Chapter 1
General Survey of Engineering Electromagnetic and Thermal Field Problems

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Abstract A number of key problems in the modeling and application of engineering electromagnetic and thermal fields, involving the advanced material property modeling under complex working conditions, the efficient analysis method and simulation software, and the rigorous examination of the effectiveness and usefulness of large-scale modeling and simulation, are briefly outlined. Based on the industrial background in large power transformers, considering the rapid development of modern transmission and transformation technology and equipment, the major and very challenging research projects, mainly concerned with the modeling and prediction of transformer core loss and stray-field loss, and the multi-physics simulation requirements, for addressing the heating and cooling issues, are highlighted. This chapter provides a short overview of the evolution of modeling and simulation worldwide and stresses that today the simulation of the electromagnetic and thermal fields can be performed with considerable accuracy, even though there are still some important studies that need to continue. Finally, the overall composition of this book is introduced.

Keywords Engineering electromagnetic and thermal field · Numerical modeling and simulation · Digital twin · Material property · Measurement and prediction · Magnetic loss · Stray-field loss · Heating and cooling · Electrical equipment · Power transmission and transformation · Industrial application

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1.1 Overview of Engineering Electromagnetic and Thermal Field Modeling

The analysis, design, manufacture, and operation of electromagnetic devices involve a large number of coupled multi-physics simulations. Engineering electromagnetic field analysis is the basis for studying the problems of loss, heating and cooling, electromagnetic force, vibration and noise, and so on. These performance parameters are closely related to reliable, safe, economical and environmentally friendly operation of electromagnetic devices throughout their life cycle.

It is difficult to analyze the large-scale engineering electromagnetic and thermal fields precisely for reasons including but not limited to the complex mathematical description and the numerical implementation of the coupled multi-physics problems; the modeling and simulation of very large electromagnetic devices, which become quite challenging, because of the existence of many types of multi-scale (or space multi-scale) problems brought about by factors such as the coexistence of large and complex geometric entities (e.g., more than 10 m level) and lamination structures (e.g., silicon steel sheet thickness usually not greater than 0.3 mm), and shallow field penetration depth (e.g., less than 1 mm); the lack of geometric or physical symmetry in the strict sense in the structure of large electromagnetic devices; the measurement and prediction of the characteristics of various materials and components in the solved region varying with external conditions such as excitation (e.g., multiple harmonics, DC bias), stress and temperature.

Looking back on the history of engineering electromagnetic and thermal field research, and its industrial application, in the past it was necessary to make significant simplifications, due to the limitations in the computing resources, when solving these problems. In the early stages of the industrial applications, simulations were performed using the 2D static field [1] solver, and later, the simulations gradually developed into 3D transient nonlinear field solutions. The problems more concerned about in electromagnetic design can be solved by decoupling the actual coupled fields or by implementing the so-called “weak coupling”.

Much of this book is devoted to the problems related to the computation of low-frequency engineering electromagnetic and thermal fields. Based on large power transformers [2, 3], the engineering science problems and the key and generic technologies related to the modeling and application of engineering electromagnetic and thermal problems are deeply investigated herein and mainly include:

(1) The study of engineering-oriented material property modeling, involving the vector electromagnetic properties of magnetic materials [4, 5] and their standardization, and the working properties of materials accounting for the practical operating conditions; and then the establishment of a platform and database for material property measurement and prediction under “standard” and various “non-standard” conditions.

(2) Compelling requirements for research and development of effective analysis methods, with stable convergence, and software for large-scale electromagnetic and thermal field problems that supports deep saturation, strong nonlinearity, anisotropy and time asymmetry (including time multi-scale), the development of efficient and parallel solutions for super-large algebraic equations [6–9], and the improvement of the efficiency of large-scale product-level modeling and simulation [10].

(3) Verification of the effectiveness and usefulness of the electromagnetic and thermal analysis and corresponding computation software, i.e., these methods and software are supposed to provide sufficient, stable, and acceptable accuracy for the solutions to various complex problems and provide stable convergence in large-scale calculations, which needs to be validated with benchmark models, rigorously investigated and tested based on product-level models and actual products, and incorporated into industrial processes [11].

