

# Contents

|   |    |
|---|----|
| <b>1. Introduction</b> .....  | 1  |
| 1.1 Electrodynamics of Moving Media .....   | 1  |
| 1.1.1 Minkowski Electrodynamics .....   | 2  |
| 1.1.2 Covariant Description in Arbitrary Frames of Reference ..                         | 5  |
| 1.1.3 Observation of Moving Electrified Matter .....                                    | 5  |
| 1.2 Some Remarks on Electrodynamics of Moving Media and<br>Restricted Relativity .....  | 6  |
| 1.3 Some Remarks on Quasistatics .....  | 8  |
| 1.4 “Cerenkov Electrodynamics” .....  | 12 |
| 1.5 Further Remarks on Quasistatics .....   | 18 |
| 1.6 Summary of Approaches .....   | 20 |
| 1.7 Outline of Contents .....   | 20 |
| <br>  |    |
| <b>2. Principles of Magneto-Electric Interactions</b> .....                             | 23 |
| 2.1 Faraday’s Law in the Presence of Moving Media .....                                 | 23 |
| 2.1.1 Overview and Basic Remarks .....  | 23 |
| 2.1.2 Fitzgerald’s Superpotential and Its Use in Different<br>Frames of Reference ..... | 25 |
| 2.1.3 Statement of Practical Problem and Basic Assumptions ..                           | 30 |
| 2.1.4 Solution .....  | 31 |
| 2.1.5 Discussion .....  | 39 |
| 2.1.6 Appendix .....  | 40 |
| 2.2 Linear Induction Devices .....  | 44 |
| 2.2.1 Definition of Problem .....   | 45 |
| 2.2.2 General Approach to Solution .....  | 46 |
| 2.2.3 Exciting Field .....  | 48 |
| 2.2.4 Reaction Field .....  | 51 |
| 2.2.5 Two Special Cases .....   | 56 |
| 2.2.6 Power and Thrust Considerations .....   | 59 |
| 2.2.7 Discussion .....  | 62 |
| 2.2.8 Appendix .....  | 62 |
| 2.3 Unipolar Induction – Basic Principles .....   | 66 |
| 2.3.1 Physical Explanation .....  | 66 |
| 2.3.2 Formulation of Problem and Approach to Solution .....                             | 69 |
| 2.3.3 Calculation of Sheet Current .....  | 72 |

|        |   |     |
|--------|---|-----|
| 2.3.4  | The Braking Force .....   | 77  |
| 2.3.5  | Appendix .....  | 78  |
| 2.4    | Unipolar Induction – Extended Array .....   | 81  |
| 2.4.1  | Formulation of Problem .....  | 81  |
| 2.4.2  | Solution .....  | 82  |
| 2.4.3  | Appendix .....  | 85  |
| 2.5    | Optimal Dimensions for Braking Electromagnet .....                                      | 94  |
| 2.5.1  | Two-Way Infinite Sheet .....  | 95  |
| 2.5.2  | Finite-Width Sheet .....  | 99  |
| 2.5.3  | Calculation of Self-Inductance per Unit Length .....                                    | 101 |
| 2.6    | Unipolar Induction – Circular Motion .....  | 103 |
| 2.6.1  | Formulation of Problem .....  | 103 |
| 2.6.2  | Solution .....  | 104 |
| 2.6.3  | Numerical Solution .....  | 109 |
| 2.6.4  | Appendix .....  | 111 |
| 3.     | <b>Electromagnetic Induction: Steady-State – Stationary Configurations .....</b>        | 119 |
| 3.1    | Eddy Currents in Thin Metal Sheets .....  | 119 |
| 3.1.1  | Formulation of Problem .....  | 119 |
| 3.1.2  | General Approach to Solution .....  | 120 |
| 3.1.3  | Primary Field .....   | 121 |
| 3.1.4  | Secondary Field .....   | 122 |
| 3.1.5  | Calculation of Current Flow .....   | 123 |
| 3.1.6  | Outer Zone, $R \leq r < \infty$ .....   | 123 |
| 3.1.7  | Inner Zone, $0 \leq r \leq R$ .....   | 125 |
| 3.1.8  | Coupling of Zones .....   | 126 |
| 3.1.9  | Calculation of Ampère-Turns .....   | 127 |
| 3.1.10 | Discussion .....  | 129 |
| 3.1.11 | Appendix .....  | 130 |
| 3.2    | Operation of Eddy Current Probe Coil .....  | 131 |
| 3.2.1  | Basic Assumptions and Statement of Problem .....  | 131 |
| 3.2.2  | Primary Field .....   | 132 |
| 3.2.3  | Secondary Field .....   | 133 |
| 3.2.4  | Secondary Axial Field at Coil Center .....  | 135 |
| 3.2.5  | Change of Coil Impedance .....  | 135 |
| 3.2.6  | Discussion .....  | 137 |
| 3.2.7  | Appendix .....  | 138 |
| 3.3    | Proximity Effect Between a Plane Metal Screen and a Rectilinear Current Conductor ..... | 139 |
| 3.3.1  | Formulation of Problem .....  | 140 |
| 3.3.2  | Primary Field .....   | 141 |
| 3.3.3  | Secondary Field .....   | 143 |
| 3.3.4  | Spectral Density of Sheet Current .....   | 143 |
| 3.3.5  | Reaction on Current-Carrying Conductor .....  | 144 |

