Computation

The maximum torque per ampere unit (MTPA) control strategy (Figure 2) is employed to compute the efficiency maps as:

- At a given operating condition, the trajectory of the current is crucial for optimal efficiency operation of PM machines.
- By varying the input voltage, there can be an infinite number of $I_d$ and $I_q$ combinations that can produce the required torque at a given speed.
- MTPA strategy is applied. The scheme results in minimizing the stator current and, thus, maximizing the efficiency below base speed, assuming that the winding loss is dominant.
- In flux-weakening regions, output power is maximized, and apparent power is minimized to improve power factor.

The MTPA control algorithm finds the optimal current angle that gives the minimum current at a given torque. An evolutionary algorithm based on nondominated sorting genetic algorithm (NSGA-II) with (Pareto) dominate solution and combined with spline interpolation technique is used for the optimization.

In this study, the MTPA control strategy is implemented in the experimental and simulation work to obtain efficiency maps for interior PM machines. The simulation is conducted with a time-domain 2-D FEA model. The machine is assumed to be current controlled, and, thus, sinusoidal currents are used in the FEA simulations. The method of computation of the efficiency map consists of the following steps:

1. Simulate a parametric sweep of transient simulations for different current magnitudes and angles, $\gamma$, at a constant speed to obtain a family of voltage and torque curves that are tabulated and used in spline interpolation.
2. Apply the MTPA algorithm using multi-objective optimization to calculate the operation points ($I_d$ and $I_q$) for the torque-speed range in motoring, generating or both modes. An evolutionary computation, NSGA-II with (Pareto) dominate solution, is used.
3. Run the final simulations using the calculated operation points found with the MTPA. These operation points are simulated at the whole torque-speed range to compute the core loss and eddy-current magnet loss at different supply frequencies.

4. Compute the efficiency from the output power and total losses that include winding loss, core loss, eddy-current loss in the magnets and mechanical loss.

The method offers the following advantages:

1. Requires only voltage and current limits as inputs and automatically applies the MTPA algorithm and computes the optimal control angle at the whole torque-speed range accordingly.

2. Requires running only a parametric sweep of the current and current angle at a single speed. The torque is assumed to be independent of the speed in current-fed machines. The voltage is assumed to satisfy constant volts per hertz relation. These are considered to be valid assumptions in synchronous machines in which the losses, including core loss and eddy-current loss, have minimal influence on the torque and back emf production.

3. Integrates various vital effects, such as skewing, DC/AC winding resistance at rated temperature, end-turn winding inductance, frequency-dependent core loss coefficients and mechanical loss.
The computational method implemented into the toolkit considers, in the same time, dynamic effects of end-winding (Figure 3) manifested in the torque-speed profile, AC winding resistance (Figure 4), temperature dependency, core-loss and skewing effect on back emf, and torque characteristics (Figure 5).

Figure 6 shows few quantitative results based on the applied efficiency map computation method. Thus, various machine characteristics are computed as torque-speed, current-speed and power-speed.

In a similar manner, other important characteristics are obtained, as illustrated in Figure 7.
Figure 7. Machine performance characteristics: (top left) current map; (top right) voltage map; (bottom left) power factor map; (bottom right) torque ripple map.
Design Challenges and Requirements
The established design flow responds to the challenges in hybrid electric technology innovation:
• Shorter design cycle
  - Industry innovations occur at a rapid pace and competition is fierce
• Increasing battery complexity
  - 3 million element cell model
  - Entire pack thermal model ~ 500 million cells, calling for meshing and simulating complex geometries accurately and quickly
• Increased performance
  - Maximize range
  - Maximize fuel efficiency
  - Maximize power delivery and power management; power available rapidly decreases with lower cell temperature
• Increased safety
  - Heating/cooling system of the pack ensures cell temperature to be lower than the maximum allowed value under all vehicle operating and ambient conditions to prevent thermal runaway
• Increased lifespan
  - Heating/cooling system of the pack maintains as constant-as-possible cell temperature of 30°C under all vehicle operating and ambient conditions
End-To-End Cell–Pack–System Solution: Rechargeable Lithium-Ion Battery

Multiscale Lithium-Ion Battery Modeling
A complete lithium-ion (li-ion) battery simulation employs not just multiple physics domains to achieve accurate performance prediction but also a detailed multiscale design concept to transfer model data from molecular level to electrode level and, furthermore, to cell and module simulation levels (Figure 1). The ultimate goal of this comprehensive simulation environment is to integrate multi-module-level information into the powertrain system to evaluate overall performance of hybrid or electric vehicle technology.

Electrode Level
At the electrode level, the electrochemistry is the physical domain that explains the solid electrolyte interface formation and generates appropriate cell model information (Figure 2).

A commonly used physics-based electrochemistry model for a lithium-ion battery cell was first proposed by Professor Newman in 1993 (Doyle, Fuller, & Newman, 1993). The model consists of a tightly coupled set of partial differential equations. The method has become known as pseudo 2-D in literature due to the 2-D implementation of particle modeling. Numerically obtaining a solution to the full 2-D implementation turns out to be challenging even for commercial software due to the tight coupling between equations. Therefore, a novel 1-D approach is used and implemented in the VHDL-AMS language for further circuit and system simulations.
The model shown in Figure 3 is based on:
- Electrochemical kinetics
- Solid-state Li transport
- Electrolytic Li transport
- Charge conservation/transport
- (Thermal) energy conservation

The concentration equation in a form ready for finite volume approach is

\begin{align*}
\frac{\partial C}{\partial t} &= -\nabla \cdot N + \frac{\nabla \cdot i_2}{F} \\
N_{i} &= -\varepsilon N_{i} D_{\text{eff}} \nabla c + \frac{i_{2}}{i_{2}} \\
\end{align*}

(1)

The governing equation for \( i_2 \) in the negative electrode is

\[ \nabla \cdot i_2 = \alpha F j \]

(2)

The governing equation for \( \phi_2 \) in the negative electrode is

\[ i_2 = -\kappa_{\text{eff}}(c) \nabla \phi_2 + \frac{\kappa_{\text{eff}}(c)RT}{F} (1 - \) \]

(3)

The governing equation for \( \phi_1 \) in the negative electrode is

\[ I - i_2 = -\sigma_{\text{eff}} \nabla \phi_1 \]

(4)

The governing equation for concentration in particles \( c_s \) is

\[ \frac{\partial c_s}{\partial t} = D_s \left( \frac{\partial^2 c_s}{\partial r^2} + \frac{2 \partial c_s}{r \partial r} \right) \]

(5)

Note that a mix of finite difference and finite volume methods is used to solve the set of equations. More specifically, the finite volume method is used for the conserved quantities of \( i_2, c \) and \( c_s \), but the finite difference method is used for potential \( \phi_1 \) and \( \phi_2 \), which are not conserved quantities. Figure 4 shows a representative mesh for the negative electrode used for the lithium-ion cell electrochemical model. The six dots represent nodes for the finite difference approach, and the five squares represent control volumes for the finite volume approach. The arrows between the particle control volumes and main control volumes represent the mass exchange between particles and the main domain due to the Butler–Volmer equation (Bard & Faulkner, 2001) (or chemical reaction occurring at the surface of the particles).
Cell Level

Detailed design simulation at the cell level uses computational fluid dynamics (CFD) analysis.