(4) Systematic study of the solutions to the problems related to engineering electromagnetic and thermal fields, in combination with the knowledge and experience of the experts in design, application, and manufacturing, is needed to establish a mature expert system by combining the material modeling, high-performance computation, and effective validation [10, 11].

As well known, it is not easy to make all problems very clear before product design, manufacturing, and even later product renewal. In other words, there will always be some problems to be further completely solved, whether or not the product is already made. Understandably, designers may rely more on the long-term accumulation of design, manufacture, test, and operation aspects when the problems they face are still at the research stage or without adequate technical support; that is, they may rely on “experience” to decide some new schemes and/or conduct costly “destructive” tests of products. In any case, we must always try to overcome those “bottlenecks,” although it needs time and great perseverance.

1.2 New Challenges Posed by UHV Transformer Engineering

The rapidly growing demand of the global power industry and the pressure to save energy, protect the environment, improve the quality of power supply, among others, have challenged the traditional transformer design and manufacture. In the face of the emerging problems, it is essential to strengthen applied basic research and not stick to convention. In the field of modern transformer engineering, a number of new problems related to engineering science and technology need to be solved by promoting in-depth exchanges of ideas in the field, through the academia.

In this respect, J. Turowski took the lead in initiating the advanced research workshop on transformers and held international workshops (in Spain) in 2004 and 2007. The purpose was to provide a forum for scholars from industrial engineering and scientific research communities, all over the world, to exchange ideas on the development of modern transformers, the difficulties and the problems to be solved, and to further discuss issues of common interest, including transformer technology, high-voltage insulation materials, heating and cooling, coupled multi-physics analysis, fault diagnosis, stray loss control [12, 13], and energy saving and reliability of large transformers. J. Turowski's systematic research on the stray-field loss problems and the simplified and fast calculation of the stray losses over the years has attracted the attention of the researchers and designers. Based on years of research findings and accumulation of industrial application experience, he led the development of a 3D reluctance network method (RNM-3D), which has been verified by applying it to industrial problems, as a fast and effective expert approach. A series of improvements have been made through fundamental research and development to the electromagnetic computation program, which has been applied by transformer companies in several countries [14–19].

Since 2009, a series of International Colloquiums "Transformer Research and Asset Management" have been organized and held in Croatia by Z. Stih et al. So far, four (in 2009, 2012, 2014, and 2017, respectively) colloquiums have been held. Representatives from well-known transformer manufacturers, scientific research institutions, and universities have attended the conferences. Three aspects, materials and components, numerical modeling, and transformer life management, were the focus as main topics.

All the international workshops on transformers held in Europe have been actively supported by the CIGRE (International Council on Large Electric Systems) and have also attracted close attention from transformer manufacturers and experts in the field of transformer design, manufacturing technology, and advanced research. Z. Cheng of Baobian Electric (the author of this chapter) participated in the international workshops on transformer research held in Croatia in 2009 and 2012 [20, 21].

The continuous progress of power transformation technology and industry has been witnessed and driven by all of this. It has been a long course since the world's first closed core-type transformer came into being (in 1884, as shown in Fig. 1.1) [3], and so many milestones have been achieved in the voltage classes and single unit's capacity of the power transformers. With the tremendous progress of the global transformer manufacturing industry, the transformer manufacturing industry in China has shown sound development momentum. Having been tested through technological development and system operation over the time, all the key technologies of power transformers with voltage levels of 500 kV and above, including the design, manufacture, test and installation, operation, and maintenance, have matured and have accumulated much experience. Moreover, the domestic transformer design and manufacturing experience have been enriched through cooperation with overseas partners. A series of flagship products created by transformer manufacturers in China have broken one record after another.

