Contents

Preface xii
About the Companion Website xv

1 Introduction to Harmonic Balance Finite Element Method (HBFEM) 1
  1.1 Harmonic Problems in Power Systems 1
     1.1.1 Harmonic Phenomena in Power Systems 2
     1.1.2 Sources and Problems of Harmonics in Power Systems 3
     1.1.3 Total Harmonic Distortion (THD) 4
  1.2 Definitions of Computational Electromagnetics and IEEE Standards 1597.1 and 1597.2 7
     1.2.1 “The Building Block” of the Computational Electromagnetics Model 7
     1.2.2 The Geometry of the Model and the Problem Space 8
     1.2.3 Numerical Computation Methods 8
     1.2.4 High-Performance Computation and Visualization (HPCV) in CEM 9
     1.2.5 IEEE Standards 1597.1 and 1597.2 for Validation of CEM Computer Modeling and Simulations 9
  1.3 HBFEM Used in Nonlinear EM Field Problems and Power Systems 12
     1.3.1 HBFEM for a Nonlinear Magnetic Field With Current Driven 13
     1.3.2 HBFEM for Magnetic Field and Electric Circuit Coupled Problems 14
     1.3.3 HBFEM for a Nonlinear Magnetic Field with Voltage Driven 14
     1.3.4 HBFEM for a Three-Phase Magnetic Tripler Transformer 14
2 Nonlinear Electromagnetic Field and Its Harmonic Problems

