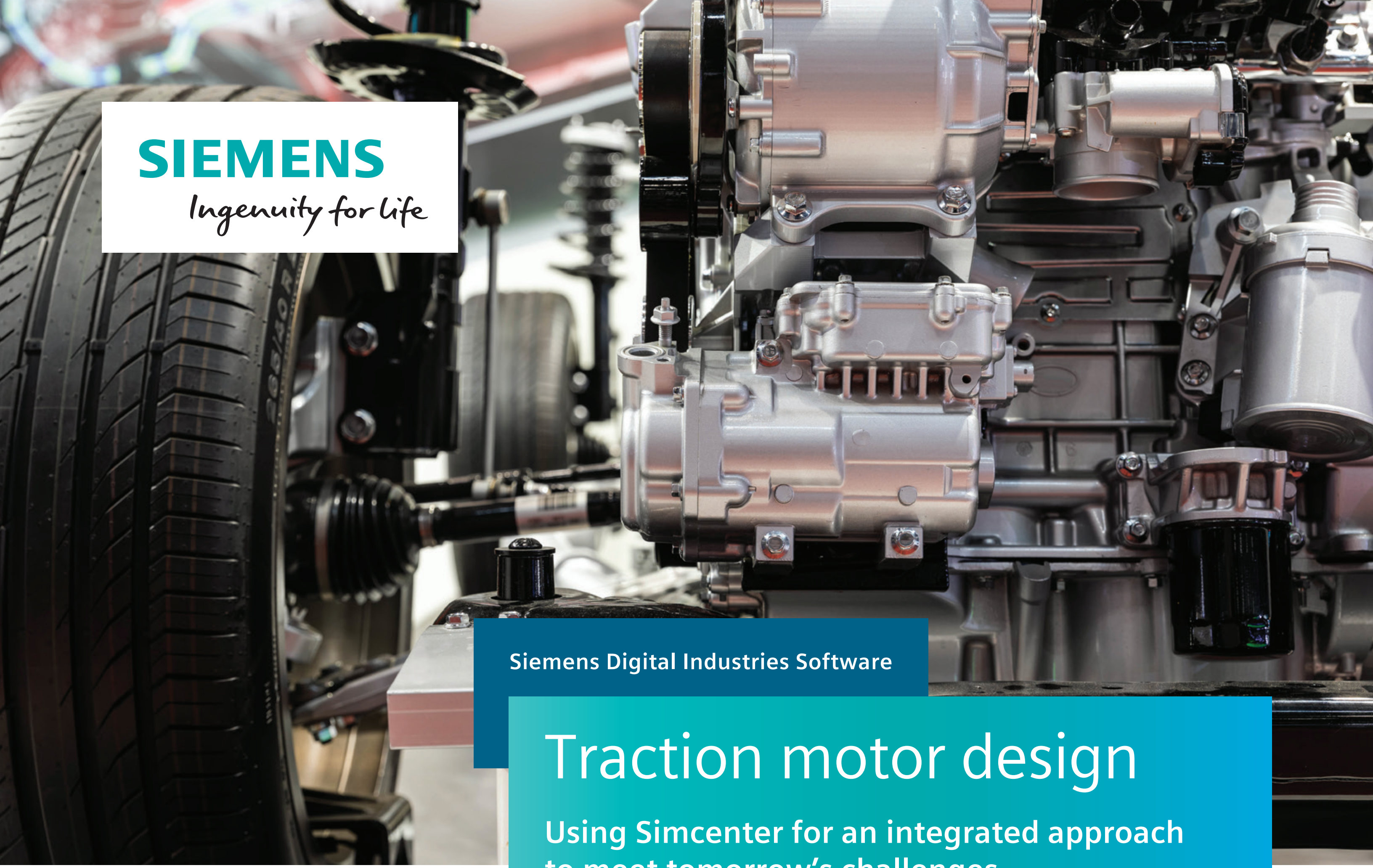


Siemens Digital Industries Software

Traction motor design

Using Simcenter for an integrated approach to meet tomorrow's challenges

Executive summary

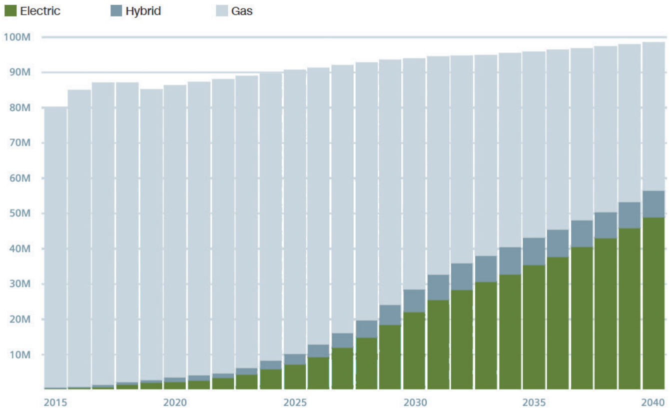
This white paper discusses the engineering, simulation and computational challenges of an end-to-end design process for traction motors for the hybrid and electric vehicle (xEV) industries. Each of these aspects are discussed with respect to a typical V-cycle, from design conception to prototype creation. The key engineering objectives include developing high-power density, high-efficiency, fault-tolerant, robust and low-cost machines. Implementing a novel and integrated design and development workflow using modern simulation tools will play a central role in achieving these objectives. In this white paper we discuss the core advantages embedded in the state-of-the-art Simcenter™ software suite of tools that are designed to meet current and future traction motor design challenges.