CFD can be used for battery thermal management analysis; however, CFD tools can be expensive for large systems-level transient analysis. Due to the size of the CFD models, the simulation software can be cumbersome to couple with an electrical circuit model for large system analysis.

The ANSYS solution for systems-level simulation design incorporates reduced-order models suitable for systems-level transient analysis. The well-known thermal network is one option. Figure 5 shows an example of a thermal network. To apply such a model, one builds thermal nodes, each associated with a thermal capacitor representing the heat capacity at that node. Nodes are connected using thermal resistors representing heat conduction to and from that node. The model has limited accuracy because, in general, one cannot afford too many nodes: A large number of thermal nodes increases the complexity and thus defeats the very purpose of using a circuit-equivalent model. The equivalent thermal model obtained needs careful calibration and calculation of thermal resistance and capacitance.

Another approach uses linear time invariant (LTI) characterization. In this method, an RC network is used; however, these RC elements serve a different purpose. In the LTI method, RCs are used to match the transfer function of the system. The method has a fixed RC topology as opposed to different topologies used in a thermal network. Such a fixed topology makes the network generation process easy and automatic. The LTI method can be as accurate as CFD results, and there is no need to calculate thermal resistance and capacitance. Unlike with the thermal network, the LTI method relies on linearity and time invariance of the system, as shown in Figure 6.

So, in this sense, although the LTI method is less general than the thermal network, for battery cooling applications it turns out that linearity and time invariance conditions can be satisfied or relaxed. Therefore, the battery cooling application can benefit from this less general but otherwise much more accurate and easier approach (Hu, Stanton, Cai, & White, 2012).
The electrical behavior of the cell model is obtained by extracting a set of input parameters for an equivalent circuit model (ECM). Figure 7 shows a newly implemented battery ECM model extraction flow.

To use the ECM model, the designer starts with some test data for a cell, namely open circuit potential versus state of charge (SOC) and transient potential under pulse discharge. The ECM extraction tool kit in ANSYS® Simplorer® takes the test data and creates the cell ECM model automatically. Once the ECM model for a cell is created, the user has the option to connect multiple cells by drag and drop to create a battery module or pack circuit model, as illustrated in Figure 7. This model then can be used to predict battery module or pack electrical performance. The validation shows that the battery ECM models give a peak error less than 0.2 percent.

Module/Pack Level
Once the ECM is developed, the module and the entire pack can be simulated at the pace of circuit simulation while preserving the accuracy of the physics-based CFD model. The major benefit of integrating such reduced models into circuit simulation resides on the flexibility of adding more components to the system to predict overall performance of the system. In such situations, more multiphysics analysis is required to fit the module/pack system validation.
As shown in Figure 8, various bus-bar topologies are used to connect electric elements within the battery module configuration. When regulated electric signals are driven from an electronic circuit unit, electromagnetic interference might occur among various conductive paths, changing the conductive profile and ultimately the power loss distribution, which has critical impact to the battery thermal management. Figure 8 shows a reduced-order model obtained from electromagnetic simulation. Electromagnetic field solvers are applied to extract an electrical frequency-dependent model of the bus-bar, which can then be imported into circuit simulation environment.

The battery module dissipates heat during power consumption and during recharging. That heat causes the module to deform due to thermal expansion, which can result in various stresses. The power loss distribution is used to drive the thermal analysis, which in turn generates the load data to drive the total deformation simulations. Figure 9 depicts the battery module on the left, and the structural deformation on the right. This study can be used to design modules that do not exhibit excessively large deformations during various loads and operating conditions.

Figure 8. Battery module/pack bus-bar parasitic model

Figure 9. Thermal-stress analysis of battery module considering structural deformation
Complete System Integration
Complete system simulation is the ultimate goal for a system engineer when overall performance of the powertrain is required. Before the entire integrated system is validated, the total battery model can be immediately implemented and verified (as shown in Figure 10). This model couples the bus-bar, individual cell models and the LTI thermal model into a single and complete module simulation.
Figure 11 depicts the definition of the HEV drive train system in which the complete battery model is integrated, including embedded software control. Several other reduced-order models are included in this schematic to provide for multiphysics system simulation at the level of circuit design. This preserves the accuracy of physics-based solutions such as ANSYS Maxwell® for electric motor electromagnetic modeling, ANSYS Q3D Extractor® for parasitic extraction of frequency-dependent behavior for inverter packages and cables, ANSYS Mechanical™ for shaft and gear design models, and ANSYS Simplorer for schematic-based system design.

A suggestive example of complete system simulation of a powertrain application is shown in Figure 12. On such implementation, one can analyze in detail with a higher level of confidence the fuel consumption at various driving profiles, monitoring battery performance at the same time.

Figure 12. Powertrain application design using ANSYS Simplorer platform

Figure 13. Fuel consumption analysis based on driving profile
Conclusion
This paper discussed several challenges and simulation-based solutions for HEV and EV energy system design. Shorter time to market, increased complexity, higher performance and higher safety requirements are driving designers to apply a dynamic simulation approach. A multiscale, multi-physics simulation flow emphasizes comprehensive modeling and a hierarchical method that leads to full system simulation. Modeling of the physics is performed using rigorous 3-D simulation to extract appropriate circuit- and system-level reduced-order models. These models are then combined in top-level system simulation, allowing engineers to predict details at any level in the hierarchy.

References


Electric Machine Design Methodology: A Revolutionary Approach

Electric machines are used in novel applications around the world, driven by the need for greater power efficiency in the transportation, aerospace and defense, and industrial automation industries. The automotive sector focuses on the need for hybrid and electric vehicle technology to meet stringent miles-per-gallon standards. The aerospace and defense industry concentrates on replacing existing aircraft power transfer technologies (such as the central hydraulic system) with fault-tolerant electric power, in which major subsystems — including engine starting, primary flight control actuation, pumps and braking — are controlled and driven electronically. In the United States’ industrial sector, more than 40 million electric motors convert electricity into useful work in manufacturing operations. Industry spends over $30 billion (US) annually on electricity dedicated to electric motor-driven systems that drive pumps, fan and blower systems, and air compression.

There is a clear global demand for a comprehensive design methodology to support these new applications and satisfy power efficiency requirements. Most research efforts to improve motor design have focused on the motor, rather than the motor-driven system as a whole. Engineers are forced to use a host of often incompatible simulation tools to address the various levels of motor and drive systems, leading to errors and delays in the design cycle or increased cost due to build-and-test iterations. ANSYS® multiphysics and multi-scale system engineering technology is ideal to meet these challenges.

Unique Solution
Several calculation techniques are available to predict electric machine performance, including classical closed-form analytical analysis, lumped parameter models based on determination of detailed parameters from finite element analysis, and nonlinear time-domain finite element analysis. Each method has advantages and disadvantages. Selecting the best method can be difficult because it requires the user to understand the differences among calculation methods. The fundamental issue differentiating these methods is the trade-off among model complexity, accuracy and computing time. Engineers use a combination of these calculation techniques as the optimal solution to simulate electric machine performance.