2.1 Harmonic Problems in Power Systems and Power Supply Transformers

2.1.1 Nonlinear Electromagnetic Field

2.1.2 Harmonics Problems Generated from Nonlinear Load and Power Electronics Devices

2.1.3 Harmonics in the Time Domain and Frequency Domain

2.1.4 Examples of Harmonic Producing Loads

2.1.5 Harmonics in DC/DC Converter of Isolation Transformer

2.1.6 Magnetic Tripler

2.1.7 Harmonics in Multi-Pulse Rectifier Transformer

2.2 DC-Biased Transformer in High-Voltage DC Power Transmission System

2.2.1 Investigation and Suppression of DC Bias Phenomenon

2.2.2 Characteristics of DC Bias Phenomenon and Problems to be Solved

2.3 Geomagnetic Disturbance and Geomagnetic Induced Currents (GIC)

2.3.1 Geomagnetically Induced Currents in Power Systems

2.3.2 GIC-Induced Harmonic Currents in the Transformer

2.4 Harmonic Problems in Renewable Energy and Microgrid Systems

2.4.1 Power Electronic Devices – Harmonic Current and Voltage Sources

2.4.2 Harmonic Distortion in Renewable Energy Systems

2.4.3 Harmonics in the Microgrid and EV Charging System

2.4.4 IEEE Standard 519-2014

References

3 Harmonic Balance Methods Used in Computational Electromagnetics

3.1 Harmonic Balance Methods Used in Nonlinear Circuit Problems

3.1.1 The Basic Concept of Harmonic Balance in a Nonlinear Circuit

3.1.2 The Theory of Harmonic Balance Used in a Nonlinear Circuit

3.2 CEM for Harmonic Problem Solving in Frequency, Time and Harmonic Domains

3.2.1 Computational Electromagnetics (CEM) Techniques and Validation

3.2.2 Time Periodic Electromagnetic Problems Using the Finite Element Method (FEM)
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2.3 Comparison of Time-Periodic Steady-State Nonlinear EM Field</td>
<td>71</td>
</tr>
<tr>
<td>Analysis Method</td>
<td></td>
</tr>
<tr>
<td>3.3 The Basic Concept of Harmonic Balance in EM Fields</td>
<td>73</td>
</tr>
<tr>
<td>3.3.1 Definition of Harmonic Balance</td>
<td>73</td>
</tr>
<tr>
<td>3.3.2 Harmonic Balance in EM Fields</td>
<td>73</td>
</tr>
<tr>
<td>3.3.3 Nonlinear Medium Description</td>
<td>75</td>
</tr>
<tr>
<td>3.3.4 Boundary Conditions</td>
<td>76</td>
</tr>
<tr>
<td>3.3.5 The Theory of HB-FEM in Nonlinear Magnetic Fields</td>
<td>76</td>
</tr>
<tr>
<td>3.3.6 The Generalized HB-FEM</td>
<td>83</td>
</tr>
<tr>
<td>3.4 HB-FEM for Electromagnetic Field and Electric Circuit Coupled</td>
<td>85</td>
</tr>
<tr>
<td>Problems</td>
<td></td>
</tr>
<tr>
<td>3.4.1 HB-FEM in Voltage Source-Driven Magnetic Field</td>
<td>85</td>
</tr>
<tr>
<td>3.4.2 Generalized Voltage Source-Driven Magnetic Field</td>
<td>86</td>
</tr>
<tr>
<td>3.5 HB-FEM for a DC-Biased Problem in High-Voltage Power Transformers</td>
<td>91</td>
</tr>
<tr>
<td>3.5.1 DC-Biased Problem in HVDC Transformers</td>
<td>91</td>
</tr>
<tr>
<td>3.5.2 HB-FEM Model of HVDC Transformer</td>
<td>91</td>
</tr>
<tr>
<td>References</td>
<td>95</td>
</tr>
<tr>
<td>4 HB-FEM for Nonlinear Magnetic Field Problems</td>
<td>96</td>
</tr>
<tr>
<td>4.1 HB-FEM for a Nonlinear Magnetic Field with Current-Driven Source</td>
<td>96</td>
</tr>
<tr>
<td>4.1.1 Numerical Model of Current Source to Magnetic Field</td>
<td>97</td>
</tr>
<tr>
<td>4.1.2 Example of Current-Source Excitation to Nonlinear Magnetic Field</td>
<td>99</td>
</tr>
<tr>
<td>4.2 Harmonic Analysis of Switching Mode Transformer Using Voltage-</td>
<td>99</td>
</tr>
<tr>
<td>Driven Source</td>
<td></td>
</tr>
<tr>
<td>4.2.1 Numerical Model of Voltage Source to Magnetic System</td>
<td>99</td>
</tr>
<tr>
<td>4.2.2 Example of Voltage-Source Excitation to Nonlinear Magnetic Field</td>
<td>106</td>
</tr>
<tr>
<td>4.3 Three-Phase Magnetic Frequency Tripler Analysis</td>
<td>107</td>
</tr>
<tr>
<td>4.3.1 Magnetic Frequency Tripler</td>
<td>107</td>
</tr>
<tr>
<td>4.3.2 Nonlinear Magnetic Material and its Saturation Characteristics</td>
<td>107</td>
</tr>
<tr>
<td>4.3.3 Voltage Source-Driven Connected to the Magnetic Field</td>
<td>109</td>
</tr>
<tr>
<td>4.4 Design of High-Speed and Hybrid Induction Machine using HB-FEM</td>
<td>115</td>
</tr>
<tr>
<td>4.4.1 Construction of High-Speed and Hybrid Induction Machine</td>
<td>115</td>
</tr>
<tr>
<td>4.4.2 Numerical Model of High-Speed and Hybrid Induction Machine using</td>
<td>117</td>
</tr>
<tr>
<td>HB-FEM, Taking Account of Motion Effect</td>
<td></td>
</tr>
<tr>
<td>4.4.3 Numerical Analysis of High Speed and Hybrid Induction Machine</td>
<td>126</td>
</tr>
<tr>
<td>using HB-FEM</td>
<td></td>
</tr>
<tr>
<td>4.5 Three-Dimensional Axi-Symmetrical Transformer with DC-Biased</td>
<td>131</td>
</tr>
<tr>
<td>Excitation</td>
<td></td>
</tr>
<tr>
<td>4.5.1 Numerical Simulation of 3-D Axi-Symmetrical Structure</td>
<td>133</td>
</tr>
</tbody>
</table>
4.5.2 Numerical Analysis of the Three-Dimensional Axi-Symmetrical Model