Contents

Abstract

The transportation industry is being transformed rapidly, driven primarily by the electrification of vehicles, development of autonomous vehicles, the application of Industry 4.0 technologies, changing consumer demographics, economic and environmental sustainability issues, among others. Some of these trends originate from the need to minimize greenhouse gas emission levels, develop safer modes of transportation, reduce operating costs and provide better product lifecycle management (PLM) systems.

Of the many changes, transport electrification has received the greatest amount of attention. Market projections predict a rapid rise in demand (figure 1) for alternatives to internal combustion engine (ICE) vehicles over the next several decades.[1] This trend is particularly important for the industrially developed regions of the Americas, Europe, the Pacific Rim, Southeast Asia and India where ambitious targets have been set to phase out the sale of ICE vehicles between 2030 and 2050.



Source: Bloomberg New Energy Finance
Graphic: Peter Valdes-Dapena and Tal Yellin, CNN

Figure 1. Relative demand for electric and hybrid vehicles compared to ICE vehicles.

The implications of these trends are widespread for all segments of the xEV industry, including drive-train component manufacturers, suppliers and integrators. The primary components of an xEV drive train are the battery or fuel cells, traction motor(s), power electronic drive and transmission system. In this white paper we consider the current state and future direction of traction motor design with respect to the industry's trends, challenges and solutions. Some key questions regarding these issues are:

- Will the demand for developing new and improved traction motors follow suit with the industry's overall growth
- What are the technical challenges and opportunities for the next generation of traction motor design engineers
- What are some of the key computational and simulation solutions that can enable today's designers to meet the engineering challenges of the future

Each of these questions are discussed in this paper. First, the traction motor market projections are considered. Then, some of the main engineering and simulation challenges faced by traction machine designers are discussed. Following this, a typical motor design V-cycle is considered. At each step key design tasks are identified including the capabilities needed to carry out these tasks using modern simulation tools. Some contemporary software solutions are presented at each step of the process. Finally, we comment on the advantages of considering an integrated design process that is enabled by some of the tools presented in this paper.

The traction motor market

Although there have been significant market studies on the xEV industry at large, the same cannot be said for the traction motor market. There are few publicly available studies. However, based on projections related to infrastructure development and the widening application of traction motors as the primary means of propulsion, it is possible to make both qualitative and quantitative predictions.

A recent study[2] projects the traction motor industry will continue to grow at nearly 43 percent compound annual growth (CAGR) for the next five years and reach nearly $13 billion USD in value by 2024 (from the $2.24 billion USD today). Furthermore, price parity between xEVs and ICE vehicles is expected to be reached by 2025. This is based primarily on the cost of high-powered batteries trending downward for the past decade.[1]

Another significant trend is the change in consumer choices. In North America, the number of xEV models to be offered is projected to rise to nearly 80 by 2025 (from about 25 today). Essentially, every original equipment manufacturer (OEM) has taken steps to ensure electrified vehicles will form their core business segment in the future. Based on these and other similar trends, it would be fair to conclude the traction motor industry will continue to grow and follow suit with the transport industry's overall projections. The next question to consider is what are the technical implications of these changes for original equipment manufacturers (OEMs), suppliers, design engineers and software developers.

Engineering challenges

The first important aspect to note is available traction motors are not capable of meeting the technical standards and performance requirements of future xEVs. The efficiency level, power density, speed range, PLM lifetime costs and other aspects of present-day machines fall short of the levels required for the next generation of machines. This presents both opportunities and challenges for OEMs and other stakeholders. Let's consider some of these.

Although the primary focus of this white paper is on technical challenges, it is worth starting with a nontechnical issue that has greatly impacted the traction motor industry – the supply and price volatility of rare earth materials, namely neodymium and dysprosium. These materials are used to create high strength permanent magnets (PMs) and are in a number of commercial electric and hybrid vehicle (Toyota Prius, NISSAN LEAF, BMW i3, Tesla Model 3, etc.) motors. The bulk of the world's rare earth materials is supplied by China. Between 2011 and 2012, restrictions placed on their export caused their prices to increase rapidly, leading to a great deal of uncertainty for the traction motor development industry.[3] Although prices have since stabilized, the impact of this event changed the course of the industry.

This was a watershed moment that led to tremendous research and development (R&D) efforts to develop motor alternatives that do not use rare earth permanent magnets or use them in reduced amounts. Ever since 2012 this issue has continued to dominate much of the discussion around the development of the next generation of traction motors. Therefore, we identify the development of high-power density traction motors that do not use or use reduced volumes of rare earth permanent magnets as one of the main challenges for the next generation of machine designers.[4]

The next important challenge is the development of highly efficient motors. In response to climate change and the energy demands of an ever-growing population, governments worldwide have mandated reduced emission levels of vehicles. This, in turn, has increased the demand for high-efficiency motors. This is a significant ask considering most traction machines currently operate at about 90 percent efficiency. Improving on this would require combining the latest technological advancements from materials engineering, robust design, manufacturing processes (for example, using additive manufacturing) and simulation technologies. One area in which significant R&D resources have been expended in both the public and private sectors is on the understanding, modeling and measurements of the so-called iron losses in traction motors.[5] Minimizing these losses is an important avenue to consider for pushing the efficiency envelope further. Some of the difficulties associated with this, especially those from simulation and computational standpoints, will be highlighted in this paper.

For a given battery, a traction motor can only operate up to a certain maximum speed (not to be confused with the vehicle range) that is quantified by its constant power to (base) speed ratio (CPSR). This is an important constraint that impacts the choice of machine type, materials, gear ratio and other powertrain details. Most modern motors exhibit a CPSR of about 2.5 to 4. Extending this range to ~7 to 10 is one of the targets for future machines. If feasible, this will help minimize powertrain transmission system costs significantly.