The ODFPS-1000MVA/1000 kV UHV (ultra-high voltage) AC transformer with the world's highest voltage level and maximum capacity of a single unit was developed in Baobian Electric., China (in July 2008), and successfully passed all

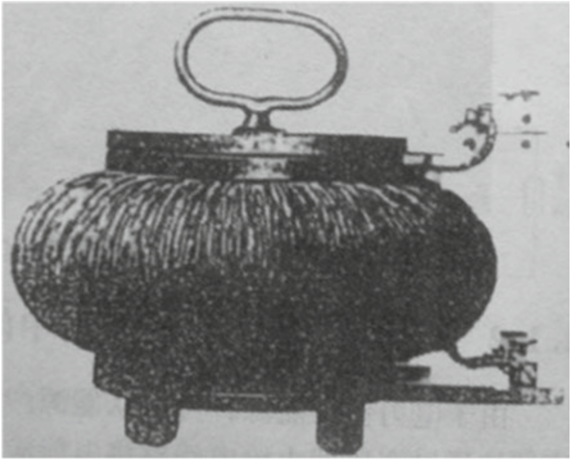

Fig. 1.1 First closed core transformer (1884, Ganz)

specified tests. It was also developed for the world's first commercial UHV project, the 1000 kV Jindongnan-Nanyang-Jingmen UHV AC Test and Demonstration Project, as shown in Fig. 1.2a. The UHV transformer mainly includes an auto-transformer body, a voltage regulator, and a low-voltage compensator, with advanced technology and rational structure. The transformer has excellent electrical, mechanical and thermal performances, and its key indicators such as insulation tolerance, partial discharge, temperature rise and noise, all reach the level of excellence at the international level for transformer products, making it the flagship product of UHV transformers. Compared with 500 kV transmission lines, UHV lines have the advantages of high transmission power, low power loss, small floor area, and low comprehensive cost. With the development of UHV grid in China, problems such as insufficient transmission capacity of existing 500 kV grid can be solved, the transmission efficiency can be improved, and the investment cost and environmental pressure can be reduced.

The major transformer manufacturers in China have all kinds of excellent production and test facilities at the international level, as well as the design, manufacture, and test technologies for the AC transformers with a voltage of up to 1000 kV and a single capacity of 1000 MVA, the converter transformers and reactors with DC ± 800 kV (as shown in Fig. 1.2b) and above, and technologies for nuclear power transformers, large shell-type transformers, various special transformers, dry-type transformers, amorphous alloy transformers and distribution transformers, among others. This is recognized worldwide.

It should be noted that even if the milestone products such as 1000 kV/ 1000 MVA AC and ± 800 kV DC (even up to ± 1100 kV DC) transformers have been produced and put into operation, some deep-seated engineering science and key technical issues still remain and need to be further studied and face a series of new challenges from the UHV transformer engineering, including stricter requirements for energy saving and consumption reduction, economic, and

(a) 1000 MVA/1000 kV UHVAC transformer (2008)

(b) ±800 kV UHVDC Converter Transformer (2009)

Fig. 1.2 UHVAC/DC transformers (Baobian Electric., Baoding) environmentally friendly operation, and improvement in reliability, among other important projects. A forward-looking transformer manufacturer would see itself clearly, paying close attention to the progress of transformer research in the world, actively invest in manpower and R & D resources, and focus on core technology issues and work on a down-to-earth basis.

1.3 Some Key Research Projects

It is believed that under the new situation where the power system is highly developed, the key projects related to electromagnetic and thermal modeling of power transformers that need to be further studied mainly include, but are not limited to, the followings.

1.3.1 Accurate Analysis of Total Core Loss

The analysis of the electromagnetic and thermal fields in the transformer core is very complicated, in which the nonlinearity, anisotropy, 3D non-uniform distribution of alternating and rotating flux, over-excitation, harmonic and DC bias effects may be involved.

(1) The alternating flux in the transformer core limb and yoke, and the losses caused thereby, wherein problems related to the 3D large multi-scale and non-uniform electromagnetic and thermal fields are involved;

(2) The rotating flux at the T-joint of the iron core and the resulting loss density concentration caused thereby. It is reported that in large transformers, huge economic losses have been brought about by overheating caused by the excessive loss density at the joints of the core, which leads to the return of large products to the factory for processing. The complex flux distribution at the joint of the iron core, coupled with the 3D distribution of flux passing through the air gap in the joint, has brought difficulties to material modeling and accurate analysis of the electromagnetic field.

In addition, the determination of the exciting power at the joint of different core materials and joint types of lamination, and at the limb and yoke, as well as the separation of the total exciting power at different positions is also complex and worthy of attention.

