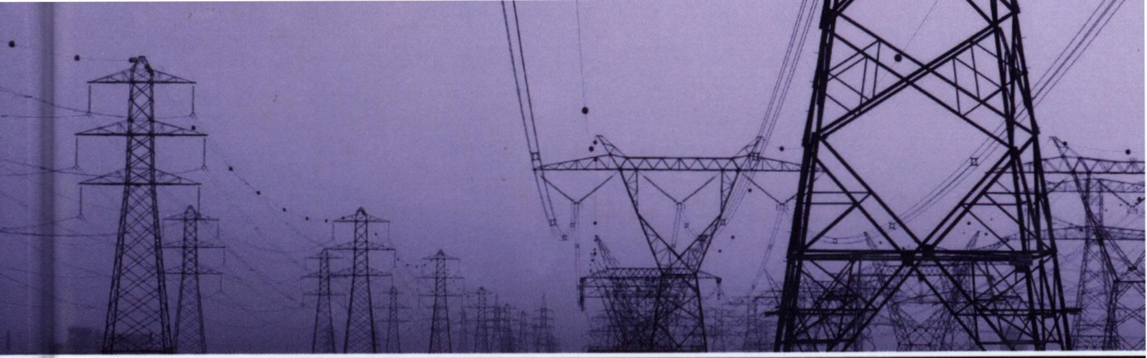
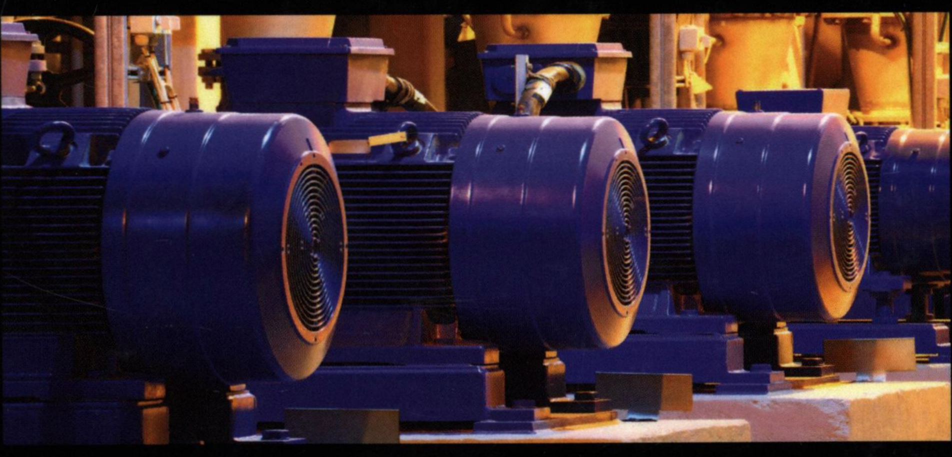


Multiphysics Simulation by Design for Electrical Machines, Power Electronics, and Drives



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Presents applied theory and advanced simulation techniques for electric machines and drives

This book combines the knowledge of experts from both academia and the software industry to present theories of multiphysics simulation by design for electrical machines, power electronics, and drives. The comprehensive design approach described within supports new applications required by technologies sustaining high drive efficiency. The highlighted framework considers the electric machine at the heart of the entire electric drive. The book also emphasizes the simulation by design concept—a concept that frames the entire highlighted design methodology, which is described and illustrated by various advanced simulation technologies.

Multiphysics Simulation by Design for Electrical Machines, Power Electronics, and Drives begins with the basics of electrical machine design and manufacturing tolerances. It also discusses fundamental aspects of the state of the art design process and includes examples from industrial practice. It explains FEM-based analysis techniques for electrical machine design—providing details on how it can be employed in ANSYS Maxwell software. In addition, the book covers advanced magnetic material modeling capabilities employed in numerical computation; thermal analysis; automated optimization for electric machines; and power electronics and drive systems. This valuable resource:

- Delivers the multi-physics know-how based on practical electric machine design methodologies
- Provides an extensive overview of electric machine design optimization and its integration with power electronics and drives
- Incorporates case studies from industrial practice and research and development projects

Multiphysics Simulation by Design for Electrical Machines, Power Electronics, and Drives is an incredibly helpful book for design engineers, application and system engineers, and technical professionals. It will also benefit graduate engineering students with a strong interest in electric machines and drives.