Minimizing costs by ensuring robustness is another important objective for all machines. Elements of robustness include sustaining machine performance against manufacturing uncertainties and tolerances, safeguarding against system faults, ensuring the ability to operate under variable environmental conditions, etc. Simulation software tools are important enablers for ensuring machine robustness.

Mitigating the noise, vibration and harshness (NVH) levels of traction motors is another major technical challenge. Reduction of NVH levels due to faults such as rotor eccentricity or harmonics arising from pulse width modulated (PWM) control strategies and other sources are difficult problems to isolate and rectify.

To summarize, some of the main design challenges for the next generation of traction motors are:

- Eliminating or reducing the dependence on rare earth permanent magnet-based motors for traction applications
- The development of highly efficient motors
- Increasing the CPSR or maximum operating speed
- Ensuring the robustness of traction motors
- Controlling or mitigating the NVH levels of traction motors

Solving these problems will lead to machines with better performance, increased efficiency, lower costs and extended operational lifetime. A great deal of effort is being expended in these areas by OEMs, research consortiums and government initiatives at both the local and international levels. For example, The FreedomCar 2020 project of the U.S. Department of Energy Council[6] has had a great impact on the development of innovative solutions that can partly address some of the problems mentioned above. There are similar projects being pursued by the European Union (EU) and the Pacific rim countries with China, amongst others, leading the charge.[7]

Modeling and computational challenges

Next, we consider some of the modeling/simulation and computational challenges associated with the engineering tasks presented above. Aside from electromagnetic design, there are four integral aspects of traction motor design: (1) thermal or cooling system design, (2) power electronic or drive design, (3) complying with NVH standards and maintaining the structural integrity of the machines and (4) the system-level integration of various subsystems and components. The design of the cooling system requires coupled electromagnetic-thermal (EM-TH) simulations. For this, EM-TH simulations based on model representations at various fidelity levels, from lumped parameters to computational fluid dynamics (CFD) based calculations, are needed. For the power electronic drive, coupled electromagnetic and power device (switches, diodes, gates, batteries, etc.) simulations are needed. The transient force distribution of a motor model is required for structural analysis and NVH simulations. For system-level design, low- to high-fidelity level model representations are needed.

Each of these present significant challenges. For example, differences of time constants and mesh requirements when performing finite element analysis (FEA) based simulations between electromagnetic, thermal and mechanical tools are just some of the many aspects one has to consider. Also, the computational costs of CFD-based simulations may render certain problems impractical to solve without using high-performance computing (HPC) capabilities. Solutions to some of these issues will be discussed.

The design space of an electric motor is high dimensional. Furthermore, the number of design objectives and constraints are also typically high (which leads to the curse-of-dimensionality that renders many optimization approaches ineffective) when one considers the multidisciplinary and multi-physical nature of the problem. Faced with numerous choices, an important challenge engineers face is to select optimal design candidates for prototyping. Taking advantage of state-of-the-art design of experiment (DOE) and multi-objective optimization algorithms may be helpful. This is a vast area of research and applying the latest technical innovations is a challenge and an opportunity for software tool developers.

When nonlinearities are important, DOE and optimization problems often require machine models to be solved using computationally intensive FEA-based analysis. These simulations can be time-consuming, ~seconds/minutes problems for 2D and often ~hours/days problems for 3D simulations. Depending on the problem at hand, thousands of evaluations may be required. In these cases, surrogate model-based performance predictions would have to be carried out. The development of low- to high-fidelity surrogate models is an important algorithmic challenge.[8]

The final modeling challenge is related to creating a comprehensive digital twin. This term has been used in many contexts across a number of industries. In this paper, we refer to the digital twin of traction motors as their representation in various forms and fidelity levels. Hence, the equivalent circuit or lumped parameter representation, low- or reduced-order models, response surface models and FEA-based models are all examples of a machine digital twin.

Ideally, the use of Industry 4.0 technologies to mobilize data, process them to create a virtual representation of a physical device on a workstation or on a network of machines based on sensor inputs is the true conception of a digital twin. The information embedded in such a representation would include manufacturing details, PLM history, etc. However, at present, developing tools that use online and offline data, artificial intelligence algorithms, cloud computing and machine representations to create a dynamic model of a unit is a work-in-process (WIP). Hence, for now, the representations of traction motors that may be updated in real time and allow seamless model exchanges between different simulation platforms for multi-physics and multi-domain analysis is what we refer to as a digital twin in this paper.

In the discussions above, we have summarized some of the most important engineering, simulation and computational challenges faced by today's traction motor designers. Simulation tools will play a central role in meeting and overcoming these challenges. In the following sections we take a deeper look at the design process of traction motors and discuss the current status of design and simulation technologies and propose some new approaches.

Traction motor design

In the following sections, we will discuss the desired simulation tool capabilities from the perspective of a designer. At each stage of the design process, we will discuss how Simcenter solutions, which are part of the Xcelerator™ portfolio, the comprehensive and integrated portfolio of software and services from Siemens Digital Industries Software, can provide the capabilities that can help you meet the challenges mentioned above.

System-level sizing and simulations

Figure 2 shows a typical approach for motor design that starts with sizing to meet vehicle performance specifications. We seek to derive the target performance of the traction machine to be designed given the vehicle class, typical drive cycle(s) and constraints, vehicle performance metrics, etc. At this stage, system-level analyses are performed during which component size and configuration as well as drive-train topologies may be varied. The results are used to determine the required motor-performance characteristics. These may include the power under peak and continuous modes of operation, speed range, efficiency levels, etc.