|   |            |
|---|------------|
| 3.3.6 Transient Phenomena .....   | 150        |
| 3.3.7 Discussion .....  | 152        |
| 3.3.8 Appendix .....  | 152        |
| 3.4 On the Inductance of Printed Spiral Coils .....                                       | 155        |
| 3.4.1 Formulation of Problem .....  | 156        |
| 3.4.2 Solution .....  | 157        |
| 3.4.3 Discussion .....  | 162        |
| 3.4.4 Appendix .....  | 162        |
| <b>4. Electromagnetic Induction: Transient Phenomena – Stationary Configuration .....</b> | <b>164</b> |
| 4.1 Surge Impedance of Extended Grounding Rods .....                                      | 164        |
| 4.1.1 Mathematical Model and Attendant Field Problem .....                                | 164        |
| 4.1.2 Solution of Field Problem .....   | 166        |
| 4.1.3 Steady-State Resistance Levels of Grounding Rods .....                              | 174        |
| 4.1.4 Discussion .....  | 175        |
| 4.1.5 Appendix .....  | 176        |
| 4.2 Field Transients in Saturable Cores .....   | 179        |
| 4.2.1 Formulation of Problem and Basic Assumptions .....                                  | 179        |
| 4.2.2 Field Solution .....  | 182        |
| 4.2.3 Velocity of Saturation Front .....  | 190        |
| 4.2.4 Discussion .....  | 191        |
| 4.2.5 Appendix .....  | 192        |
| 4.3 Field Switching in the Presence of Superconducting Material ..                        | 192        |
| 4.3.1 Formulation of Problem and Approach to Solution .....                               | 193        |
| 4.3.2 Field Analysis .....  | 195        |
| 4.3.3 Concluding Remarks .....  | 202        |
| 4.3.4 Appendix .....  | 202        |
| 4.4 Electromechanical Transients in Liquid Metal upon Field Disruption .....              | 214        |
| 4.4.1 Formulation of the Problem .....  | 215        |
| 4.4.2 Approach to the Solution .....  | 215        |
| 4.4.3 Electrical Problem .....  | 216        |
| 4.4.4 Mechanical Problem .....  | 220        |
| 4.4.5 Discussion .....  | 222        |
| 4.4.6 Appendix .....  | 224        |
| <b>5. Dynamic Phenomena .....</b>   | <b>230</b> |
| 5.1 Wave Interaction with Moving Layers .....   | 230        |
| 5.1.1 Dielectric Sheet .....  | 230        |
| 5.1.2 Conducting Sheet .....  | 239        |
| 5.1.3 Discussion .....  | 243        |
| 5.2 Wave Propagation Inside Moving Nonmagnetic Media .....                                | 244        |
| 5.2.1 Basic Assumptions and Statement of Problem .....                                    | 245        |

|   |            |
|---|------------|
| 5.2.2 Solution of Field Problem .....   | 245        |
| 5.2.3 Some Kinematic Considerations .....   | 252        |
| 5.2.4 Concluding Remarks .....  | 255        |
| 5.2.5 Appendix .....  | 255        |
| 5.3 Electrodynamics of Shielding: Cylindrical Configuration and<br>Exterior Hertz Wave .....    | 256        |
| 5.3.1 Formulation and Problem .....   | 256        |
| 5.3.2 Approach to Solution .....  | 257        |
| 5.3.3 Primary Field .....   | 258        |
| 5.3.4 Secondary Field .....   | 259        |
| 5.3.5 Shielding of Electric Field .....   | 261        |
| 5.3.6 Shielding of Magnetic Field .....   | 264        |
| 5.3.7 Concluding Remarks .....  | 267        |
| 5.3.8 Appendix .....  | 268        |
| 5.4 Electrodynamics of Shielding: Spherical Configuration and<br>Interior Fitzgerald Wave ..... | 271        |
| 5.4.1 Definition of Problem .....   | 271        |
| 5.4.2 Approach to Solution .....  | 272        |
| 5.4.3 Exciting Field .....  | 272        |
| 5.4.4 Secondary Field .....   | 274        |
| 5.4.5 Resultant Field .....   | 276        |
| 5.4.6 Concluding Remarks .....  | 278        |
| 5.4.7 Appendix .....  | 278        |
| <b>References .....</b>   | <b>283</b> |
| <b>Acknowledgement .....</b>  | <b>286</b> |
| <b>Subject Index .....</b>  | <b>287</b> |