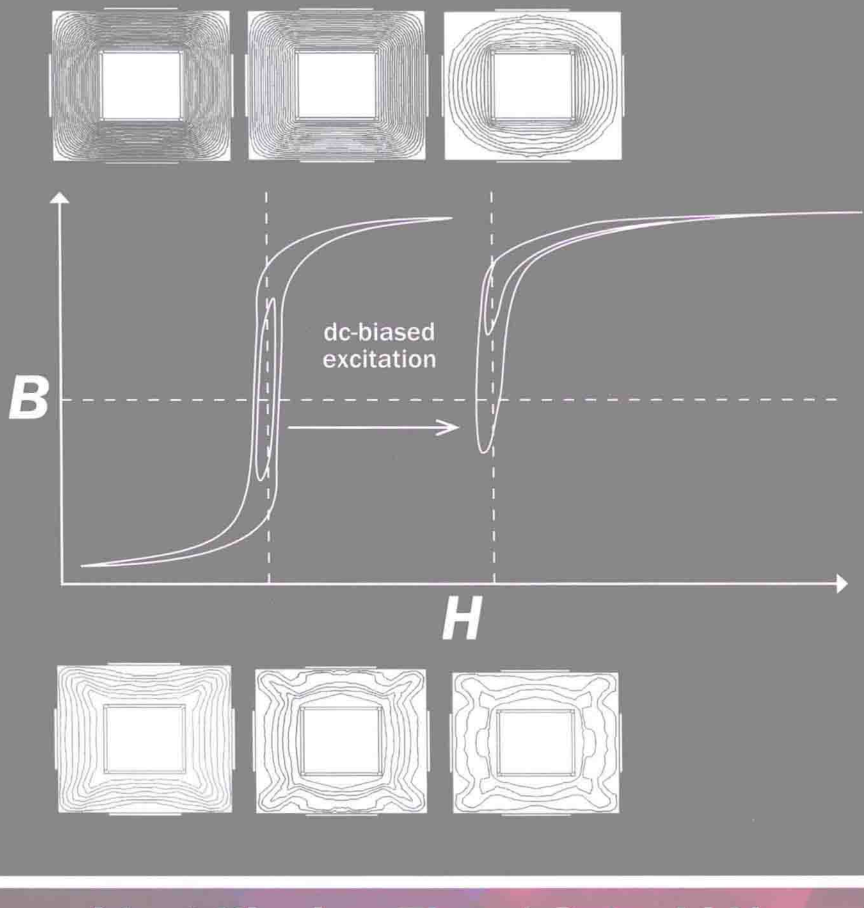
Harmonic Balance Finite Element Method

Applications in Nonlinear Electromagnetics and Power Systems



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HARMONIC BALANCE FINITE ELEMENT METHOD

This book is dedicated to my wife Michelle, without her support I would never complete this book, and in memory to my parents.

– Junwei Lu

This book is dedicated to my wife Weichun Cui, since she has helped me a lot during the writing of this book. I also would like to express my gratitude to my beloved parents, who have always supported me.

– Xiaojun Zhao

Preface

In writing this book on the *Harmonic Balance Finite Element Method (HBFEM): Applications in Nonlinear Electromagnetics and Power Systems*, two major objectives were borne in my mind. Firstly, the book intends to teach postgraduate students and design engineers how to define quasi-static nonlinear electromagnetic (EM) field and harmonic problems, build EM simulation models, and solve EM problems by using the HBFEM. Secondly, this book will delve into a field of challenging innovations pertinent to a large readership, ranging from students and academics to engineers and seasoned professionals.

The art of HBFEM is to use Computational Electromagnetics (CEMs) with harmonic balance theories, and CEM technologies (with IEEE Standard 1597.1 and IEEE Standard 1597.2) to analyze or investigate nonlinear EM field and harmonic problems in electrical and electronic engineering and electrical power systems. CEM technologies have been significantly developed in the last three decades, and many commercially available software packages are widely used by students, academics and professional engineers for research and product design. However, it takes untrained engineers or users several months to understand how to use those packages properly, due to a lack of knowledge on CEMs and EM modeling, and computer simulation techniques. This is particularly true for the harmonic analysis technique, which has not been fully presented in any CEM textbook or used in any commercially available packages. Although a number of CEM-related books are available, these books are normally written for experts rather than students and design engineers. Some of these books only cover one or a few areas of CEMs, and many common CEM techniques and real-world harmonic problems are not introduced. This book attempts to combine the fundamental elements of nonlinear EM, harmonic balance theories, CEM techniques and HBFEM approaches, rather than providing a comprehensive treatment of each area.

This book covers broad areas of harmonic problems in electrical and electronic engineering and power systems, and includes the basic concepts of CEMs, nonlinear EM field and harmonic problems, IEEE Standards 1597.1 and 1597.2, and various numerical analysis methods. In particular, it covers some of the methods that are very useful in solving harmonic-related problems – such as the HBFEM – that are not mentioned in any other numerical calculation books or commercial software packages. In relation to computational technology, this book introduces high-performance parallel computation, cloud computing, and visualization techniques. It covers application problems from component level to system level, from low-frequency to high-frequency, and from electronics to power systems.