From a software perspective, a fast 1D system simulation tool is needed to consider multiple xEV powertrain configurations and component size variations. For the motor component, the speed-torque-efficiency maps of different motor types are needed to calculate the well-to-wheel efficiency and other performance parameters such as energy efficiency, acceleration time, vehicle range and gradeability. Along with efficiency map variations, the effects of changing the battery type and size, inverter/converter switching strategy, switching losses, current or power limitations, single or multi-speed transmission, cooling methodology, NVH characteristics and the simulation of regenerative braking modes may be studied during sizing. Ultimately, the system-level simulator would ideally facilitate model parametrization for varying machine types, drive-train configurations, power-electronic simulations and gear configurations.

The utility of the system-level simulator is not confined to sizing exercises; it may be used during all stages of design to assess device performance for thermal, NVH and/or other analyses. What is critical from the perspective of traction motor design is the tool does not restrict the designer to any specific motor type or configuration and enables design exploration without constraints. For example, for traction motor design it would be desirable to have the capability of scaling the efficiency maps of motors (a nontrivial technical task). At the same time,

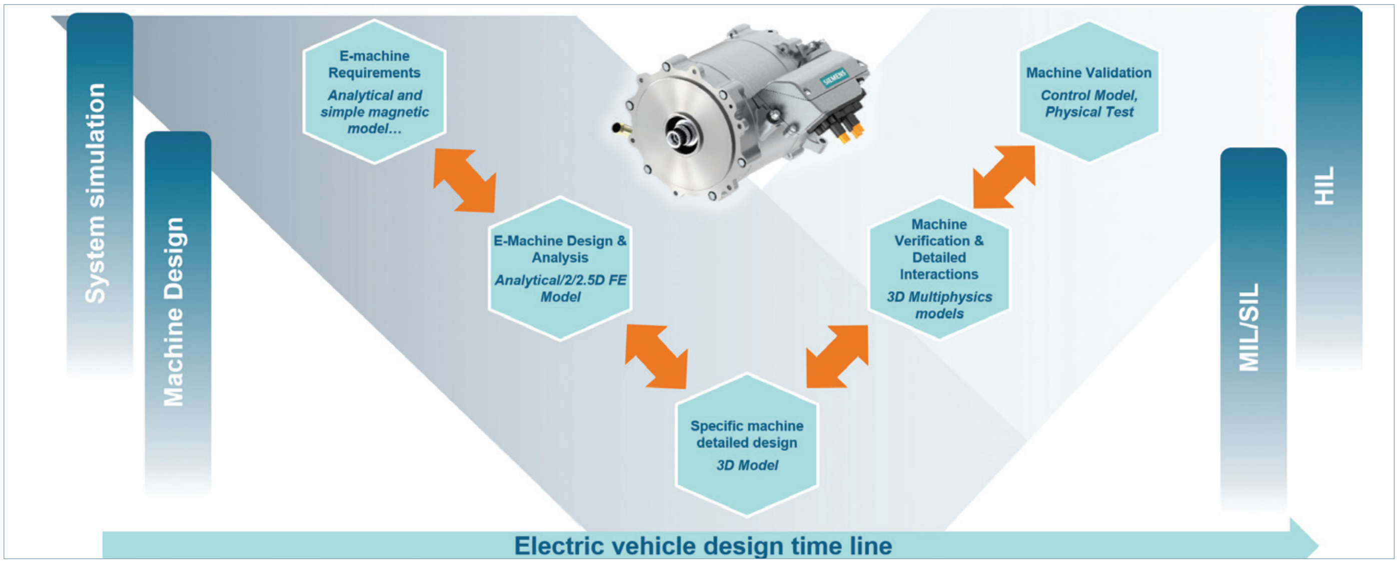


Figure 2. A typical traction motor design process.

the designer should be able to take into account temperature effects on the motor outputs. These are just some of the important functions expected from a system-level simulation software for traction motor design during the iterative stages of the design process.

Simcenter Amesim™ software has been designed to meet these challenges. It is an industry leader in 1D simulations for multi-domain, multi-physical systems. By closely linking with Simcenter motor design and other domain-specific multi-physical tools, it allows designers and analysts to evaluate the impact of design iterations at any stage of the development process and optimize their designs. One of the most powerful aspects is the built-in capabilities for representing scalable traction motor models at multiple fidelity levels. The various fidelity levels of the motor representation within Simcenter Amesim include linearized, fully nonlinear and temperature-dependent models. These models are needed for drive design, thermal system design, NVH characteristic assessment and, ultimately, for the creation of a comprehensive digital twin. An example of a system-level vehicle model using Simcenter Amesim has been shown in figure 3. It shows the system subcomponents, including the traction motor, an internal permanent magnet (IPM) machine.

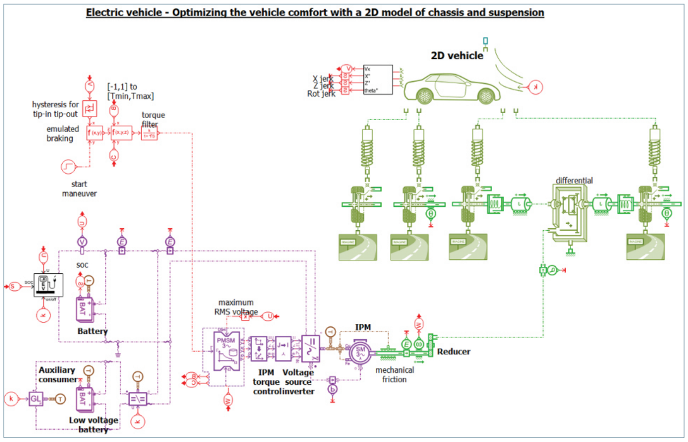


Figure 3. This diagram shows a system-level Simcenter Amesim model of a Class II electric vehicle to determine the optimal component sizes for drivability and comfort.