(3) Additional core loss caused by the leakage magnetic flux of transformer windings, entering the core (particularly the component of leakage flux perpendicular to the core lamination). The iron core of the power transformer is formed by a stack of laminated sheets of different widths in a given inscribed

circle. The lamination with the smallest width (in multi-stage laminated core) is called the “outermost core lamination” in transformer engineering. The eddy current losses induced in the outermost core lamination, due to the perpendicular component of the leakage flux, cannot be ignored. Moreover, such loss is different from the “standard” iron loss measured by the standard method and can be called additional iron loss, which probably results in excessive concentration of loss density. Notice that this loss is also called “surprising loss” in reference [12]. As an effective response in transformer design, such core lamination is divided into “narrow strips” in the longitudinal direction to reduce eddy current loss. See Chap. 13 of this book for more detail.

A custom software tool for the design and calculation of the outermost core lamination (other layers closely adjacent thereto may also be considered) and the core tie-plate adjacent thereto needs to be developed to calculate the loss and the temperature rise of the components [22, 23]. The precise analysis of the rotational power loss caused by the rotating flux at the T-joint is a tough job and requires extensive experience in product design and testing. Designers are required to be experienced in dealing with rotational power losses for different capacities, core structures and joint types (e.g., multi-step lap joint). The core loss is often multiplied by a “loss factor” (or building factor) in design and calculation to give an overall consideration.

Experience in design and manufacture indicates that the advantage of high-quality silicon steel sheet is actually weakened when the ratio of the zone affected by rotating flux of core to the total volume of the total magnetic circuit is relatively large.

(4) In the construction process of UHV AC and DC power transmission project, multi-harmonic, DC bias, no-load and load over-excitation are found in large transformers. Therefore, manufacturers are required, by the power system, to promise that their products could withstand the specified level of over-excitation and DC bias. Therefore, the accurate measurement and prediction of electromagnetic properties of iron core under complex operating conditions (e.g., harmonic and DC bias excitation), including core loss, exciting power, magnetization, magnetostriction, etc., are required to further investigate the electromagnetic, thermal, mechanical and acoustic (vibration and noise) behaviors of the device under the above conditions, so as to formulate the corresponding standards for tolerance. Chapter 15 of this book shows the DC-biased transformer modeling in some detail.

On the other hand, it should be noted that significant progress has been made in silicon steel manufacturing technology and very low loss, very high magnetic induction, and low noise products. This also puts forward higher requirements for the design, modeling, and simulation of major equipment and the property modeling and selection of new materials.

1.3.2 *Efficient Solution of Transformer Winding Loss*

The total loss of transformer windings, as usually considered in electromagnetic design, includes several loss components: (1) the resistive loss, and it is the major part of the total winding loss and even the load loss; (2) the eddy current loss in conducting wires of the windings, caused by 3D leakage flux, and it is dependent on both the wire's size and the electromagnetic field distribution; (3) the circulating current loss generated in parallel wires of transformer winding, due to the non-uniform leakage flux linked with closed parallel wires of the windings, although the transposition technology for such parallel wire structure has been widely applied in transformer winding design and manufacture.

In order to model and predict the winding's losses, probably taking account of the effect of the heavy current leads, some specialized calculation method and design-oriented programs have been developed by designers and application engineers based on long-term design and application experience. Refer to Chap. 5 of this book for a script used for winding's performance analysis.

However, it is still challenging to accurately compute the total loss of transformer winding in the cases of very complex windings' structure and/or non-sinusoidal excitation conditions (e.g., including harmonic and/or DC bias). Moreover, in the related modeling and simulation of coupled electromagnetic and thermal fields, the effect of the non-uniform temperature on electromagnetic properties (e.g., conductivity or permeability) of all the related material and components should be taken into account.

1.3.3 *Modeling and Control of Stray-Field Loss in Structural Parts*

In addition to the losses in the windings, the stray-field losses in structural parts, mainly distributed in the transformer oil tank and various solid and laminated components (using magnetic or non-magnetic materials), including core tie-plates, clamps, and different kinds of shields, etc., are a problem that needs special attention and an in-depth study. The study of stray-field loss is of great significance to energy conservation and consumption reduction, avoidance of possible hazardous local overheating, and the improvement of operational reliability [11, 12].

