

# Contents

<b>Abstract</b>	v
<b>List of Abbreviations</b>	vii
<b>List of Symbols</b>	ix
<b>Contents</b>	xiii
<b>1 Introduction</b>	1
1.1 Wireless Power Transmission	1
1.2 Types of Wireless Power Transmission	2
1.2.1 Radiative	2
1.2.2 Conductive	3
1.2.3 Capacitive	4
1.2.4 Inductive	5
1.3 A Biomedical Perspective	6
1.3.1 Instrumentated Implants	6
1.3.2 Transcutaneous Powering	7
1.4 Inductive Links	9
1.4.1 Powering System	9
1.4.2 Data Communication	10
1.5 Conclusions	11
1.6 What to Expect	12
<b>2 Magnetic Induction</b>	13
2.1 Maxwell's Equations	13
2.1.1 Time-Domain, Integral Form	13
2.1.2 Time-Harmonic, Differential Form	14
2.1.3 Constitutive Relations and Ohm's Law	14
2.1.4 Magnetic and Electric Potential	15
2.1.5 Current and Flux	16
2.2 Conductive Wire	17

xiii

2.3	Inductance . . . . .	18
2.4	Inductor Models . . . . .	21
2.5	Finite Element Modelling . . . . .	24
2.5.1	Axisymmetric Geometries . . . . .	25
2.5.2	2-D Wire Models . . . . .	32
2.5.3	3-D Models . . . . .	33
2.5.4	Mutual Inductance . . . . .	36
2.6	Conclusions . . . . .	36
<b>3</b>	<b>Inductive Link Design . . . . .</b>	<b>39</b>
3.1	Link Equations . . . . .	39
3.1.1	Important Quantities . . . . .	39
3.1.2	Equivalent Two-Port Representations . . . . .	42
3.1.3	Secondary Resonance . . . . .	43
3.1.4	Transmitted Power . . . . .	45
3.1.5	Link Efficiency . . . . .	46
3.1.6	Link Gain and Critical Coupling . . . . .	48
3.1.7	Parallel vs. Series Resonance . . . . .	50
3.1.8	Summary . . . . .	53
3.2	Loose-Coupling Approximation . . . . .	53
3.3	Tertiary Circuits . . . . .	55
3.3.1	Conductive Objects . . . . .	56
3.3.2	Coupled Resonators . . . . .	61
3.4	Link Optimisation . . . . .	65
3.4.1	Operating Frequency: $\omega$ . . . . .	65
3.4.2	Magnetic Design: $M_0$ . . . . .	66
3.4.3	Winding Losses: $R_{10}$ and $R_{20}$ . . . . .	68
3.4.4	Secondary Coil Optimisation: $N_2$ . . . . .	71
3.4.5	Secondary Coil and Capacitance Tapping . . . . .	75
3.4.6	Advanced Gain Stabilisation . . . . .	77
3.5	Misconceptions About $k$ and $Q$ . . . . .	78
3.6	Conclusions . . . . .	80
<b>4</b>	<b>Power Converters and Voltage Regulators . . . . .</b>	<b>83</b>
4.1	Rectifiers . . . . .	83
4.1.1	Diodes . . . . .	84
4.1.2	Peak Rectifiers . . . . .	85
4.1.3	Class D Rectifiers . . . . .	88
4.1.4	Class E Rectifiers . . . . .	91
4.1.5	To Conclude . . . . .	91
4.2	Inverters . . . . .	92
4.2.1	Semiconductor Switches . . . . .	93
4.2.2	Saturating Class C Inverter . . . . .	94
4.2.3	Class D Inverters . . . . .	96
4.2.4	Class E Inverters . . . . .	97
4.2.5	Alternative Load Networks . . . . .	102

4.2.6	Design of an Inductive Link Driver . . . . .	104
4.3	Voltage Regulators . . . . .	112
4.3.1	Linear Regulators . . . . .	113
4.3.2	Switching Regulators . . . . .	115
4.4	Conclusions . . . . .	116
<b>5</b>	<b>Omnidirectional Coupling . . . . .</b>	<b>119</b>
5.1	Problem Definition . . . . .	119
5.2	Multiple Primary Coils . . . . .	120
5.2.1	System Concept . . . . .	120
5.2.2	Worst-Coupling Map . . . . .	121
5.2.3	Capsule Endoscope with One Secondary Coil . . . . .	123
5.3	Multiple Secondary Coils . . . . .	127
5.3.1	Power-Combining Rectifiers . . . . .	127
5.3.2	Worst-Case Conditions . . . . .	129
5.3.3	Capsule Endoscope with Three Secondary Coils . . . . .	134
5.4	Conclusions . . . . .	137
<b>6</b>	<b>Biological Tissue Interaction . . . . .</b>	<b>139</b>
6.1	Electromagnetic Fields in Biological Tissue . . . . .	139
6.1.1	Near Field . . . . .	139
6.1.2	Far Field . . . . .	142
6.2	Health Effects of Electromagnetic Fields . . . . .	143
6.2.1	Directly Observable Effects . . . . .	143
6.2.2	Other Biological Effects . . . . .	145
6.3	Exposure Limits and Regulations . . . . .	145
6.4	Examples from Biomedical Engineering Practice . . . . .	148
6.5	Conclusions . . . . .	150
<b>7</b>	<b>An Inductive Power Link for a Capsule Endoscope . . . . .</b>	<b>151</b>
7.1	Wireless Endoscopy . . . . .	151
7.2	Design: Choices and Motivation . . . . .	152
7.2.1	Specifications . . . . .	152
7.2.2	Operating Frequency . . . . .	152
7.2.3	Coil Configuration . . . . .	153
7.2.4	Voltage Regulator and Rectifier . . . . .	153
7.2.5	Power Optimisation . . . . .	154
7.2.6	Verification . . . . .	155
7.3	Fabrication . . . . .	156
7.4	Measurement . . . . .	160
7.5	Biological Tissue Interaction . . . . .	163
7.5.1	ICNIRP Compliance . . . . .	165
7.5.2	Link Efficiency . . . . .	169
7.5.3	Class E Tuning . . . . .	170
7.5.4	Secondary Resonance Tuning . . . . .	172
7.6	Conclusions . . . . .	172

**8 A Class E Driver for Deformable Coils . . . . . 175**

8.1 Class E ZVS Inverter with Transductor . . . . . 175

8.2 Control Loop . . . . . 179

8.3 Measurement Results . . . . . 183

8.3.1 Deforming the Primary Coil . . . . . 184

8.3.2 Varying the Frequency . . . . . 186

8.4 Conclusions . . . . . 187

**9 Conclusions . . . . . 191**

9.1 Comprehensive Summary . . . . . 191

9.2 Main Contributions and Achievements . . . . . 193

9.3 Further Research . . . . . 194

**Appendix: Coil Measurements . . . . . 197**

A.1 Single Coil Characterisation . . . . . 197

A.1.1 General Considerations . . . . . 197

A.1.2 One-Port  $S_{11}$  Measurement . . . . . 199

A.1.3 Two-Port  $Q'$  Measurement . . . . . 200

A.1.4 Impedance Analysers and LCR Meters . . . . . 203

A.2 Coupling Characterisation . . . . . 204

**References . . . . . 211**

**Index . . . . . 219**



<http://www.springer.com/978-1-4020-9074-5>

Omnidirectional Inductive Powering for Biomedical  
Implants

Lenaerts, B.; Puers, R.

2009, XVI, 222 p., Hardcover

ISBN: 978-1-4020-9074-5