This book is divided into six chapters and three appendices. Chapter 1 provides a short introduction to the HBFEM used for solving various harmonic problems in nonlinear electromagnetic field and power systems. This chapter will also discuss definitions of CEM techniques and the various methods used for nonlinear EM problem solving. It also describes high-performance computation, visualization and optimization techniques for EMs, and CEM standards and validation (IEEE Standard 1597.1 and IEEE Standard 1597.2, 2010).

Chapter 2 highlights some fundamental EM theory used in nonlinear EM fields, harmonic problems in transformer power supplies, DC-biased phenomenon in High Voltage Direct Current (HVDC) power transformers, harmonic problems in geomagnetic disturbances (GMDS), geomagnetic induced current (GIC), harmonic problems in distributed energy resource (DER) systems and microgrids, and future smart grids with electric vehicles (EV) and vehicle to grid (V2G).

Chapter 3 covers: the fundamental theory of harmonic balance methods used in nonlinear circuit problems; CEM for nonlinear EM field and harmonic problems; basic concepts of HBFEM used in nonlinear magnetic field analysis; HBFEM for electric circuits and magnetic field coupled problems; HBFEM for three-phase electric circuits coupled with magnetic field; and HBFEM for DC-biased HVDC power transformers.

Chapter 4 investigates HBFEM and its applications in nonlinear magnetic fields and harmonic problems. Several case study problems are presented, such as: HBFEM for a nonlinear magnetic field with current driven (inductor and single phase transformer); HBFEM for a nonlinear magnetic field with voltage-driven (switch mode power supply transformer); three-phase magnetic tripler transformer (electric circuit and magnetic field coupled problems); three-phase high speed motor based on frequency tripler using HBFEM; DC-biased 3D asymmetrical magnetic structure transformer using HBFEM.

Chapter 5 is devoted to the advanced numerical approaches of HBFEM. These include: the decomposed algorithm of HBFEM; HBFEM with a fixed-point technique; hysteresis model based on a neural network and consuming function; and analysis of hysteretic characteristics under sinusoidal and DC bias excitation, parallel computing techniques for multi-frequency domain problem.

Chapter 6 discusses: three-phase power supply transformer model; magnetically controlled shunt reactors (MCSR); computation taking account of hysteresis effects based on fixed-point reluctance; harmonics analysis in HVDC transformers (three phase model) with geo-magnetics and geomagnetic induced current (GIC); HBFEM used for low-voltage network transformers in renewable energy and microgrid grid systems with distributed energy resource (DER); and electric vehicle (EV) charging systems and vehicle to grid (V2G).

There are three appendices included in this book: MATLAB Program 1 (magnetic circuit analysis of a single phase transformer) and MATLAB Program 2 (main program for 2D magnetic field analysis in current driven); and Fortran program 3 (3D Asymmetrical magnetic structure transformer using HBFEM).

Junwei Lu

About the Companion Website

Don't forget to visit the companion website for this book:

www.wiley.com/go/lu/HBFEM

There you will find valuable material designed to enhance your learning, including:

- HBFEM program codes
- Explanations

Scan this QR code to visit the companion website

Contents

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Introduction to Harmonic Balance Finite Element Method (HBFEM)

1.1 Harmonic Problems in Power Systems

The harmonics problem in power systems is not a new problem. It has existed since the early 1900s – as long as AC power itself has been available. The earliest harmonic distortion issues were associated with third harmonic currents produced by saturated iron in machines and transformers, or so-called ferromagnetic loads. Later, arcing loads, like lighting and electric arc furnaces, were also shown to produce harmonic distortion. The final type, electronic loads, burst onto the power scene in the 1970s and 1980s, and has represented the fastest growing category ever since [1].

Since power system harmonic distortion is mainly caused by non-linear loads and power electronics used in the electrical power system [2, 3], the presence of non-linear loads and the increasing number of distributed generation power systems in electrical grids contributes to changing the characteristics of voltage and current waveforms in power systems (which differ from pure sinusoidal constant amplitude signals). The impact of non-linear loads and power electronics used in electrical power systems has been increasing during the last decade.

Such electrical loads, which introduce non-sinusoidal current consumption patterns (current harmonics), can be found in power electronics [4], such as: DC/AC inverters; switch mode power supplies; rectification front-ends in motor drives; electronic ballasts for discharge lamps; personal computers or electrical appliances; high-voltage DC (HVDC) power systems; impulse transformers; magnetic induction devices; and various

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electric machines. In addition, the harmonics can be generated in distributed renewable energy systems, geomagnetic disturbances (GMDs) and geomagnetic induced currents (GICs) [5, 6].