To reduce the loss, first of all, the distribution of the loss, the key factors affecting the loss distribution and the effective measures to control the loss, should be ascertained. Some of the structural designs adopted in the project have gone through a lot of twists and turns from being conceived, tested, and improved to being optimized into a mature design and are not so easy to be quantitatively analyzed and evaluated, involving the large-scale complicated structures, the working properties of materials and components, the 3D multi-scale modeling and simulation, and the effective prediction of electromagnetic and thermal behavior.

In order to reduce the stray-field loss in structural components, for instance, the designers' efforts include as follows: 1. Non-magnetic steel is locally used in the oil tank of ordinary magnetic steel, i.e., to form a hybrid steel structure, to reduce loss, and to avoid hazardous local overheating; a natural question would be under what circumstances does non-magnetic steel need to be used and how can it be determined, and how to correctly evaluate the general effect of the hybrid structure composed of magnetic and non-magnetic steels; 2. the principle of material (magnetic steel and non-magnetic steel) selection and the structural design of the transformer core components (including core tie-plates and clamps) is determined; 3. the optimized design of magnetic and electromagnetic shields, the stray-field loss control, and the related application research on various effective measures for reducing the total loss and the local loss density must be carried out.

Note that the testing electromagnetic analysis methods (TEAM) benchmark problem 21 (3D stray-field loss model: Benchmark Family, available at www.compumag.org/team) has been well-established by the authors to study and validate the modeling and simulation available of the stray-field losses in transformer components. See the Chap. 12 of this book for more detail.

1.3.4 Numerical Prediction and Measurement of Electromagnetic and Thermal Fields

The heating and cooling in transformer engineering is a complex coupled multi-physics problem, involving 3D electromagnetic, thermal and oil flow fields, even considering the forced oil flow in large oil-immersed type transformers. The temperature distribution and local overheating, particularly the hot-point temperature rise, are still common concerns for manufacturers and the power system. It is considered a knotty issue in both experimental study and design calculation, as so many factors could affect the accuracy of the result, such as the deviation of 3D multi-field coupled modeling, the inaccuracy and incompleteness of the integrated performance parameters of materials, and the empirical formulae adopted, which often cannot meet the design requirements.

As mentioned above, the solution to the above problems is closely related to material property modeling. Establishing a property database for materials (and components consisting of such materials) operating under standard or possible working conditions to meet the needs of industrial applications is, therefore, a key topic.

In addition to these key projects that must be studied in-depth, the following practical problems or needs that may arise should be fully taken into account, such as: The post-processing of the general commercial software cannot meet the special but important needs of users; the software is not adapted to complete property data support provided by advanced material modeling; computational efficiency is not satisfactory, or application engineers cannot develop "customized scripts" according to certain necessary requirements based on the field calculation results of some commercial software (see Chap. 5 of this book for the development of script in some detail). The dilemma of high computational cost needs to be solved, and both the convergence and stability in large-scale calculation should be improved.

Note that Chap. 14 of this book demonstrates the electromagnetic and thermal modeling based on large power transformers, and furthermore, a typical heating and cooling model used for transformer engineering is well-established by the authors in Chap. 16 of this book, to facilitate the study of effective modeling and simulation for transformer heating and cooling.

1.4 Realization of Accurate Modeling and Simulation of Electromagnetic and Thermal Performance

The comprehensive performance analysis of the electromagnetic device has come a long way since the very beginning. Looking back, in the early days of computer application (more than 40 years ago), the author of this chapter and his colleagues did not have their own computers and rented computers from other units. Moreover, limited to the IO technology back then, the program input required paper tape; i.e., the program and the data had to be "punched" on the paper tape in advance, and the source program tape had to be manually modified. Figure 1.3 shows the punch machine used by the author in the 1970s and the manual tool used to modify the

(a) Puncher for making paper-tape program (b) Hand tool for modifying paper-tape program

Fig. 1.3 Old tools used for making and modifying paper tape program (the 1970s)