Success in using any simulation software is usability. Ease of use plays a significant role in speeding time to market, because engineers will quickly discard software that is difficult to use or requires in-depth knowledge of numerical simulation techniques. Launching a product quickly requires simulation software that serves a number of purposes: accurate and suitable for use throughout an organization at different stages of the design process by engineers with various levels of knowledge in numerical simulation.
Electric Machine Design Methodology:
A Revolutionary Approach

The ANSYS electric machine design solution is unique in the simulation industry:
• Employs the most efficient numerical techniques
• Provides highly accurate, comprehensive multiphysics simulation design of an electric machine
• Includes distributed parametric analysis and HPC for robust design
• Enables power electronics and embedded control software to be simulated with a detailed finite element model

Workflow
The ANSYS integrated electric machine design methodology enables users to design, analyze and deliver efficient, optimized electric machine and drive designs. The design methodology encompasses a number of ANSYS software programs that address the many design variables involved with creating such a system.

Figure 1 shows the main design flow. The initial design stage is addressed with ANSYS RMxprt™. This specialized software allows users to quickly create a geometric model of the machine from a template-based interface, calculate its performance, and make sizing decisions. Once the initial design is completed, RMxprt creates the complete setup of the 2-D/3-D magnetic design in ANSYS Maxwell®.

Maxwell can execute rigorous performance calculations of the machine, including the motion-induced physics caused by linear translational and rotational motion, advanced hysteresis analysis, demagnetization of permanent magnets and other critical electromagnetic machine parameters. Maxwell is integrated into ANSYS Workbench™, where it can share the same CAD source with other ANSYS physics-based solvers and couple with ANSYS Mechanical™, ANSYS Fluent® or ANSYS Icepak®.

Workbench also links Maxwell to the system design optimization capability provided by ANSYS DesignXplorer™ software.

Figure 2 illustrates the optimum design scheme employed, based exclusively on the electromagnetic design flow. Narrowing the design space with RMxprt, the magnetic transient design setup is automatically generated as either 2-D or 3-D designs. The benefit of 2-D symmetry is due to the radial magnetic field topology for most electrical machines. However, axial field or transversal field topologies require 3-D designs. Nevertheless, for accuracy reasons, 3-D designs are required even if radial field topologies are considered whenever the user employs end effects, multi-axial segmented permanent magnets or skewing topologies. Although Maxwell software is a general FEA tool, its capabilities enable users to customize and apply very specific analyses for electrical machines, such as D-Q solution computation (Figure 3). Maxwell also enables users to employ even-more complex algorithms as maximum torque per ampere unit (MTPA) control strategy (Figure 4) to compute efficiency maps (Figure 5).
Design optimization of interior permanent magnet (IPM) machines is complicated by the fact that the maximum torque production is a function of the advance angle of the current, which, in turn, is a function of design parameters. This means that for a systematic comparison of candidate designs, a search/optimization of the optimum operating point (MTPA) has to be performed for every candidate design. The multi-objective definition can be summarized as follows: minimize torque ripple and total losses (core and copper) while maximizing torque production per unit volume at rated load.

Within ANSYS Workbench (Figure 6), ANSYS Mechanical’s stress, thermal, CFD and acoustic solvers provide important multiphysics capabilities required for detailed analysis of the electric machine. Losses calculated by Maxwell can be used as inputs to the thermal or CFD solver to calculate the machine’s temperature distribution (Figure 7) and to evaluate cooling strategies. Electromagnetic forces and torque calculated in Maxwell are used as inputs to the stress solver to analyze deformations and further assess potential vibrations (Figure 8).

Once the machine is designed, the Maxwell model can be integrated into ANSYS Simplorer® (Figure 9). Simplorer is a multi-domain circuit and system simulator for designing high-performance systems. At this stage, the objective is to validate the electric machine works with the electric drive and digital control system. Simplorer unites circuit simulation with block diagrams, state machines and VHDL-AMS to add power electronic circuits and controls to the motor model created by Maxwell. Additionally, the embedded software of the digital control can be incorporated through cosimulation with the Esterel SCADE suite (Figure 10).

The capability to simulate these highly complex systems at various levels of abstraction is another distinguishing feature of the ANSYS integrated electric machine design methodology.

**Conclusion**

The ANSYS robust electrical machine and drive design approach delivers the computational power and ease of use demanded by today’s overloaded engineers. The main benefit customers receive by using ANSYS solutions is increased productivity from engineering teams, which results in:

- Shorter time to market
- Comprehensive multiphysics from a single vendor
- Robust design and optimization
- Ability to validate all aspects of the system (electric machine, power electronics, control, embedded software) prior to prototyping
Electric Machine Design Methodology:
A Revolutionary Approach

Frequency controlled speed
Fed by ac-dc-ac inverter

Figure 9. PWM-driven induction machine control

Figure 10. Software-hardware codesign

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ANSYS Maxwell Magnetic Field Formulation

There are various variational electromagnetic field formulations using FEA to numerically solve Maxwell’s equations. When choosing the right formulation to be implemented in FEA special mathematical handling is required in order to avoid unphysical solutions and to provide numerical stability and computational efficiency. This application brief describes the basis for formulation employed in ANSYS Maxwell.

ANSYS Maxwell magnetic field formulation is founded on Maxwell’s equations starting with the basic field equations:

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]  
(Faraday’s law) \hspace{1cm} (1)

\[ \nabla \cdot \mathbf{B} = 0 \]  
(Gauss’s law) \hspace{1cm} (2)

\[ \nabla \times \mathbf{H} = \mathbf{J} \]  
(Ampere’s law) \hspace{1cm} (3)

in which \( \mathbf{E} \) is the electric field strength, \( \mathbf{B} \) is the magnetic flux density, \( \mathbf{H} \) is the magnetic field strength, and \( \mathbf{J} \) is the electric current density. Obviously, these equations are considered together with the constitutive material equations for both electric fields as \( \mathbf{E} = f(\mathbf{J}) \) and magnetic field as \( \mathbf{B} = f(\mathbf{H}) \).

Numerical solution of such equations is based on \( T-\Omega \) formulation in which \( \Omega \) is nodal-based magnetic scalar potential, defined in the entire solution domain, and \( T \) is edge-based electrical vector potential, defined only in the conducting eddy-current region (Figure 1).

There are several advantages of this formulation:
- Avoid unphysical solution due to utilization of edge elements to model a source component and induced eddy current
- Computationally efficient because in the nonconducting region, only scalar potential is employed
- Numerical stability because no gauging is required to obtain unique solutions
In T-Ω formulation, the key to allow the use of scalar potential is that the solution domain has to be single connected. In the eddy-conducting region, field \( H \) is described by both electrical vector potential \( T \) and magnetic scalar potential \( \Omega \), and \( \text{curl} \) of the electrical vector potential \( T \) is the induced eddy-current density. In the source conductor region, field \( H \) is described by both applied source field \( H_p \) and magnetic scalar potential \( \Omega \), in which \( \text{curl} \) of \( H_p \) is the source current density \( J \). In the non-source, non-eddy-conductor region, since \( \nabla \times H = 0 \) and \( \text{curl} \) of any gradient is always zero, then \( H \) can be represented by the gradient of the magnetic scalar potential as long as the domain is single connected.