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MULTIPHYSICS SIMULATION BY DESIGN FOR ELECTRICAL MACHINES, POWER ELECTRONICS, AND DRIVES

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PREFACE

ELECTRIC MACHINES are being used in wide and novel applications throughout the world, driven by the need for greater power efficiency in the transportation, aerospace and defense, and industrial automation markets. The automotive sector is driven by the need for hybrid and electric vehicle technology to meet ever-stringent miles-per-gallon standards. The aerospace and defense sectors are focused on replacing existing power transfer technologies in an aircraft such as the central hydraulic system, with fault-tolerant electric power, where major subsystems such as engine starting, primary flight control actuation, pumps, and braking would be controlled and driven electronically. In the US industrial sector, over 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, air compression, and motion control. Globally, 42% of all electricity is used in power industries, where two-thirds of this is consumed by electric motors. There is a clear global demand for a comprehensive design methodology to support these new applications and satisfy power efficiency requirements.

With the present trend of global industrial automation, the application of electric drive systems (including power electronics and drive control) is expected to grow rapidly in the next decade. In the automotive sector, the utilization of power electronics and their control to drive electric motors can significantly contribute to control environmental pollution. In addition, intensive environmentally clean photovoltaic and wind energy resources also show a bright future.

As part of electric drive systems, the power semiconductor devices at the heart of modern power electronics are under continuous development. The improved technology in semiconductor processing, device fabrication, and packaging to produce high-density, high-performance, high-reliability, and high-yielding microelectronic chips, together with new semiconductor material discovery, made possible significant reduction in energy consumption, driving these systems to an incredible economical price.

Without doubt, these achievements force the control strategy techniques to evolve rapidly to the newly created drive conditions and adapt to the overall systems performance requirements. In recent years, soft switching converters became the center of interest when compared with more conventional hard switching converters due to their major advantages such as:

- Minimization of switching loss
- Improved efficiency

- Improved reliability due to soft stress
- Reduced electromagnetic emission

The continuous growing interest in the electric drive area relates to the intelligent power electronics modules, where the power and the control are embedded in the same package and interface directly with logic signals. For variable frequency drives, the converter modules and control are mounted directly on the machine for the low and medium power applications.

READERS' ADVANTAGE

The book is mainly addressed to design engineers, application engineers, technical professionals, and graduate engineering students with a strong interest in electric machines and drives.

The comprehensive design approach described in this book supports new applications required by technologies, sustaining high drive efficiency. The highlighted framework considers the electric machine at the heart of the entire electric drive. The book delivers the multiphysics know-how based on practical electric machine design methodologies. Simulation by design concept elevated in the book constitutes the new paradigm that frames the entire highlighted design methodology, which is described and illustrated by various advanced simulation technologies.

Which Design Problems Are We Trying to Solve?

Throughout this book, we apply knowledge of design best practices into multiphysics and multidomain simulation processes to address a complete electrical machine and drive design.

In the face of global competition, electric machine manufacturers, like manufacturers in most industries, are searching for ways to reduce cost, optimize designs, and deliver them quickly to market. Companies able to achieve these objectives hold a competitive advantage in the marketplace. The ability to predict design performance with simulation software without the time and expense of constructing prototypes plays a significant role in creating this competitive advantage.

Several computation approaches are available to predict electric machine performance, including classical closed-form analytical analysis, lumped parameter models based on the 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 may not be straightforward because it requires the user to understand the differences among the 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 performances.

What Motivated Us to Write This Book?

This collaborative work brought together a group of experts from both academia and software industry with strong expertise on electrical machine design and manufacturing. The main idea that fueled our initiative and commitment to make this project a reality was to bring back to the engineering and academic communities a comprehensive expertise and validated know-how on designing electrical machines by simulation.

Why Simulation by Design?

The advancements in modern digital computers brought CAD (computer-aided design) and CAE (computer-aided engineering) tools at the heart of virtual prototyping, reducing the time to design and market and saving cost by reducing and eliminating the physical prototyping need. The embedded 3D-physics design into drive system coupling with the power electronics and control algorithms enables the electric drive community to accurately predict the efficiency and performance of the electrical machine at the heart of the entire drive system.

Without doubt, the design of a simulation model—a virtual prototype—can help tremendously the engineers to build confidence on validating the required technical specifications making critical decisions on design realization and understanding the level of design complexity considering inter-dependencies and design parameter variations, and collaboratively to examine strategic choices for optimization and robustness.