Motor sizing and design iterations

Following the determination of the motor characteristics needed for a given application, the design continues with model initiation followed by iterations. This is one of the main steps of the conceptual development process during which a viable design or a few candidates that satisfy the target performance criteria derived from the previous step is sought. Aside from obtaining design candidates that fulfill the target performance objectives, it is also important to ensure the resulting design(s) is/are compatible with an appropriate cooling system and can maintain structural integrity under various load conditions. The key steps of this stage are design initialization, material selection, winding pattern selection and the fine-tuning of geometry. From a software tool perspective, a number of important capabilities are needed.

First, fast results and performance calculations are critical at this stage. Exploring designs by varying machine topologies, winding configurations and materials are just a few of the many parameters that are studied in search of possible candidates. Quick assessments are needed to understand the effects of these variations on machine performance. This means the overhead associated with exploring various options must be minimal. Ideally, fast (analytic or semi-analytic) calculation methodologies applied in a template-based interface is what's needed at this stage.

Second, there must be the flexibility to innovate. Some of the most promising design options being explored for the next-generation high-power-density machines are based on unconventional topologies stemming from additive manufacturing processes and the application of novel materials.[9] Any software used during this design step should support design exploration of typical and atypical topologies.

Third, as mentioned above one of the main avenues to explore for achieving the target performances of the next generation of traction motors is material engineering related innovations. A good motor design software should contain an extensive library of materials, including a comprehensive database of electromagnetic, thermal and mechanical characteristics. The solver technology within the software should be able to be used to accurately calculate machine hysteresis and eddy current losses based on manufacturer-supplied material and loss data. It also must be able to account for changes to material properties due to physical effects arising from temperature variations, mechanical stresses, etc.

Fourth, traction machines are driven by inverters that can have significant effects on machine performance and system efficiency. Design engineers generally need access to analysis capabilities that can take the effects of inverters and their control strategies into account. This includes the evaluation of switching losses and the effects of drive harmonics on the machine performance and its NVH characteristics.

Fifth, there is a need to generate reduced order models (ROMs) that can be exported to system-level simulation software (for example, Simcenter Amesim) or real time hardware-in-loop (HiL) simulators and power electronic design tools. These models should be available at various fidelity levels (linearized models, nonlinear models, multi-physical models, etc.) so design iterations may be facilitated swiftly. The importance of ROMs for the design, optimization and digital twin creation of electric machines is quite significant.

Next, the importance of multi-physics simulations was discussed earlier in this paper. At this stage of design, it is not critical to carry out detailed multi-physical cooling system design or NVH analysis. However, it is important to ensure the ohmic and other losses will not degrade machine performance, or worse, cause a catastrophic failure. Hence, it is important to be able to compute some parameters that will help to ensure machine safety will not be compromised under normal operation. Ideally, lumped parameters based or low dimensional coupled EM-TH simulations would be available to ensure thermal soundness of the machine.

Similarly, detailed NVH analysis is not needed during this stage. However, the ability to assess the force distribution between component interfaces, surface nodal force distributions, air gap flux density harmonic content and the assessment of local stress levels are important. Aside from these, the ability to simulate typical machine faults such as short circuits, mechanical bearing degradation, etc., may also be sought at this stage but that is not a necessity.

The design paradigm for this stage has changed in the past decade or so. In the 1980s, empirical knowledge, analytical and in-house generated computational programs or commercial FEA-based software were the design tools of choice. However, since then, two main events changed the design approach. First, the commercialization of the analytic magnetic circuits and templated-based approach by Simcenter SPEED™ software (late 1980s) and second, the release of the FEA and template-based Simcenter Motorsolve software in 2008. These events enabled a simulation-driven design development approach that could not have been considered previously. Since then the template-based approach has become the most efficient method for executing this stage of design. The Simcenter SPEED and Simcenter Motorsolve duo form an excellent combination that provides fast (~seconds) magnetic circuit-based and high accuracy FEA-based (~seconds/minutes) motor performance results. Together, they can be used to harness the power of the two approaches simultaneously.

Some of the essential capabilities of these tools are multiple analysis options at various fidelity levels. These include current and voltage-driven simulations, equivalent circuit-based PWM analysis, D and Q-axis analysis, complete FEA-based transient with motion simulations, etc. Simcenter Motorsolve includes a comprehensive magnetic materials library covering a wide range of soft and hard magnetic materials, cooling materials, etc. For connecting to other Simcenter simulation tools, reduced order models can be created that are geometrically scalable and temperature dependent. Some other capabilities include the prediction of permanent magnet (PM) demagnetization, force calculations at model interfaces and surfaces, the ability to export nodal forces, the calculation of temperature distribution and the identification of hot spots using coupled electromagnetic-thermal simulations. Models can also be exported for CFD-based EM-TH simulations in Simcenter STAR-CCM+™ software or Simcenter FLOEFD™ software. Seamless connections to Simcenter Amesim for system-level analysis and connectivity to HEEDS™ software, the Simcenter flagship multi-objective design optimization, design exploration and sensitivity analysis tool, may also be used.