To make the domain single connected, you need to introduce a cut so that Ampere’s law can hold with respect to \( T \) in the cut region. This means in the nonconducting cut region, even though there is no current, field \( H \) is also described by both \( \Omega \) and \( T \), not just by \( \Omega \) alone.

Therefore, for the T-Ω formulation with multiple connected domains, you identify the nonconducting cut domain. In ANSYS Maxwell, the process of cut domain generation is automatically done based on the automatic identification of tree and cotree algorithm (Figure 2).

**Case Study**

This case study illustrates the automatic creation of a cut domain for a one-phase winding in a three-phase synchronous generator with damper. The one-phase winding is colored brown (Figure 3), and the automatically identified cut represented by one layer of elements is blue. Taking advantage of the periodic boundary condition, only one quarter is modeled. For the damper with induced eddy current, a total of 16 cuts are automatically identified, which precisely matches the number of 16 holes; even one hole is cut into two halves by the master/slave boundary (Figure 4).
When rigid motion is involved in magnetic transient analysis, two independent meshes must be coupled together after an arbitrary displacement of the moving part. To achieve maximum flexibility, non-conforming meshes are used for the coupling (Figure 5). This means that the scalar potential at each node, the vector field at each edge on the slave coupling surface, has to be mapped onto the master coupling surface to eliminate all unknowns on the slave surface.

For mapping a vector field, the process of splitting slave edge variables with respect to the trace of the master mesh while preserving valid cutting domains is very complicated. To overcome this difficulty, a separation technique is introduced to confine each cut generated to either the stationary or moving part without crossing the coupling interface. As a result, the process of mapping the vector field is completely avoided, and only the node-based scalar potential is involved in the coupling.

Figure 5. Moving mesh coupling technology
ROBUST ELECTRIC MACHINE DESIGN THROUGH MULTIPHYSICS

Electromagnetic, mechanical and thermal simulation plus design optimization help to improve energy efficiency, noise and bearing life of robust electric motors.

By Cassiano A. Cezario, Brian C. Bork, Marcelo Verardi, Research and Technological Innovation Department, and José R. Santos, Product Development and Application Department, WEG Equipamentos Elétricos S.A. — Motores, Jaraguá do Sul, Brazil
Electric motors are the single biggest consumer of electricity, accounting for about two-thirds of industrial power consumption and about 45 percent of global power consumption, according to an analysis by the International Energy Agency. The World Energy Outlook 2012 states that the developed world is planning to increase its energy efficiency by 1.8 percent annually over the next 25 years. Much of this improvement must come from advancements in electric motor design. Companies that develop these devices must ensure that motors have low operating noise and long life. Engineers have worked to balance these demands to improve and optimize the design of electric motors for almost two centuries, and now new methods and tools are needed to generate further progress.

WEG is the largest industrial electric motor manufacturer in the Americas and one of the largest manufacturers of industrial electric motors in the world, producing more than 10 million units annually. WEG engineers used the ANSYS comprehensive design solution for electric motors to leverage electromagnetic, mechanical and thermal simulation. Design optimization helped the engineering team to deliver optimal energy efficiency, low operating noise and long bearing life on the new W50 electric line.

### WEG’s Robust Design of Electric Machines

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<td>Computational fluid dynamics (CFD)-electromagnetic simulation</td>
<td>Reduce fan losses and improve energy efficiency</td>
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<td>Minimize total noise generated by motor • Predict aerodynamic noise • Predict electromagnetic noise</td>
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<td>Lower operating noise</td>
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<td>Automate design exploration</td>
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WEG engineers used a wide range of ANSYS tools to deliver optimal energy efficiency, low operating noise and long bearing life on its new line of electric motors.
of motors. The broad range of ANSYS capabilities was instrumental in designing and optimizing the electric motor without the need to individually evaluate each design alternative.

**IMPROVING ENERGY EFFICIENCY**

Large electric motors in the 125 horsepower to 1,750 horsepower range typically have two fans: one to cool the motor interior and the other to cool its exterior. These fans consume a considerable amount of power, and WEG engineers believed that a promising approach to improving energy efficiency was to improve fan efficiency. They focused on the internal fan, particularly on reducing losses as air flows through the motor. The airflow generated by the fan flows through openings in the frame. Losses could be reduced by increasing these openings — but this strategy would reduce the motor’s electromagnetic performance.

WEG engineers used ANSYS CFD software to model the airflow through the interior of the motor. They defined key parameters, such as the openings where air passes through the frame, as parametric dimension variables. Since many of these design parameters impact the motor’s electromagnetic performance, engineers produced an ANSYS Maxwell electromagnetic model of the motor with the same parametric variables as the CFD model. They generated a table of varying values for each of the parameters.

WEG employed ANSYS DesignXplorer to create a design of experiments (DOE) that subdivided the design space to efficiently explore it with a relatively small number of simulation experiments and to run multiphysics simulations without human intervention. Comprehensive simulation tools in the ANSYS Workbench environment and design optimization with ANSYS DesignXplorer enabled WEG to increase the number of simulations performed from four per month in 2005 to 800 per month currently. High-performance computing (HPC) also helped enable this improvement. WEG uses HPC Packs for CFD, and Maxwell runs with 64 cores distributed across eight workstations.

Output results for each design point were stored in a table and visualized with a response surface map that completely maps out the design space. The response surface was used to graphically plot the effect of variables on fan losses. Simulations were not coupled in this case due to computing resource limitations; however, in the future, WEG will use coupled multiphysics simulations to even more accurately determine optimal values for parametric variables by considering all of the physics. WEG engineers manually compared response surface maps, plots and tables for the CFD and electromagnetic analysis to determine the

![Before-and-after comparison of ANSYS CFX simulations shows improved airflow that reduces fan losses in W50 motor compared to previous-generation design.](attachment:image)
robust electric
machine design

combinations of parametric variables that delivered the best mix of performance. Engineers then reran the electromagnetic and CFD simulation for the best combinations and selected the one that delivered the best performance: a substantial reduction in fan losses and a resulting improvement in energy efficiency without any sacrifice in electromagnetic performance.

Reducing noise
WEG engineers also wanted to reduce the noise generated by the new W50 motor design. An electric motor primarily generates noise through two independent sources: aerodynamic and electromagnetic. Aerodynamic noise is generated by the fan rotor and transmitted through the air; WEG engineers used ANSYS CFD to optimize the fan rotor geometry to minimize aerodynamic noise. Electromagnetic noise is created by the interaction of magnetic fields produced by stator and rotor. In extreme cases in which the resultant force frequency excites the natural frequencies of the mechanical structure, this noise will be dramatically amplified.

WEG engineers used ANSYS CFD to optimize the internal fan system. Engineers designed a new internal fan system to reduce the length of the motor, which improved the dynamic performance. However, the original design was not acceptable, so engineers used ANSYS DesignXplorer to optimize the internal fan geometry and develop a new solution that met the requirements. The new internal fan reduces vibration, improves power density of the motor, and increases the maximum rotating speed.

To predict and avoid electromagnetic noise of the motor prior to the prototyping stage, WEG engineers used electromagnetic simulation to calculate the electromagnetic force and losses. These quantities are used as inputs to the structural and thermal simulation to predict mechanical vibrations. WEG engineers used the ANSYS Application Customization Toolkit to implement the methodology of topological optimization to increase the natural frequency of the frame. They then set up parametric variables and used ANSYS DesignXplorer to run a table of design points and optimize the design to produce the lowest levels of noise.