Harmonics in power systems means the existence of signals, superimposed on the fundamental signal, whose frequencies are integer numbers of the fundamental frequency. The presence of harmonics in the voltage or current waveform leads to a distorted signal for the voltage or current, and the signal becomes non-sinusoidal. Thus, the study of power system harmonics is an important subject for electrical engineers. Electricity supply authorities normally abrogate responsibility on harmonic matters by introducing standards or recommendations for the limitation of voltage harmonic levels at the points of common coupling between consumers.

1.1.1 Harmonic Phenomena in Power Systems

A better understanding of power system harmonic phenomena can be achieved by consideration of some fundamental concepts, especially the nature of non-linear loads, and the interaction of harmonic currents and voltages within the power system. By definition, harmonic (or non-linear) loads are those devices that naturally produce a non-sinusoidal current when energized by a sinusoidal voltage source. As shown in Figure 1.1, each "waveform" represents the variation in instantaneous current over time for two different loads each energized from a sinusoidal voltage source. This pattern is repeated continuously, as long as the device is energized, creating a set of largely-identical waveforms that adhere to a common time period. Both current waveforms were produced by turning on some type of load device. In the case of the current on the left, this device was probably an electric motor or resistance heater. The current on the right could have been produced by an electronic variable-speed drive, for example. The devices could be single- or three-phase, but only one phase current waveform is shown for illustration. The other phases would be similar.

A French mathematician, Jean Fourier, discovered a special characteristic of periodic waveforms in the early 19th century. The method describing the non-sinusoidal

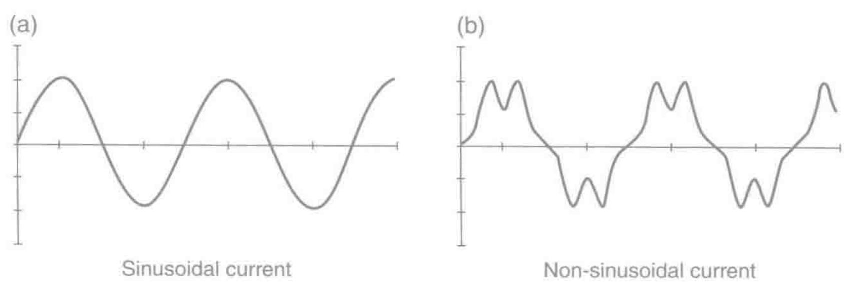

Figure 1.1 (a) Sine wave. (b) Distorted waveform or non-sinusoidal

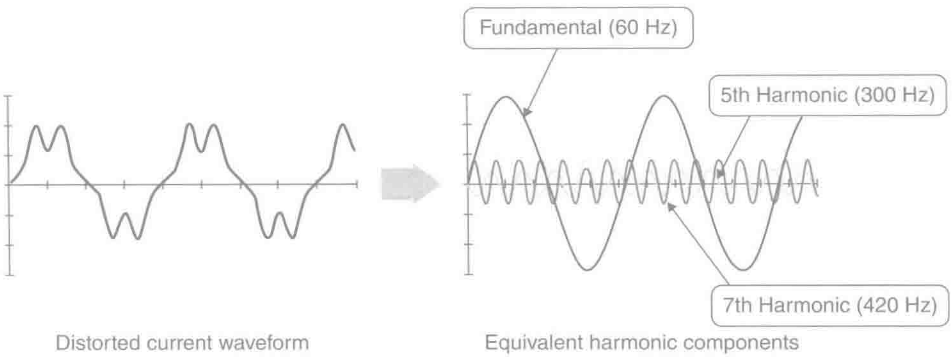

Figure 1.2 Distorted waveform and number of harmonics by Fourier series

waveform is called its Fourier Series. The Fourier theorem breaks down a periodic wave into its component frequencies. Periodic waveforms are those waveforms comprised of identical values that repeat in the same time interval, as shown in Figure 1.2. Fourier discovered that periodic waveforms can be represented by a series of sinusoids summed together. The frequency of these sinusoids is an integer multiple of the frequency represented by the fundamental periodic waveform.

The distorted (non-linear) waveform, however, deserves further scrutiny. This waveform meets the continuous, periodic requirement established by Fourier. It can be described, therefore, by a series of sinusoids. This example waveform is represented by only three harmonic components, but some real-world waveforms (square wave, for example) require hundreds of sinusoidal components to describe them fully. The magnitude of these sinusoids decreases with increasing frequency, often allowing the power engineer to ignore the effect of components above the 50th harmonic.

1.1.2 Sources and Problems of Harmonics in Power Systems

Harmonic sources generated in power systems can be divided into two categories: established and known; and new and future. Table 1.1 presents sources and problems of harmonics. Harmonic problems in power systems can be traced to a number of factors [3], such as: (a) the substantial increase of non-linear loads resulting from new technologies such as silicon-controlled rectifiers (SCRs), power transistors, and microprocessor controls, which create load-generated harmonics throughout the system; and (b) a change in equipment design philosophy.

In the past, equipment designs tended to be under-rated or over-designed. Nowadays, in order to be competitive, power devices and equipment are more critically designed and, in the case of iron-core devices, their operating points are more focused on non-linear regions. Operation in these regions results in a sharp rise in harmonics.