Having access to such a comprehensive set of capabilities within a single software family is unique. It is aimed at providing the best possible solution for solving the problems and challenges mentioned earlier. Figure 4

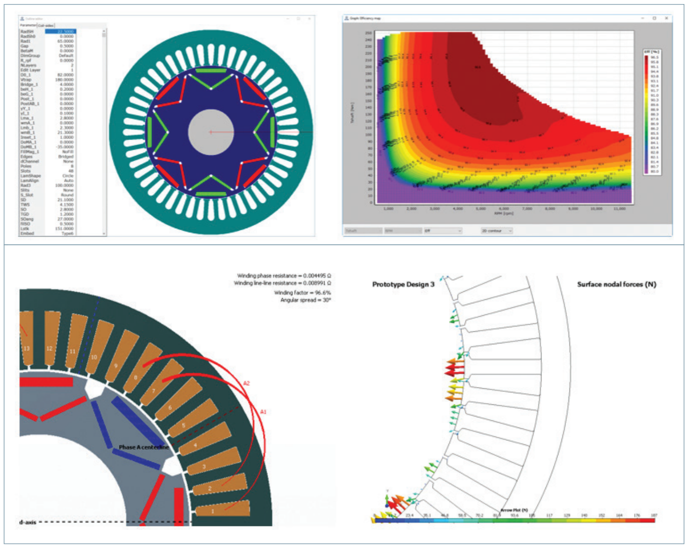


Figure 4. Simcenter SPEED (top) and Simcenter Motorsolve (bottom) examples.

shows examples of Simcenter SPEED and Simcenter Motorsolve IPM models. A model view and the speed-torque-efficiency map of an 8-pole 48-slot IPM is shown. This model is based on the machine used in the NISSAN LEAF vehicle. Also shown is a version with a modified rotor topology of the same machine modeled using Simcenter Motorsolve and the surface nodal force distribution.

Design validation and multi-physics analysis

The main objective of the previous step was to obtain a single or multiple design options that satisfy the performance criteria determined during system-level sizing. Another important objective was to ensure that practical, cost-effective and viable motor drive and cooling systems could also be implemented for these choices. Having narrowed it down to a few candidates, detailed analyses are performed next.

At this stage, 2D and/or 3D FEA-based electromagnetic simulations for validating machine performance, refining geometries to optimize the flux distribution and reduce leakages, analyzing system faults including demagnetization prediction, sensitivity analysis, coupled electromagnetic-thermal simulations, structural analysis and design optimization, are likely carried out. The performance of the machine under various load conditions (continuous, peak, startup and maximum speeds) are also evaluated.

It should be noted that some of these analyses may, in fact, be carried out during the previous step as well, although at a low-fidelity level. The computationally intensive ones (3D FEA and multi-physics) are typically left to this stage. What is important to note is the analysis methodologies used at this stage should be the most accurate that are computationally feasible. For most problems this means that an FEA-based approach would be used. From a software standpoint, similar to the previous stage, much can be said about the desired capabilities. However, we will focus on the aspects that are directly linked to the engineering and simulation challenges identified earlier starting with those related to the development of high-efficiency motors.

There are two main requirements to accurately calculate traction motor efficiency: First, obtaining accurate field solutions and second, calculating losses. These requirements are, in fact, linked to each other. There are two main electromagnetic sources of loss in electric machines; ohmic (DC and AC) and iron losses (including hysteresis and eddy current losses). DC-ohmic losses are well understood and they can be calculated accurately using analytic approaches. AC-ohmic losses require either an analytic/time harmonic FEA or transient FEA-based simulations. Further, calculating iron losses pose a significant challenge.[10] The reasons for the difficulties of calculating iron losses is complex (it includes modeling complex material behavior under various environmental conditions, manufacturing effects, the effects of motor control strategy, etc.) and beyond the scope of this paper. Suffice to say there are extensive and ongoing R&D activities related to modeling iron loss measurements.

Another significant challenge is related to multi-physics simulations. At this stage of design, once the electromagnetic performances have been validated, fully coupled EM-TH simulations are needed to ensure that under peak and rated conditions the motor's performance level can be maintained with an appropriate cooling system. For this, there needs to be seamless model sharing between the electromagnetic and thermal solvers. The effects of temperature rise on the electrical and the magnetic properties of materials are needed. Ideally, FEA-based EM-TH simulations in which the heat transfer coefficients are based on empirical analysis and/or CFD-based calculations are required. In some cases, a coupling of FEA-based 2D electromagnetic with 3D CFD-based thermal analysis would also provide a good option. Ultimately, the required fidelity level of the electromagnetic model is dependent on the specific problem being addressed.

Mechanical analysis and NVH analysis of traction motors are needed to safeguard against structural failures for reducing the effects of harmonics, avoiding resonances and complying with health and safety standards. To carry out structural and NVH analysis, we need the force distribution in the air gap of machines, the Lorentz forces on the conductors and the forces between device components. Whereas standard computational methods exist for computing the forces between model components that are physically separated, this is not the case between solid interfaces. For example, the forces between the PMs and the soft iron cores of motors are essential for evaluating local stresses but are difficult to evaluate.

Let's now consider the Simcenter solution to these problems. Simcenter contains electromagnetic, thermal (including empirical and CFD-based solvers) and structural simulation tools that are ideal for addressing the domain-specific and multi-physics simulations described above. These are best-in-class tools that contain the latest technologies from their respective domains. In many cases, Simcenter tools are at the forefront, leading the development of new technologies in response to market needs. For example, Simcenter MAGNET™ software is a premier general purpose 2D/3D electromagnetic analysis tool. It is the first commercial software to apply FEA-based algorithms to solve Maxwell's Equations. Since its inception it has led the way in developing cutting-edge simulation capabilities for electromagnetic device design problems. Most recently, Siemens Digital Industries Software has added a hysteresis field solver to Simcenter MAGNET that is an industry leader for providing accurate field solutions.

Considering the design challenges discussed earlier it is obvious that we are entering an era of traction motor design in which high-order effects will need to be incorporated during the design cycle. The hysteresis solver in Simcenter MAGNET is an example of the type of technology needed to get there. This technology significantly has improved the accuracy of the field solutions and the iron loss calculations compared to conventional approaches.