Improving bearing life
Bearings are usually the first component to fail during the lifetime of an electric motor. WEG engineers used ANSYS DesignXplorer to optimize the bearing system to increase the life of the motor. They then set up parametric variables and used ANSYS DesignXplorer to run a table of design points and optimize the design to produce the lowest levels of noise.

ANSYS multiphysics tools help WEG deliver best-in-class performance for electric motors while substantially reducing the lead time and cost of the product development process.
motor, and the life of bearings is strongly correlated with the operating temperature. The cooler the bearing runs, the longer is its life and the longer its lubrication intervals (how often grease is required), so the motor will require less maintenance. The team ran a CFD analysis of the airflow around the bearing and changed the shape and dimensions of some components in the region to ensure a constant airflow and reduce operating temperature.

Based on these and several other multiphysics simulations, WEG engineers developed the detailed design for the W50 motor. The company then built a prototype. Physical testing showed that the design worked exactly as predicted by simulation. As a result, only a few very minor changes were required during the prototype phase. Normally, a larger number of more substantial design changes are required. The ability to get the design right the first time provided a major cost saving.

The new W50 motors deliver significant improvements in performance over existing electric motors in their class. Energy efficiency varies depending on the application, but it is generally significantly better than today’s best-in-class motors in the same applications. The new motors offer exceptionally low noise levels of 82 dB(A) at 3,600 rpm (60 Hz) and 78 dB(A) at 3,000 rpm (50 Hz). Bearing life has been improved to 100,000 hours of L10h life over the 40,000 hours previously offered. At least 90 percent of all motors produced will achieve the L10h life. The use of ANSYS multiphysics tools helps WEG to deliver best-in-class performance for electric motors while substantially reducing the lead time and cost of the product development process.

Technical support and sales for WEG is provided by ESSS, ANSYS channel partner for South America.
ANSYS Maxwell magnetic field formulation is founded on Maxwell’s equations starting with the basic field equations:

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]  
(Faraday’s law)  

(1)

\[ \nabla \cdot \mathbf{B} = 0 \]  
(Gauss’s law)  

(2)

\[ \nabla \times \mathbf{H} = \mathbf{J} \]  
(Ampere’s law)  

(3)

in which \( \mathbf{E} \) is the electric field strength, \( \mathbf{B} \) is the magnetic flux density, \( \mathbf{H} \) is the magnetic field strength, and \( \mathbf{J} \) is the electric current density. Obviously, these equations are considered together with the constitutive material equations for both electric fields as \( \mathbf{E} = f(\mathbf{J}) \) and magnetic field as \( \mathbf{B} = f(\mathbf{H}) \).

Numerical solution of such equations is based on \( T-\Omega \) formulation in which \( \Omega \) is nodal-based magnetic scalar potential, defined in the entire solution domain, and \( T \) is edge-based electrical vector potential, defined only in the conducting eddy-current region (Figure 1).

There are several advantages of this formulation:
- Avoid unphysical solution due to utilization of edge elements to model a source component and induced eddy current
- Computationally efficient because in the nonconducting region, only scalar potential is employed
- Numerical stability because no gauging is required to obtain unique solutions
In T-Ω formulation, the key to allow the use of scalar potential is that the solution domain has to be single connected. In the eddy-conducting region, field H is described by both electrical vector potential T and magnetic scalar potential Ω, and curl of the electrical vector potential T is the induced eddy-current density. In the source conductor region, field H is described by both applied source field Hp and magnetic scalar potential Ω, in which curl of Hp is the source current density J. In the non-source, non-eddy-conductor region, since \( \nabla \times \mathbf{H} = 0 \) and curl of any gradient is always zero, then H can be represented by the gradient of the magnetic scalar potential as long as the domain is single connected.

To make the domain single connected, you need to introduce a cut so that Ampere’s law can hold with respect to T in the cut region. This means in the nonconducting cut region, even though there is no current, field H is also described by both Ω and T, not just by Ω alone.

Therefore, for the T-Ω formulation with multiple connected domains, you identify the nonconducting cut domain. In ANSYS Maxwell, the process of cut domain generation is automatically done based on the automatic identification of tree and cotree algorithm (Figure 2).

Case Study
This case study illustrates the automatic creation of a cut domain for a one-phase winding in a three-phase synchronous generator with damper. The one-phase winding is colored brown (Figure 3), and the automatically identified cut represented by one layer of elements is blue. Taking advantage of the periodic boundary condition, only one quarter is modeled. For the damper with induced eddy current, a total of 16 cuts are automatically identified, which precisely matches the number of 16 holes; even one hole is cut into two halves by the master/slave boundary (Figure 4).
When rigid motion is involved in magnetic transient analysis, two independent meshes must be coupled together after an arbitrary displacement of the moving part. To achieve maximum flexibility, non-conforming meshes are used for the coupling (Figure 5). This means that the scalar potential at each node, the vector field at each edge on the slave coupling surface, has to be mapped onto the master coupling surface to eliminate all unknowns on the slave surface.

For mapping a vector field, the process of splitting slave edge variables with respect to the trace of the master mesh while preserving valid cutting domains is very complicated. To overcome this difficulty, a separation technique is introduced to confine each cut generated to either the stationary or moving part without crossing the coupling interface. As a result, the process of mapping the vector field is completely avoided, and only the node-based scalar potential is involved in the coupling.
Electric Machine Design Methodology: A Revolutionary Approach

Electric machines are used in novel applications around the world, driven by the need for greater power efficiency in the transportation, aerospace and defense, and industrial automation industries. The automotive sector focuses on the need for hybrid and electric vehicle technology to meet stringent miles-per-gallon standards. The aerospace and defense industry concentrates on replacing existing aircraft power transfer technologies (such as the central hydraulic system) with fault-tolerant electric power, in which major subsystems — including engine starting, primary flight control actuation, pumps and braking — are controlled and driven electronically. In the United States’ industrial sector, more than 40 million electric motors convert electricity into useful work in manufacturing operations. Industry spends over $30 billion (US) annually on electricity dedicated to electric motor-driven systems that drive pumps, fan and blower systems, and air compression.

There is a clear global demand for a comprehensive design methodology to support these new applications and satisfy power efficiency requirements. Most research efforts to improve motor design have focused on the motor, rather than the motor-driven system as a whole. Engineers are forced to use a host of often incompatible simulation tools to address the various levels of motor and drive systems, leading to errors and delays in the design cycle or increased cost due to build-and-test iterations. ANSYS® multiphysics and multi-scale system engineering technology is ideal to meet these challenges.

Unique Solution

Several calculation techniques are available to predict electric machine performance, including classical closed-form analytical analysis, lumped parameter models based on determination of detailed parameters from finite element analysis, and nonlinear time-domain finite element analysis. Each method has advantages and disadvantages. Selecting the best method can be difficult because it requires the user to understand the differences among calculation methods. The fundamental issue differentiating these methods is the trade-off among model complexity, accuracy and computing time. Engineers use a combination of these calculation techniques as the optimal solution to simulate electric machine performance.