4.5.3 Eddy Current Calculation of DC-Biased Switch Mode Transformer

References

5 Advanced Numerical Approach using HBFEM

5.1 HBFEM for DC-Biased Problems in HVDC Power Transformers

5.1.1 DC Bias Phenomena in HVDC

5.1.2 HBFEM for DC-Biased Magnetic Field

5.1.3 High-Voltage DC (HVDC) Transformer

5.2 Decomposed Algorithm of HBFEM

5.2.1 Introduction

5.2.2 Decomposed Harmonic Balanced System Equation

5.2.3 Magnetic Field Coupled with Electric Circuits

5.2.4 Computational Procedure Based on the Block Gauss-Seidel Algorithm

5.2.5 DC-Biasing Test on the LCM and Computational Results

5.2.6 Analysis of the Flux Density and Flux Distribution Under DC Bias Conditions

5.3 HBFEM with Fixed-Point Technique

5.3.1 Introduction

5.3.2 DC-Biasing Magnetization Curve

5.3.3 Fixed-Point Harmonic-Balanced Theory

5.3.4 Electromagnetic Coupling

5.3.5 Validation and Discussion

5.4 Hysteresis Model Based on Neural Network and Consuming Function

5.4.1 Introduction

5.4.2 Hysteresis Model Based on Consuming Function

5.4.3 Hysteresis Loops and Simulation

5.4.4 Hysteresis Model Based on a Neural Network

5.4.5 Simulation and Validation

5.5 Analysis of Hysteretic Characteristics Under Sinusoidal and DC-Biased Excitation

5.5.1 Globally Convergent Fixed-Point Harmonic-Balanced Method

5.5.2 Hysteric Characteristic Analysis of the Laminated Core

5.5.3 Computation of the Nonlinear Magnetic Field Based on the Combination of the Two Hysteresis Models

5.6 Parallel Computing of HBFEM in Multi-Frequency Domain

5.6.1 HBFEM in Multi-Frequency Domain

5.6.2 Parallel Computing of HBFEM

5.6.3 Domain Decomposition

5.6.4 Reordering and Multi-Coloring
6 HBFEM and Its Future Applications 222
6.1 HBFEM Model of Three-Phase Power Transformer 222
   6.1.1 Three-Phase Transformer 222
   6.1.2 Nonlinear Magnetic Material and its Saturation Characteristics 223
   6.1.3 Voltage Source-Driven Model Connected to the Magnetic Field 224
   6.1.4 HBFEM Matrix Equations, Taking Account of Extended Circuits 225
6.2 Magnetic Model of a Single-Phase Transformer and a Magnetically Controlled Shunt Reactor 231
   6.2.1 Electromagnetic Coupling Model of a Single-Phase Transformer 231
   6.2.2 Solutions of the Nonlinear Magnetic Circuit Model by the Harmonic Balance Method 233
   6.2.3 Magnetically Controlled Shunt Reactor 235
   6.2.4 Experiment and Computation 237
6.3 Computation Taking Account of Hysteresis Effects Based on Fixed-Point Reluctance 240
   6.3.1 Fixed-Point Reluctance 240
   6.3.2 Computational Procedure in the Frequency Domain 242
   6.3.3 Computational Results and Analysis 243
6.4 HBFEM Modeling of the DC-Biased Transformer in GIC Event 245
   6.4.1 GIC Effects on the Transformer 245
   6.4.2 GIC Modeling and Harmonic Analysis 248
   6.4.3 GIC Modeling Using HBFEM Model 249
6.5 HBFEM Used in Renewable Energy Systems and Microgrids 253
   6.5.1 Harmonics in Renewable Energy Systems and Microgrids 253
   6.5.2 Harmonic Analysis of the Transformer in Renewable Energy Systems and Microgrids 254
   6.5.3 Harmonic Analysis of the Transformer Using a Voltage Driven Source 256
   6.5.4 Harmonic Analysis of the Transformer Using a Current-Driven Source 258
References 261

Appendix 263
   Appendix I & II 263
      Matlab Program and the Laminated Core Model for Computation 263
   Appendix III 265
      FORTRAN-Based 3D Axi-Symmetrical Transformer with DC-Biased Excitation 265

Index 267