CHAPTER DESCRIPTION

Chapter 1: Basics of Electrical Machines Design and Manufacturing Tolerances

This chapter discusses fundamental aspects of the state-of-the-art design process and includes examples from industrial practice and case studies to introduce basic concepts and methods. This chapter emphasizes the basic steps in designing a typical electrical machine using power traction application as an example. The chapter starts with magnetic sizing steps and it extends the basic design to thermal constraints. Typical electric motor characteristics used in traction applications such as efficiency map of standardized driving cycles are considered to highlight the electric motor sustainability on dynamic performance. The chapter concludes with the robust design analysis framing a methodology that applies stochastic analysis to study manufacturing tolerances.

Chapter 2: FEM-Based Analysis Techniques for Electrical Machine Design

In this chapter, a detailed description of finite element method (FEM) employed in ANSYS Maxwell software is presented. The numerical technique developed to account for eddy currents in conductive domains on configurations that involve rigid motion is presented, the numerical technique related to multiply connected regions is highlighted, and it also presents the algorithms used for nonlinear iterations and strategies to accelerate the nonlinear convergence. Filed-circuit coupling technology is explained and specific algorithms used to reduce the computation time to reach steady-state conditions are described. High-performance computing (HPC) is a key technology, increasing the capacity of solving large design spaces and reducing significantly the total time computation by solving the time steps on magnetic transient problem simultaneously rather than sequentially. All technologies highlighted in this chapter are explained through sets of case studies.

Chapter 3: Magnetic Material Modeling

This chapter introduces advanced magnetic material modeling capabilities employed in numerical computation. From isotropic nonlinear characteristics to anisotropic behavior corresponding to grain-oriented magnetic materials, the chapter describes the implementation aspects and detailed modeling techniques. Lamination topologies are considered based on special modeling technique with emphasis on core loss computation. Advanced magnetic modeling on vector magnetic hysteresis is presented and specific case studies are used to highlight the computational merits.

Chapter 4: Thermal Problems in Electrical Machines

In this chapter, the heat generation and extraction in electrical motors are investigated. Using the three thermal paths—conduction, convection, and radiation—an electromagnetic device can be cooled within the acceptable limits for the environment and corresponding application. A highly efficient electrical machine is required in most industrial fields, but the high efficiency is not telling us the full story of a good motor performance. The losses—electromagnetic and mechanical—must be dissipated from the machine into the ambient and the mode in which the cooling system manages to do that represents the key in a reliable and high-performance electrical machine. Within the chapter, the theoretical aspects of thermal management are illustrated with a state-of-the-art collection of practical examples for cooling electrical machines published in the literature.

Chapter 5: Automated Optimization for Electric Machines

This chapter discusses optimization as applied to electrical machine design. Some commonly used optimization methods are explained. Case studies illustrating the utility of systematic design optimization to compare different machine topologies, to develop design rules, and to quantify the effect of different design features are included.

Chapter 6: Power Electronics and Drive Systems

This chapter describes the entire drive system from semiconductor as the main component of any modern power electronics circuit to more complex topologies that include active components to rectify the energy, reduce harmonic distortions, and correct power factors in various drive systems. Electrical machines need drive systems to be correctly controlled if they need to be operated at variable speed. This can be achieved by modulating the energy flow to/from them. The chapter also highlights the need of multiphysics studies for such designs to account for thermal analysis under certain cooling conditions. For instance, inverter modules need a careful design approach as losses vary continuously during normal operation. Poor thermal management can lead to overheating and thus degrade the reliability of the components.

FRAMING THE MULTIPHYSICS DESIGN METHODOLOGY

The electric machine is a very complex device, being multidomain by nature involving electromagnetics, thermal, and mechanical aspects. The multiphysics methodology built around the core of electric machine design encompasses a systematic approach to develop a platform where comprehensive analysis is the key to understand and design a complex drive system to predict their performances and analyze their robustness. The multiphysics simulation technology enables users to design, analyze, and deliver efficient, optimized electric machine and drive designs.