Success in using any simulation software is usability. Ease of use plays a significant role in speeding time to market, because engineers will quickly discard software that is difficult to use or requires in-depth knowledge of numerical simulation techniques. Launching a product quickly requires simulation software that serves a number of purposes: accurate and suitable for use throughout an organization at different stages of the design process by engineers with various levels of knowledge in numerical simulation.
The ANSYS electric machine design solution is unique in the simulation industry:

- Employs the most efficient numerical techniques
- Provides highly accurate, comprehensive multiphysics simulation design of an electric machine
- Includes distributed parametric analysis and HPC for robust design
- Enables power electronics and embedded control software to be simulated with a detailed finite element model

**Workflow**

The ANSYS integrated electric machine design methodology enables users to design, analyze and deliver efficient, optimized electric machine and drive designs. The design methodology encompasses a number of ANSYS software programs that address the many design variables involved with creating such a system.

Figure 1 shows the main design flow. The initial design stage is addressed with ANSYS RMxprt™. This specialized software allows users to quickly create a geometric model of the machine from a template-based interface, calculate its performance, and make sizing decisions. Once the initial design is completed, RMxprt creates the complete setup of the 2-D/3-D magnetic design in ANSYS Maxwell®.

Maxwell can execute rigorous performance calculations of the machine, including the motion-induced physics caused by linear translational and rotational motion, advanced hysteresis analysis, demagnetization of permanent magnets and other critical electromagnetic machine parameters. Maxwell is integrated into ANSYS Workbench™, where it can share the same CAD source with other ANSYS physics-based solvers and couple with ANSYS Mechanical™, ANSYS Fluent® or ANSYS Icepak®.

Workbench also links Maxwell to the system design optimization capability provided by ANSYS DesignXplorer™ software.

Figure 2 illustrates the optimum design scheme employed, based exclusively on the electromagnetic design flow. Narrowing the design space with RMxprt, the magnetic transient design setup is automatically generated as either 2-D or 3-D designs. The benefit of 2-D symmetry is due to the radial magnetic field topology for most electrical machines. However, axial field or transversal field topologies require 3-D designs. Nevertheless, for accuracy reasons, 3-D designs are required even if radial field topologies are considered whenever the user employs end effects, multi-axial segmented permanent magnets or skewing topologies. Although Maxwell software is a general FEA tool, its capabilities enable users to customize and apply very specific analyses for electrical machines, such as D-Q solution computation (Figure 3). Maxwell also enables users to employ even-more complex algorithms as maximum torque per ampere unit (MTPA) control strategy (Figure 4) to compute efficiency maps (Figure 5).
Design optimization of interior permanent magnet (IPM) machines is complicated by the fact that the maximum torque production is a function of the advance angle of the current, which, in turn, is a function of design parameters. This means that for a systematic comparison of candidate designs, a search/optimization of the optimum operating point (MTPA) has to be performed for every candidate design. The multi-objective definition can be summarized as follows: minimize torque ripple and total losses (core and copper) while maximizing torque production per unit volume at rated load.

Within ANSYS Workbench (Figure 6), ANSYS Mechanical’s stress, thermal, CFD and acoustic solvers provide important multiphysics capabilities required for detailed analysis of the electric machine. Losses calculated by Maxwell can be used as inputs to the thermal or CFD solver to calculate the machine’s temperature distribution (Figure 7) and to evaluate cooling strategies. Electromagnetic forces and torque calculated in Maxwell are used as inputs to the stress solver to analyze deformations and further assess potential vibrations (Figure 8).

Once the machine is designed, the Maxwell model can be integrated into ANSYS Simplorer® (Figure 9). Simplorer is a multi-domain circuit and system simulator for designing high-performance systems. At this stage, the objective is to validate the electric machine works with the electric drive and digital control system. Simplorer unites circuit simulation with block diagrams, state machines and VHDL-AMS to add power electronic circuits and controls to the motor model created by Maxwell. Additionally, the embedded software of the digital control can be incorporated through cosimulation with the Esterel SCADE suite (Figure 10).

The capability to simulate these highly complex systems at various levels of abstraction is another distinguishing feature of the ANSYS integrated electric machine design methodology.

Conclusion
The ANSYS robust electrical machine and drive design approach delivers the computational power and ease of use demanded by today’s overloaded engineers. The main benefit customers receive by using ANSYS solutions is increased productivity from engineering teams, which results in:
- Shorter time to market
- Comprehensive multiphysics from a single vendor
- Robust design and optimization
- Ability to validate all aspects of the system (electric machine, power electronics, control, embedded software) prior to prototyping
Electric Machine Design Methodology:  
A Revolutionary Approach

Frequency controlled speed

Fed by ac-dc-ac inverter

Figure 9. PWM-driven induction machine control

Figure 10. Software-hardware co-design

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End-To-End Cell–Pack–System Solution: Rechargeable Lithium-Ion Battery

Industry has become more interested in developing optimal energy storage systems as a result of increasing gasoline prices and environmental concerns. A major application for energy storage use is hybrid electric vehicles (HEVs) and electric vehicles (EVs). The rechargeable energy storage system is a key design issue, as it dominates overall vehicle performance. The system as a whole must deliver high performance in terms of energy density and power management throughout a variety of driving profiles. The batteries are key elements in sustaining power and energy requirements of the system. However, in many applications the required power and thermal management are key factors for battery sizing. Thermal stability, charge capabilities, lifecycle and cost are also important considerations during the system design process.

ANSYS helps engineers deliver hybrid electric vehicle innovation through end-to-end cell–pack–system simulation that includes multiple physics (electrochemistry, electrical, electronics, thermal, fluidic) and controls (embedded software). A simulation-based approach enables designers to achieve shorter design cycles and optimize battery performance, safety and lifespan.

Design Challenges and Requirements
The established design flow responds to the challenges in hybrid electric technology innovation:
• Shorter design cycle
  - Industry innovations occur at a rapid pace and competition is fierce
• Increasing battery complexity
  - 3 million element cell model
  - Entire pack thermal model ~ 500 million cells, calling for meshing and simulating complex geometries accurately and quickly
• Increased performance
  - Maximize range
  - Maximize fuel efficiency
  - Maximize power delivery and power management; power available rapidly decreases with lower cell temperature
• Increased safety
  - Heating/cooling system of the pack ensures cell temperature to be lower than the maximum allowed value under all vehicle operating and ambient conditions to prevent thermal runaway
• Increased lifespan
  - Heating/cooling system of the pack maintains as constant-as-possible cell temperature of 30 C under all vehicle operating and ambient conditions
End-To-End Cell–Pack–System Solution: Rechargeable Lithium-Ion Battery

Multiscale Lithium-Ion Battery Modeling
A complete lithium-ion (li-ion) battery simulation employs not just multiple physics domains to achieve accurate performance prediction but also a detailed multiscale design concept to transfer model data from molecular level to electrode level and, furthermore, to cell and module simulation levels (Figure 1). The ultimate goal of this comprehensive simulation environment is to integrate multi-module-level information into the powertrain system to evaluate overall performance of hybrid or electric vehicle technology.

Electrode Level
At the electrode level, the electrochemistry is the physical domain that explains the solid electrolyte interface formation and generates appropriate cell model information (Figure 2).

