Contents

Preface ix

Chapter 1. Magnetic Field 1

1.1. Overview of history 1
1.2. Magnetic fields and magnetic forces 6
1.2.1. First experiments 7
1.2.2. Topography: invariances and symmetries 8
1.3. Magnetic fields created by currents 11
1.3.1. Magnetic field created by a volume current distribution 11
1.3.2. Magnetic field created by a surface current distribution or by a filiform current element 12
1.4. Biot–Savart experiment 13
1.5. From field B to vector potential A 14
1.6. Symmetry and invariance properties of the magnetic field related to the symmetry and invariances of the current distribution 15
1.6.1. Distribution of currents having a plane of symmetry 17
1.6.2. Current distribution and anti-symmetry plane 17
1.6.3. Invariance 18
1.7. Calculation of the magnetic field (principle of) 20
1.7.1. Examples of field calculations 20
1.8. Circulation properties of B. Ampère's theorem 36
1.8.1. Integral form of Ampère's theorem 37
1.8.2. Local form of Ampère's theorem 43
1.9. Magnetic field flux conservation – vector potential 43
1.9.1. Local relationship 43
1.9.2. Integral relationship – magnetic flux 44
1.9.3. Potential vector of the magnetic field 45
1.10. Transit relationships 52

1.10.1. Circulation property of B. Discontinuity of the tangential component of B 53
1.10.2. Flow property of B. Continuity of the normal component of B 55

Chapter 2. Magnetic Forces and their Work 57

2.1. Introduction: Academy of Sciences 57
2.2. Action of a magnetic field on a circuit through which a current flows. 59
2.2.1. Ampère/Laplace force 59
2.3. Current in a conductor subjected to an electromagnetic field 63
2.3.1. Examples: action of a rectilinear wire, through which a current flows on another rectilinear wire. 63
2.4. Local Ohm's law. 64
2.5. Hall effect 65
2.5.1. Hall effect applications (Figure 2.9). 67
2.6. Ampère/Laplace magnetic forces on a conductor (Figures 2.10 and 2.11) . . . 68
2.6.1. Ampère definition. 72
2.7. Work of electromagnetic forces 72
2.7.1. Cut-off flow theorem 73
2.7.2. Case of a closed circuit through which a constant current I flows: Maxwell's theorem. 73
2.8. Application to the study of torsor of magnetic forces exerted by an invariable field on a rigid circuit 80
2.9. Potential energy 81
2.9.1. Case of a transverse displacement 82
2.9.2. Case of a rotation 83
2.10. Example: flux of a turn in a magnetic field 84
2.10.1. Turn in a transverse displacement 84
2.10.2. Turn in rotation 85
2.11. Potential energy of interaction with a magnetic field: magnetic dipole 86
2.11.1. Magnetic force and moment acting on the loop. 88
2.12. Electrostatic/magnetostatic analogy 89

Chapter 3. Magnetic Media 91

3.1. Introduction: orbital and spin magnetic moments. 91
3.2. Experimental studies 93
3.3. Microscopic origins of magnetism: basic concepts 95
3.3.1. Diamagnetism 95
3.3.2. Paramagnetism 96
3.3.3. Ferromagnetism 98
3.4. Macroscopic appearance; magnetization intensity 100
3.4.1. Diamagnetic and paramagnetic materials 101

3.5. Determining the magnetic field created by a magnetized medium 101
3.5.1. Vector potential of a closed circuit, at a point in the vacuum 103
3.6. Macroscopic aspects; magnetization currents 104
3.6.1. Total magnetic field in the presence of magnetic media. 108
3.6.2. General equations of magnetostatics in the presence of magnetized media 109
3.7. Generalized Ampère's theorem: magnetic excitation. 110
3.7.1. Transit relationships 111
3.8. Perfect magnetic media or HLI media – homogeneous, linear, isotropic (Figure 3.21) 113
3.8.1. Definition 113
3.9. Magnetic field equations for perfect materials and vacuum 116
3.9.1. Hysteresis loop 118
3.9.2. Applications 121

Chapter 4. Induction 123

4.1. Introduction: variable regimes 123
4.2. Properties of electrical induction and magnetic field 127
4.3. Phenomenon of electromagnetic induction 127
4.3.1. Faraday–Lenz law 130
4.3.2. Terminology and classification of induction phenomena 132
4.3.3. Static or Neumann induction and motional or Lorentz induction. 136
4.3.4. Motional or Lorentz induction 140
4.4. Different inductions 149
4.4.1. Auto-induction electromotive force 149
4.4.2. Mutual inductance – coupling coefficient. 150
4.5. Applications 154
4.6. Electromechanical conversion; moving bar in a uniform B-field 154
4.6.1. We place ourselves in the laboratory repository 154
4.6.2. We place ourselves in the frame of reference to the bar 156
4.7. Vector potential and quantum mechanics 157
4.8. Appendix: another example of an induction problem 170
4.8.1. Coil with tube-shaped conductive core 170

Chapter 5. Propagation: Special Relativity 179

5.1. Introduction 179
5.1.1. Potential of a moving charge: general solution by Liénard and Wiercherts 180
5.1.2. Spherical waves 182
5.2. Light and electromagnetic waves. 184
5.2.1. Spherical wave from a point source 186
5.2.2. Paradox of advanced actions 189

5.3. Relativity 195
5.3.1. Galileo's relativity 195
5.3.2. Special relativity 196
5.3.3. Charges in motion: from "Coulomb" to "Ampère" 217
5.3.4. Note on Lorentz equations 225

Conclusion 227

Appendices 229

Appendix 1. Ampère/Laplace Magnetic Actions Undergone by a Current Loop Placed in an External Magnetic Field 231

Appendix 2. Magnetostatic Potential Energy of a Current System (Perfect Media) 241

Appendix 3. Operator Expressions in Cartesian Coordinates 249

Appendix 4. Some Key Players in Electromagnetism and Special Relativity 261

References 277

Index 279