As shown in Figure 1, the first step in the overall workflow is to develop design requirements. Those requirements may be created within a particular design organization, or they may be provided from a purchaser of the electric machine. Requirements may include machine speed, output power, input power, torque, efficiency, thermal properties, weight, size, etc. At this stage, motor sizing and model creation take place,

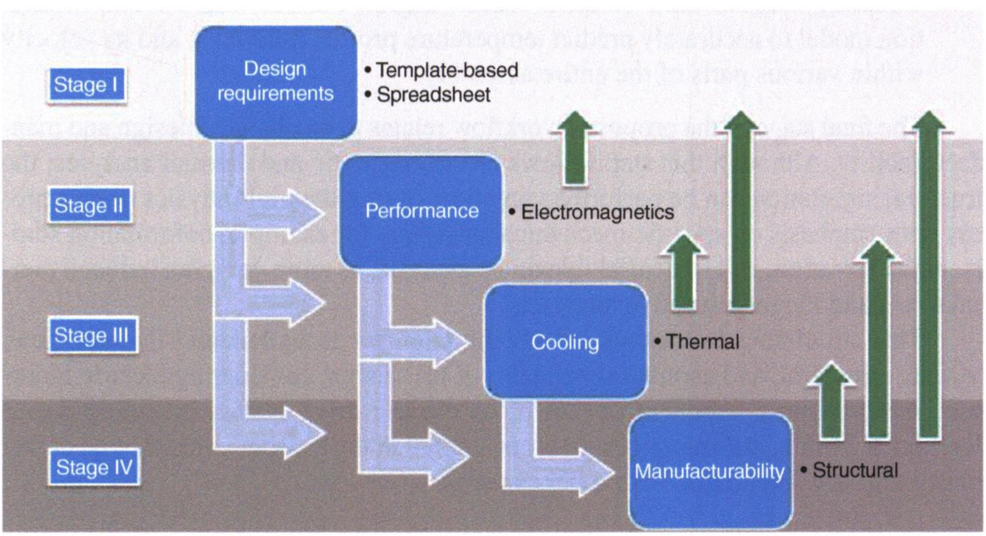

Figure 1 Multiphysics design methodology.

where many motor configurations may be considered. Often, engineers will use classical, closed-form analytical methods to select appropriate motor configurations that will meet requirements. In a similar manner, both magnetic and thermal designs can be evaluated using template-based approaches that are using such closed-form analytical methods. At the end of this stage, the designer acquires knowledge about the most suitable motor topology to fulfill the level of technical specifications with a degree of confidence on practical realization.

At the second stage of the workflow with the set of knowledge already acquired, accurate and detailed motor studies using 2D and 3D finite element analysis are performed. This important step in the design process further qualifies electromagnetically the topologies selected by the magnetothermal sizing analysis. Various design characteristics are numerically evaluated employing cutting-edge techniques, for example, permanent magnet demagnetization due to irreversible temperature effect, power electronics switching loss effect on electric motor core-loss, efficiency and power loss maps.

The thermal study can be developed similar to electromagnetic analysis as a separate design simulation or in connection with electromagnetic solution. With feedback from electromagnetic losses from either template-based solution or finite element analyses, the thermal study can be migrated from simple temperature rise computation based on thermal conduction to more complex studies involving computational fluid dynamics (CFD), where convection and radiation are considered. In such configurations, detailed cooling systems can be evaluated and optimized. Speeding up the entire thermal profile prediction is a key in the overall design process, that provides with design alternatives as,

- Creating an equivalent thermal model (ETM) for motor topology to be used within CFD environment to build around it the physical cooling system configuration with focus on outside enclosure optimization analysis or,
- Coupling detailed finite element-based integrated losses with thermal simulation model to accurately predict temperature profile, fluid flow, and its velocity within various parts of the entire assembly.

The final stage of the proposed workflow relates to mechanical design and manufacturability. Although this step follows electromagnetic and thermal analyses, the structural simulation can be performed any time during the multiphysics design process with emphasis on specific mechanical analyses, for example, deformation studies, noise vibration, and structural dynamics analysis, to more complex induced thermal stress and magnetostrictive analyses.

This simulation framework allows the engineer to understand the electrical, thermal, structural, and acoustical behavior of the design, considering electric motor as an independent component or part of an electric drive system including power electronics. Finally, the motor design is considered in the broader context of its power control unit and integration with other systems.

The flexibility of such a design flow is provided by the data exchange among all physics involved, providing various design adoption alternatives.

The multiphysics design flow can be further detailed at each and every individual stage. In spite of this granularity, the Chapter 1 will focus on Stage I regarding the generic design flow for topology selection during a motor design to examine the process of basic design.

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