A commonly used physics-based electrochemistry model for a lithium-ion battery cell was first proposed by Professor Newman in 1993 (Doyle, Fuller, & Newman, 1993). The model consists of a tightly coupled set of partial differential equations. The method has become known as pseudo 2-D in literature due to the 2-D implementation of particle modeling. Numerically obtaining a solution to the full 2-D implementation turns out to be challenging even for commercial software due to the tight coupling between equations. Therefore, a novel 1-D approach is used and implemented in the VHDL-AMS language for further circuit and system simulations.
The model shown in Figure 3 is based on:

- Electrochemical kinetics
- Solid-state Li transport
- Electrolytic Li transport
- Charge conservation/transport
- (Thermal) energy conservation

The concentration equation in a form ready for finite volume approach is

\[
\begin{align*}
\frac{\partial c}{\partial t} &= -\nabla \cdot (\text{\textit{i}}_2) + \frac{\text{\textit{c}}}{F} \\
\text{\textit{N}}_s &= -\varepsilon_{\text{n}} \text{D}_{\text{eff}} \nabla \text{c} + \frac{\text{\textit{i}}_2}{F} 
\end{align*}
\]  

(1)

The governing equation for \( \text{\textit{i}}_2 \) in the negative electrode is

\[
\nabla \cdot \text{\textit{i}}_2 = \alpha F j_n
\]  

(2)

The governing equation for \( \varphi_2 \) in the negative electrode is

\[
\text{\textit{i}}_2 = -\kappa_{\text{eff}}(c) \nabla \varphi_2 + \frac{\kappa_{\text{eff}}(c)RT}{F} (1 - 
\]  

(3)

The governing equation for \( \varphi_1 \) in the negative electrode is

\[
1 - \text{\textit{i}}_2 = \sigma_{\text{eff}} \nabla \varphi_1
\]  

(4)

The governing equation for concentration in particles \( cs \) is

\[
\frac{\partial c_s}{\partial t} = \text{\textit{D}}_s \left( \frac{\partial^2 c_s}{\partial r^2} + \frac{2 \partial c_s}{r \partial r} \right)
\]  

(5)

Note that a mix of finite difference and finite volume methods is used to solve the set of equations. More specifically, the finite volume method is used for the conserved quantities of \( \text{\textit{i}}_2 \), \( \text{c} \), and \( c_s \), but the finite difference method is used for potential \( \varphi_2 \) and \( \varphi_1 \), which are not conserved quantities.

Figure 4 shows a representative mesh for the negative electrode used for the lithium-ion cell electrochemical model. The six dots represent nodes for the finite difference approach, and the five squares represent control volumes for the finite volume approach. The arrows between the particle control volumes and main control volumes represent the mass exchange between particles and the main domain due to the Butler–Volmer equation (Bard & Faulkner, 2001) (or chemical reaction occurring at the surface of the particles).
Cell Level
Detailed design simulation at the cell level uses computational fluid dynamics (CFD) analysis.

CFD can be used for battery thermal management analysis; however, CFD tools can be expensive for large systems-level transient analysis. Due to the size of the CFD models, the simulation software can be cumbersome to couple with an electrical circuit model for large system analysis.

The ANSYS solution for systems-level simulation design incorporates reduced-order models suitable for systems-level transient analysis. The well-known thermal network is one option. Figure 5 shows an example of a thermal network. To apply such a model, one builds thermal nodes, each associated with a thermal capacitor representing the heat capacity at that node. Nodes are connected using thermal resistors representing heat conduction to and from that node. The model has limited accuracy because, in general, one cannot afford too many nodes: A large number of thermal nodes increases the complexity and thus defeats the very purpose of using a circuit-equivalent model. The equivalent thermal model obtained needs careful calibration and calculation of thermal resistance and capacitance.

Another approach uses linear time invariant (LTI) characterization. In this method, an RC network is used; however, these RC elements serve a different purpose. In the LTI method, RCs are used to match the transfer function of the system. The method has a fixed RC topology as opposed to different topologies used in a thermal network. Such a fixed topology makes the network generation process easy and automatic. The LTI method can be as accurate as CFD results, and there is no need to calculate thermal resistance and capacitance. Unlike with the thermal network, the LTI method relies on linearity and time invariance of the system, as shown in Figure 6.

So, in this sense, although the LTI method is less general than the thermal network, for battery cooling applications it turns out that linearity and time invariance conditions can be satisfied or relaxed. Therefore, the battery cooling application can benefit from this less general but otherwise much more accurate and easier approach (Hu, Stanton, Cai, & White, 2012).
The electrical behavior of the cell model is obtained by extracting a set of input parameters for an equivalent circuit model (ECM). Figure 7 shows a newly implemented battery ECM model extraction flow.

To use the ECM model, the designer starts with some test data for a cell, namely open circuit potential versus state of charge (SOC) and transient potential under pulse discharge. The ECM extraction tool kit in ANSYS® Simplorer® takes the test data and creates the cell ECM model automatically. Once the ECM model for a cell is created, the user has the option to connect multiple cells by drag and drop to create a battery module or pack circuit model, as illustrated in Figure 7. This model then can be used to predict battery module or pack electrical performance. The validation shows that the battery ECM models give a peak error less than 0.2 percent.

Module/Pack Level

Once the ECM is developed, the module and the entire pack can be simulated at the pace of circuit simulation while preserving the accuracy of the physics-based CFD model. The major benefit of integrating such reduced models into circuit simulation resides on the flexibility of adding more components to the system to predict overall performance of the system. In such situations, more multiphysics analysis is required to fit the module/pack system validation.
As shown in Figure 8, various bus-bar topologies are used to connect electrical elements within the battery module configuration. When regulated electric signals are driven from an electronic circuit unit, electromagnetic interference might occur among various conductive paths, changing the conductive profile and ultimately the power loss distribution, which has critical impact to the battery thermal management. Figure 8 shows a reduced-order model obtained from electromagnetic simulation. Electromagnetic field solvers are applied to extract an electrical frequency-dependent model of the bus-bar, which can then be imported into circuit simulation environment.

The battery module dissipates heat during power consumption and during recharging. That heat causes the module to deform due to thermal expansion, which can result in various stresses. The power loss distribution is used to drive the thermal analysis, which in turn generates the load data to drive the total deformation simulations. Figure 9 depicts the battery module on the left, and the structural deformation on the right. This study can be used to design modules that do not exhibit excessively large deformations during various loads and operating conditions.
Complete System Integration
Complete system simulation is the ultimate goal for a system engineer when overall performance of the powertrain is required. Before the entire integrated system is validated, the total battery model can be immediately implemented and verified (as shown in Figure 10). This model couples the bus-bar, individual cell models and the LTI thermal model into a single and complete module simulation.
Figure 11 depicts the definition of the HEV drive train system in which the complete battery model is integrated, including embedded software control. Several other reduced-order models are included in this schematic to provide for multiphysics system simulation at the level of circuit design. This preserves the accuracy of physics-based solutions such as ANSYS Maxwell® for electric motor electromagnetic modeling, ANSYS Q3D Extractor® for parasitic extraction of frequency-dependent behavior for inverter packages and cables, ANSYS Mechanical™ for shaft and gear design models, and ANSYS Simplorer for schematic-based system design.