Simcenter MAGNET Thermal, Simcenter 3D, Simcenter FLOEFD and Simcenter STAR-CCM+ CFD are industry leaders in multi-physics and multidisciplinary simulation. Together, they provide a powerful platform for carrying out multi-physics and multidisciplinary analysis of traction motors. Many options are provided for coupled EM-TH simulations for cooling system design. For EM-TH problems requiring the finest fidelity, HPC and CFD-based analysis can be carried out using the Simcenter STAR-CCM+ software. For faster analysis, convective and radiative loss coefficients based on empirical approaches can be carried out using Simcenter MAGNET Thermal software.

For NVH and structural analysis, surface nodal and interface force information imported from Simcenter MAGNET can be used in Simcenter 3D. In addition to nodal force export, it is also possible to identify areas of high stress from the force density plots that are part of the built-in capabilities in both Simcenter MAGNET and Simcenter Motorsolve. Forces between model components in solid contact, identified as a difficult calculation earlier, can be carried out in Simcenter MAGNET and Simcenter Motorsolve.

Designing fault-tolerant and robust designs are two additional machine-design challenges. Some typical sources of machine faults include short circuits in coils and windings, bearing degradation leading to shaft eccentricity, current surges from voltage fluctuations, permanent magnet demagnetization (for PMSMs) from overcurrent or temperature surges and/or other physical damages. Furthermore, manufacturing and handling effects and tolerances also fall under the criteria of fault-tolerant and robust designs.

There are significant R&D activities being carried out by the motor design community on these effects and their modeling. System-fault simulations due to short circuits are fairly straightforward to carry out. On the other hand, modeling the effects of bearing degradation leading to eccentricities (which may introduce harmful harmonics into the system and create unbalanced magnetic pulls as well as energy losses) require coupled six degrees-of-freedom (DOF) electromechanical simulations that are time-consuming and difficult. Statistical models have to be incorporated for taking the effects of uncertainties originating from manufacturing processes into account. For soft iron materials, the magnetic (B-H) characteristics and iron losses may vary significantly from manufacturer supplied data.[11] Modeling these effects, including material nonlinearities, may require thousands of motor performance evaluations using FEA. Instead, high-fidelity surrogate models are needed as an alternative. Furthermore, manufacturing processes such as shrink fitting, laser cutting and die-punching may also affect the local magnetic characteristics of irons. These effects are also quite difficult to model[12] but some progress has been made recently.

The discussion above underscores the difficulty of ensuring fault tolerance and robustness. Let's have a look at some of their solutions using Simcenter tools. Fault conditions due to electrical and/or thermal system breakdowns may be simulated using Simcenter MAGNET, including the use of coupled EM-TH analysis capabilities. Mechanical faults such those due to bearing degradation can be analyzed using the Simcenter MAGNET six-DOF motion modeling capability. To protect against short circuits between high-voltage components, electric field stresses may be calculated using the Simcenter MAGNET electric field solver. Simcenter MAGNET 3D demagnetization prediction capability can be used to identify local regions in permanent magnets that are susceptible to demagnetization due to faults from over currents and/or elevated temperature. In general, Simcenter MAGNET may be used to ensure fault-tolerance with respect to most electrical failures.

To model the statistical uncertainties originating from manufacturing and other sources, HEEDS may be used with any of the domain-specific Simcenter tools discussed above. HEEDS may also be used to carry out sensitivity analysis, dimensionality reduction in multi-objective optimization problems, correlation space studies, etc.

Figure 5 shows a 3D Simcenter MAGNET model of a 10-pole 12-slot PM machine, including its demagnetization proximity field prediction. The field values can be used to identify regions that would be susceptible to remanence field weakening that may affect machine performance. These types of results help to safeguard machine performance against faults in the system.

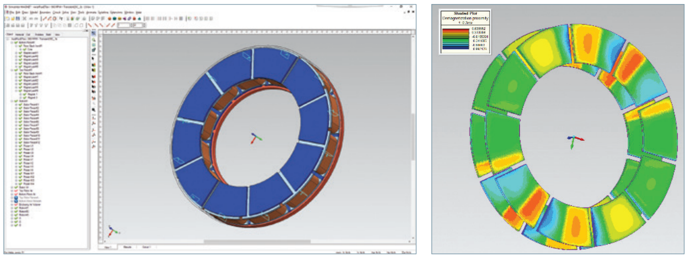


Figure 5. An axial flux PM motor (left) and its demagnetization prediction field at high temperature.

Connectivity and reduced order models

During the final stages of design, once a model has been selected and following the validation of its electromagnetic, thermal and structural characteristics and ensuring its robustness, system-level integration, verification and validation are carried out. At this stage, simulations similar to the initial sizing step are needed to validate the vehicle's performance and optimize the drive train's components. One aspect would be to carry out 1D thermal-system analysis for the vehicle's powertrain cooling loop (motor, inverter and battery). Another important task is to create model representations that may be used for the motor's drive design. This may also require HiL simulation capabilities. What is needed are model representations at various fidelity levels that can be imported from domain-specific design and analysis tools into a system-level simulation tool.

Reduced order models are used to link machine models between domain-specific and system-level software. At later stages of development highly accurate multi-physics-based nonlinear ROMs can be created using Simcenter Motorsolve to link with Simcenter Amesim. In addition, from Simcenter MAGNET, so called very high speed integrated circuit hardware description Language (VHDL) and FPGA-based HIL models can also be created. The VHDL models may be used with a motor drive design software such as XPEDITION™ software for power electronic components design or using other options. If needed, co-simulations may also be carried out between Simcenter MAGNET and XPEDITION or other tools. In summary, Simcenter SPEED, Simcenter Motorsolve and Simcenter MAGNET are designed to generate a comprehensive set of ROMs that can be used to connect to Simcenter Amesim and other products for system-level diagnostics.