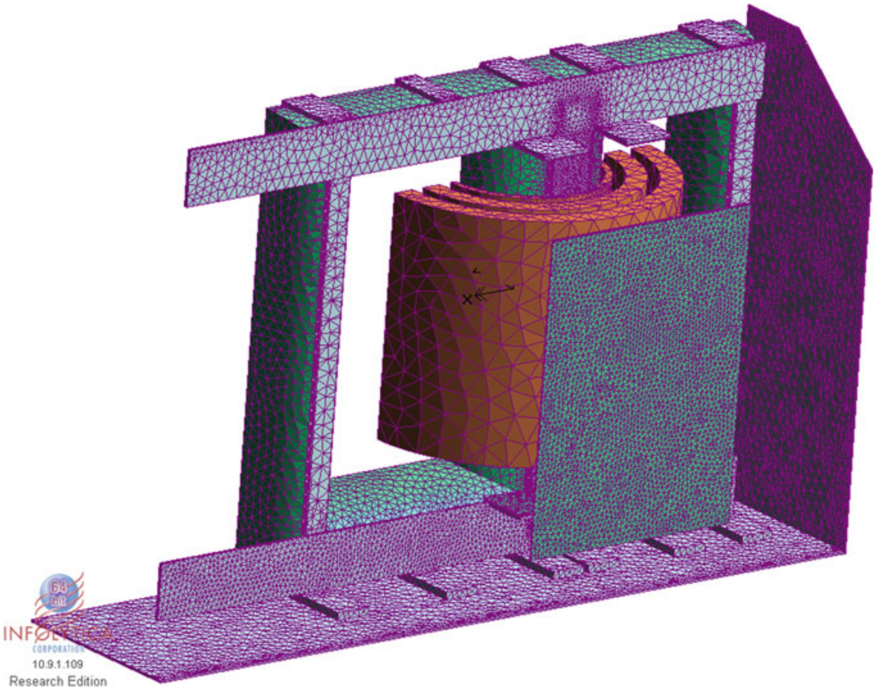

Fig. 1.4 3D finite element calculation model of typical transformer (by Simcenter MAGNET)

program (can be called as punch board). It must be hard to imagine the difficulty of manually modifying a program statement. Over time, the round holes in the steel punch board had been polished into oval shape. It was a witness of hard work of the application engineers in the "primitive days" of the computational electromagnetics (CEM). These pictures, like the first closed core transformer in 1884 to today's UHV transformers, hopefully, will inspire future generations to stay forward in the research and development process.

Fortunately, with the rapid development of power transmission and transformation systems and related manufacturing industries, it has become increasingly necessary to solve the problems using large-scale 3D coupled multi-physics simulation systems. As the theoretical basis for solving the thermal, mechanical and acoustic (vibration and noise) problems of electromagnetic devices, the research and industrial applications of international computational electromagnetics have made great progress [24]. Today, the 3D finite element model established in Fig. 1.4 (using Simcenter MAGNET) along with the corresponding electromagnetic and thermal modeling and simulation has become an ordinary application example.

As the two top international conferences held alternately, Compumag and IEEE CEFC have played an irreplaceable leading role in the sustainable development of computational electromagnetics. It is noted that the plenary speech (title:

Some Key Developments in Computational Electromagnetics and their Attribution) given by C. W. Trowbridge and J. K. Sykulski at the Compumag 2005, China, can be regarded as a historical overview on international computational electromagnetics. In the speech, the milestones in the field up to the turn of the century were reviewed, and the remarkable contributions of many pioneers were cited [25]; those outstanding achievements include:

- Delaunay meshing
- Kelvin transformation
- Automatic "cutting" of multiply connected regions
- Incomplete Cholesky conjugate gradient method (ICCG)
- 'Edge elements' and differential forms
- Dual energy methods
- Material modeling
- Forces
- Motion
- Fast multipole
- Transmission-line matrix (TLM) method
- Finite-difference time-domain method (FD-TD)
- Finite integration.