A suggestive example of complete system simulation of a powertrain application is shown in Figure 12. On such implementation, one can analyze in detail with a higher level of confidence the fuel consumption at various driving profiles, monitoring battery performance at the same time.
Conclusion

This paper discussed several challenges and simulation-based solutions for HEV and EV energy system design. Shorter time to market, increased complexity, higher performance and higher safety requirements are driving designers to apply a dynamic simulation approach. A multiscale, multi-physics simulation flow emphasizes comprehensive modeling and a hierarchical method that leads to full system simulation. Modeling of the physics is performed using rigorous 3-D simulation to extract appropriate circuit- and system-level reduced-order models. These models are then combined in top-level system simulation, allowing engineers to predict details at any level in the hierarchy.

References


Electromagnetic, mechanical and thermal simulation plus design optimization help to improve energy efficiency, noise and bearing life of robust electric motors.

By Cassiano A. Cezario, Briam C. Bork, Marcelo Verardi, Research and Technological Innovation Department, and José R. Santos, Product Development and Application Department, WEG Equipamentos Elétricos S.A. — Motores, Jaraguá do Sul, Brazil
Electric motors are the single biggest consumer of electricity, accounting for about two-thirds of industrial power consumption and about 45 percent of global power consumption, according to an analysis by the International Energy Agency. The World Energy Outlook 2012 states that the developed world is planning to increase its energy efficiency by 1.8 percent annually over the next 25 years. Much of this improvement must come from advancements in electric motor design. Companies that develop these devices must ensure that motors have low operating noise and long life. Engineers have worked to balance these demands to improve and optimize the design of electric motors for almost two centuries, and now new methods and tools are needed to generate further progress.

WEG is the largest industrial electric motor manufacturer in the Americas and one of the largest manufacturers of industrial electric motors in the world, producing more than 10 million units annually. WEG engineers used the ANSYS comprehensive design solution for electric motors to leverage electromagnetic, mechanical and thermal simulation. Design optimization helped the engineering team to deliver optimal energy efficiency, low operating noise and long bearing life on the new W50 electric line.

**WEG’s Robust Design of Electric Machines**

<table>
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<th>APPLICATION</th>
<th>TECHNOLOGY</th>
<th>EXPECTED RESULTS OR TARGET</th>
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<td>Evaluate a wide range of cooling air passage designs</td>
<td>Computational fluid dynamics (CFD)-electromagnetic simulation</td>
<td>Reduce fan losses and improve energy efficiency</td>
</tr>
<tr>
<td>Minimize total noise generated by motor • Predict aerodynamic noise • Predict electromagnetic noise</td>
<td>Electromagnetic-structural-thermal analyses</td>
<td>Lower operating noise</td>
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<tr>
<td>Reduce operating temperature of bearing</td>
<td>CFD-thermal simulations</td>
<td>Increase bearing life</td>
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<tr>
<td>Automate design exploration</td>
<td>ANSYS DesignXplorer and ANSYS Workbench</td>
<td>Optimize motor design without having to manually evaluate each design alternative</td>
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</table>

**WEG engineers used a wide range of ANSYS tools to deliver optimal energy efficiency, low operating noise and long bearing life on its new line of electric motors.**
of motors. The broad range of ANSYS capabilities was instrumental in designing and optimizing the electric motor without the need to individually evaluate each design alternative.

**IMPROVING ENERGY EFFICIENCY**

Large electric motors in the 125 horsepower to 1,750 horsepower range typically have two fans: one to cool the motor interior and the other to cool its exterior. These fans consume a considerable amount of power, and WEG engineers believed that a promising approach to improving energy efficiency was to improve fan efficiency. They focused on the internal fan, particularly on reducing losses as air flows through the motor. The airflow generated by the fan flows through openings in the frame. Losses could be reduced by increasing these openings — but this strategy would reduce the motor’s electromagnetic performance.

WEG engineers used ANSYS CFD software to model the airflow through the interior of the motor. They defined key parameters, such as the openings where air passes through the frame, as parametric dimension variables. Since many of these design parameters impact the motor’s electromagnetic performance, engineers produced an ANSYS Maxwell electromagnetic model of the motor with the same parametric variables as the CFD model. They generated a table of varying values for each of the parameters.

WEG employed ANSYS DesignXplorer to create a design of experiments (DOE) that subdivided the design space to efficiently explore it with a relatively small number of simulation experiments and to run multiphysics simulations without human intervention. Comprehensive simulation tools in the ANSYS Workbench environment and design optimization with ANSYS DesignXplorer enabled WEG to increase the number of simulations performed from four per month in 2005 to 800 per month currently. High-performance computing (HPC) also helped enable this improvement. WEG uses HPC Packs for CFD, and Maxwell runs with 64 cores distributed across eight workstations.

Output results for each design point were stored in a table and visualized with a response surface map that completely maps out the design space. The response surface was used to graphically plot the effect of variables on fan losses. Simulations were not coupled in this case due to computing resource limitations; however, in the future, WEG will use coupled multiphysics simulations to even more accurately determine optimal values for parametric variables by considering all of the physics. WEG engineers manually compared response surface maps, plots and tables for the CFD and electromagnetic analysis to determine the

Before-and-after comparison of ANSYS CFX simulations shows improved airflow that reduces fan losses in W50 motor compared to previous-generation design.
ROBUST ELECTRIC MACHINE DESIGN

combinations of parametric variables that delivered the best mix of performance. Engineers then reran the electromagnetic and CFD simulation for the best combinations and selected the one that delivered the best performance: a substantial reduction in fan losses and a resulting improvement in energy efficiency without any sacrifice in electromagnetic performance.

REDUCING NOISE

WEG engineers also wanted to reduce the noise generated by the new W50 motor design. An electric motor primarily generates noise through two independent sources: aerodynamic and electromagnetic. Aerodynamic noise is generated by the fan rotor and transmitted through the air; WEG engineers used ANSYS CFD to optimize the fan rotor geometry to minimize aerodynamic noise. Electromagnetic noise is created by the interaction of magnetic fields produced by stator and rotor. In extreme cases in which the resultant force frequency excites the natural frequencies of the mechanical structure, this noise will be dramatically amplified.

WEG engineers used ANSYS CFD to optimize the internal fan system. Engineers designed a new internal fan system to reduce the length of the motor, which improved the dynamic performance. However, the original design was not acceptable, so engineers used ANSYS DesignXplorer to optimize the internal fan geometry and develop a new solution that met the requirements. The new internal fan reduces vibration, improves power density of the motor, and increases the maximum rotating speed.

To predict and avoid electromagnetic noise of the motor prior to the prototyping stage, WEG engineers used electromagnetic simulation to calculate the electromagnetic force and losses. These quantities are used as inputs to the structural and thermal simulation to predict mechanical vibrations. WEG engineers used the ANSYS Application Customization Toolkit to implement the methodology of topological optimization to increase the natural frequency of the frame. They then set up parametric variables and used ANSYS DesignXplorer to run a table of design points and optimize the design to produce the lowest levels of noise.

IMPROVING BEARING LIFE

Bearings are usually the first component to fail during the lifetime of an electric

ANSYS multiphysics tools help WEG deliver best-in-class performance for electric motors while substantially reducing the lead time and cost of the product development process.
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