Traction machine design: towards integrated design

The discussions above have described a typical traction motor design process. The design tasks, software requirements and their solutions have been presented in the context of a traction motor design V-cycle and the engineering, computational and simulation challenges presented earlier. Although these discussions have focused primarily on electromagnetic design, it should be noted that other design tasks associated with the development of a traction motor such as power electronic drive design, detailed thermal or cooling system design and the mechanical (structural) design, have their own V-cycles.

Traditionally, the design sequence of traction motors has been treated as a disparate and a linear process. However, advances in computational electromagnetics, applying HPC to problems in electromagnetics when coupled with CFD or structural simulation tools, advances in multi-objective optimization algorithms, surrogate or reduced order model development, and most importantly, the connectivity between different tools are challenging contemporary design paradigms.

Design solutions obtained from a disparate approach are decidedly different from those using an integrated approach. For example, if the machine drive design problem is combined with the electromagnetic design of the motor, it has been shown there are clear performance and cost benefits.[13] Another important aspect is to use high-fidelity models during earlier design stages for multi-physics analysis with ROMs and artificial intelligence algorithms. For a synchronous reluctance motor design problem,[14] the electromagnetic, thermal and structural problems have been combined and the benefits of acquiring a superior design has been proven compared to the results of a disparate process.

The tools in Simcenter and their direct and indirect connectivity provide a unique platform that can be used to explore alternatives to traditional design approaches. Simcenter provides the required tools to make these commercially viable.

Conclusion

Figure 6 presents a summary of Simcenter design solutions for traction motors. Siemens' Simcenter simulation tools are being developed with the vision of giving users the ability to implement an optimal, simulation-driven design paradigm of their choice. These tools contain multiple modeling and analysis options at various fidelity levels, can be used to take advantage of high-performance computing capabilities, are open and scalable and contain state-of-the-art technologies for allowing innovation, efficient calculations, robust design, multi-objective optimization, etc. Finally, it maintains the central role Industry 4.0 technologies will play in creating the ultimate comprehensive digital twin for traction motors.

The four core aspects of these tools are 1) frontloading engineering, which allows multiple stakeholders of the design process to be integrated during early stages of design (system level, electromagnetic design and analysis, thermal and structural engineers), 2) generative engineering, which enable users to leverage Simcenter to narrow design choices effectively and rapidly, 3) model-based engineering, which allows much of the design process to be based on simulations rather than physical prototypes that can be expensive and 4) continuous engineering, taking advantage of the latest developments in Industry 4.0 technologies to create the ultimate digital twin for traction motors that can help implement new paradigms for PLM.

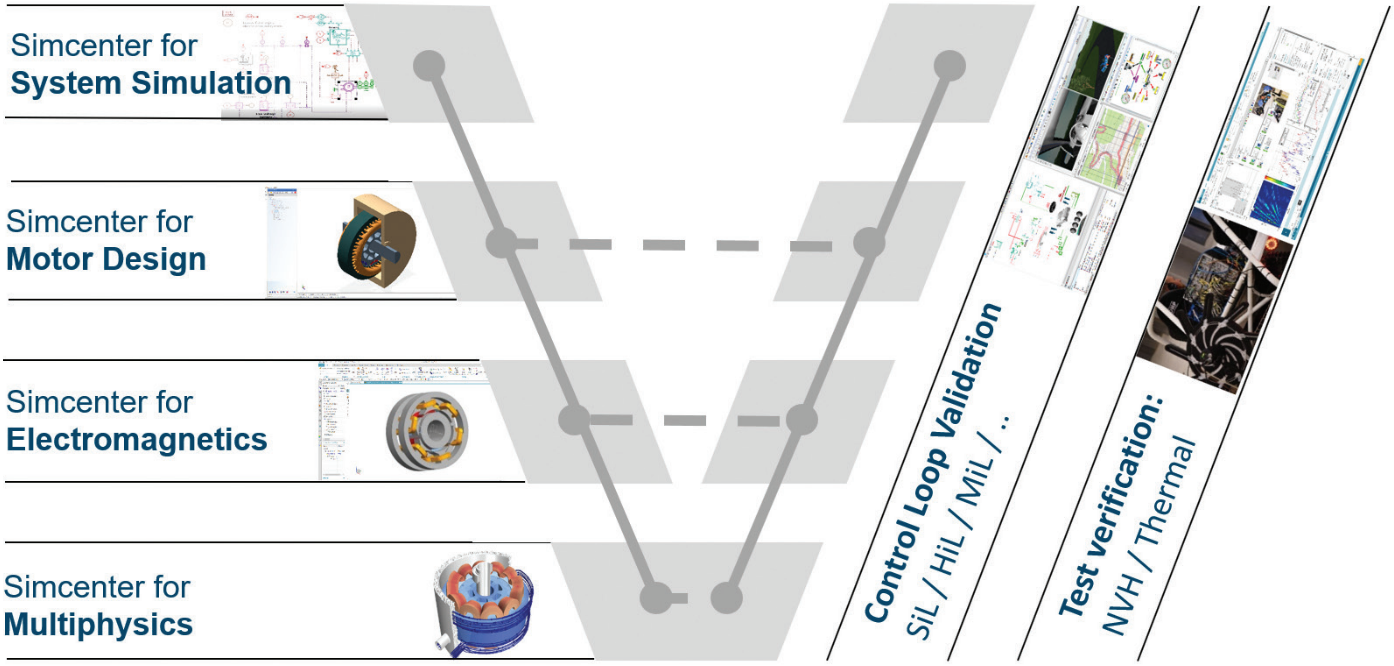


Figure 6. Simcenter traction motor design solution.

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