As well known, the analysis and design of electromagnetic devices are the two key links. The purpose of analysis is to model and predict the comprehensive performance of electromagnetic devices and key structures. Only the hot-spot temperature rise prediction [11, 17] in large transformers, which endangers the product safety and reliability service, is taken as an example here. It is still a problem to be solved for both numerical modeling and experimental study and involves the engineering effectiveness and feasibility of correctly handling the coupling of multiple electromagnetic fields, temperature fields, and fluid fields. It also involves reasonable simplification of practical engineering electromagnetic and thermal field problems, material property modeling under operating conditions, 3D finite element mesh generation, efficient solutions [26], improving the calculation efficiency and accuracy of large and complex engineering electromagnetic and thermal field problems [10], and scripting for special engineering needs.

In order to effectively reduce the computation cost of large and complex electromagnetic and thermal field problems, a series of efficient algorithms have been proposed and implemented, such as the homogenization models of the laminated core [6, 7, 26–28], the sub-region perturbation finite element method [29], the domain decomposition method [30], and the element by element parallel finite element method [31–34], which significantly improve the efficiency in solving large multi-scale complex problems.

By now, the accurate modeling and prediction of the comprehensive performance of large electromagnetic devices are no longer a dream, thanks to the rapid improvement of computer technology and high-performance computing capability, the construction of virtual numerical laboratory, the development of cloud computing, the multi-physical field coupling technology, and the maturing commercial software. As David Lowther pointed out that, in his plenary speech entitled "The Design of Electromagnetic Devices: From Simulation to Reality" at Compumag 2017, Korea, the simulation of the physics system can now be performed with considerable accuracy, the performance predicted often deviates from that measured on the actual physical device. This is due to the uncertainties involved in the input data to the system such as the material properties, the physical dimensions, the operating conditions.

The accurate modeling and prediction of the performance of electromagnetic devices, as "digital twins" of the physical devices, can be fully realized, so as to finally reach the design target. Certainly, it is needed to further study and solve the key problems that lead to the deviations encountered in modeling and simulation, in order to confidently construct and verify the validity of the digital twin.

1.5 Overall Composition of the Book

This book is primarily written to study the engineering electromagnetic and thermal modeling and related issues in the industrial application. Based on the large power transformers, the book brings together the major engineering scientific research achievements made through the long-term cooperation among the R&D teams of researchers from China, Japan, Canada, and Germany (Hebei Key Laboratory of Electromagnetic and Structural Performance of Power Transmission and Transformation Equipment, Baobian Electric; State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology; North China Electric Power University, China; Okayama University, Japan; Mentor Infolytica, a Siemens Business, Canada; IEC Tech Committee (Magnetic Alloys and Steels), Germany), including the recent important contributions created by the joint team in material modeling [35–38], electromagnetic calculation methods [39–43], benchmarking-based validation [44–47], and industrial application [48–51].

It consists of five parts. The main contents of each part are as follows: (1) An overview of engineering electromagnetic and thermal field modeling, the new challenges arising from UHV transformer engineering with the rapid development of manufacturing industry, the modeling and simulation under complex operating conditions, and the foundation of finite element method; (2) a number of key problems in modeling and simulation of engineering electromagnetic and thermal fields, including the engineering-oriented coupled electromagnetic and thermal field solutions, customized API-based script development, and the harmonic balance finite element method (HBFEM) and its application; (3) the foundation of the magnetic materials' property modeling, the experimental study on the anisotropy of silicon steel sheet and the performance of square and ring iron cores of product level for engineering-oriented requirements, the measurement and modeling of rotational magnetic properties, and the magnetic measurement and prediction of materials and components under complex operating conditions; (4) the establishment and development of the Benchmark Family (P21), the determination of the additional core loss caused by 3D leakage flux in the GO silicon steel laminations, the validation of engineering effectiveness of analysis method; (5) industrial application, including electromagnetic and thermal modeling based on large power transformers, the engineering-oriented investigation of DC-biased transformer, and modeling and validation of thermal fluid field of transformer winding based on a well-designed heating and cooling model.

In this book, the close combination of advanced and efficient numerical analysis methods with reliable and accurate material's working property modeling and the rigorous validation of effectiveness of modeling and simulation is strongly emphasized in response to the growing demand of engineering science research and industry development.

In addition, the basic formulation and numerical implementation based on different potential sets, the well-established magnetic measurement and benchmarking system, the application research based on product-level model or large power transformer, and the valuable experimental and computational results are presented in detail and in a way that is easy to understand.

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