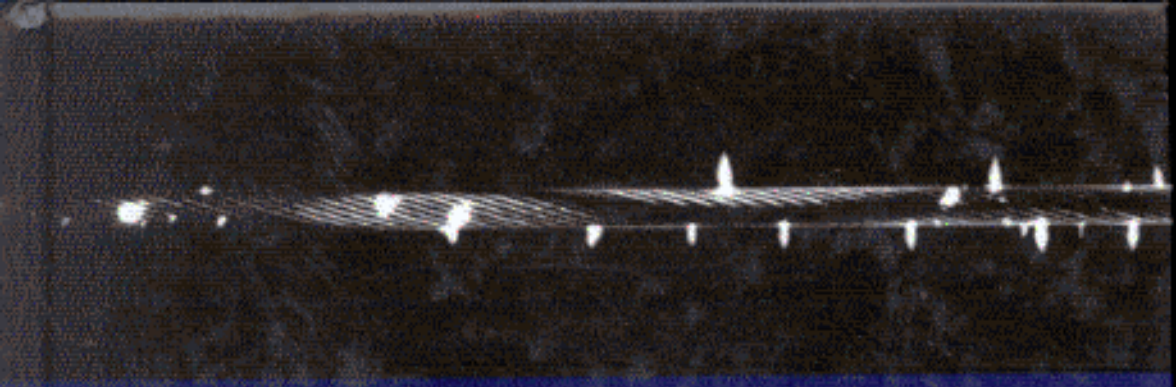

Corona Performance of High-Voltage Transmission Lines

P Sarma Maruvada

TABLE OF CONTENTS

		Page
	PREFACE	xiii
	ACKNOWLEDGEMENT	xvii
	PART 1. BASIC CONCEPTS	
1.	**High-Voltage Power Transmission**	3
	1.1 Electric Power Systems	3
	1.2 High-Voltage AC Transmission Lines	4
	1.2.1 History of Development	4
	1.2.2 Power Transfer Capability	5
	1.2.3 Line Configurations	7
	1.3 High-Voltage DC Transmission Lines	9
	1.3.1 History of Development	9
	1.3.2 Technical and Economic Considerations	9
	1.3.3 Line Configurations	10
	1.4 Electromagnetic Modeling of Transmission Lines	12
	1.4.1 Idealized Line Configuration	12
	1.4.2 Modeling Based on Field Theory	13
	1.4.3 Modeling Based on Circuit Theory	17
	1.5 Electrical Design Considerations	18
	1.6 Influence of Weather Conditions and Statistical Description of Corona Effects	19
	REFERENCES	22
2.	**Conductor Surface Electric Fields**	25
	2.1 Introduction	25
	2.1.1 Bundled Conductors	26
	2.1.2 Definition of Terms	27
	2.2 Calculation of Conductor Surface Electric Fields	28
	2.2.1 Isolated Conductor	29
	2.2.2 Single Conductor Above Ground	30
	2.3 Transmission Lines With Single Conductors	31
	2.4 Isolated Conductor Bundle	34
	2.4.1 Equivalent Radius of the Bundle	39
	2.4.2 Application to Practical Lines	40
	2.5 Accurate Methods	41

2.5.1 Method of Successive Images 41
2.5.2 Method of Moments 46
2.5.3 Charge Simulation Method 51
REFERENCES 51

3. Corona and Gap Discharges **55**
3.1 Basic Ionization Processes 55
3.1.1 Ionization and Excitation 56
3.1.2 Electron Attachment and Detachment 58
3.1.3 Recombination 59
3.1.4 Electron Emission from Conductor Surfaces 60
3.1.5 Diffusion and Drift of Charged Particles 60
3.1.6 Basic Discharge Parameters for Air 61
3.2 Discharge Phenomena 64
3.3 Corona Discharges on Cylindrical Conductors in Air 67
3.3.1 Negative DC Corona Modes 67
Trichel Streamer Discharge 69
Negative Pulseless Glow Discharge 70
Negative Streamer Discharge 70
3.3.2 Positive DC Corona Modes 71
Burst Corona 72
Onset Streamer Discharge 73
Positive Glow Discharge 73
Breakdown Streamer Discharge 74
3.3.3 AC Corona Modes 75
3.4 Corona Discharge Currents 77
3.4.1 Shockley-Ramo Theorem 77
3.4.2 Induced Currents in the Concentric-Cylindrical Configuration 79
3.5 Corona Onset Gradients 82
3.6 Gap Discharges 85
REFERENCES 86

PART 2. AC TRANSMISSION LINES

4. Corona Loss and Ozone **91**
4.1 Physics of AC Corona Loss 91
4.2 Theoretical Analysis of Corona Loss 96
4.3 Corona Loss Generation Function 99
4.4 Factors Influencing Corona Loss 101
4.5 Empirical Methods for Predicting Corona Loss 104
4.6 Ozone 108
REFERENCES 108

5. Electromagnetic Interference 111
5.1 Introduction 111
5.2 Physical Description of Corona-Generated EMI 113
5.3 Frequency Domain Analysis of Corona Pulses 113
5.3.1 Fourier Analysis 115
5.3.2 Power Spectral Density 118
5.4 RI Excitation Function 120
5.5 Propagation Analysis 123
5.5.1 Single Conductor Line 123
5.5.2 Multi Conductor Line: Simplified Analysis 128
5.5.3 Transmission Line with Ground Wires 134
5.5.4 Modal Attenuation Constants 135
5.5.5 Multi Conductor Line: More Accurate Methods 137
5.6 Factors Influencing RI Characteristics of Transmission Lines 144
5.7 Empirical and Semi-Empirical Methods for Evaluating RI 147
5.7.1 Empirical Methods 147
5.7.2 Semi-Empirical Methods 151
5.8 Prediction of Corona-Generated TVI 154
Appendix 5A Vectors and Matrix Operators 155
REFERENCES 159

6. Audible Noise 163
6.1 Introduction 163
6.2 Physical Description of Corona-generated AN 164
6.3 Theoretical Analysis of AN Propagation 165
6.4 AN Characteristics of Transmission Lines 170
6.5 Prediction of AN from Transmission Lines 172
REFERENCES 174

PART 3. DC TRANSMISSION LINES

7. Space Charge Environment and Corona Losses 179
7.1 Unipolar DC Transmission Lines 179
7.1.1 Physical Description of Unipolar Corona 179
7.1.2 Defining Equations of Unipolar Corona 181
7.1.3 Analysis for Simple Configurations 183
7.1.4 Simplified Analysis for a Conductor-Plane Configuration 187
7.1.5 Analysis for General Unipolar Transmission Line Configurations 188
7.2 Bipolar DC Transmission Lines 192
7.2.1 Physical Description of Bipolar Corona 192
7.2.2 Defining Equations of Bipolar Corona 193
7.2.3 Simplified Analysis 195
7.2.4 Analysis for General Bipolar Transmission Line Configurations 196

7.3 Improved Methods of Analysis 199
7.3.1 Comparison with Experiment 200
7.3.2 Limitations of Improved Methods 202
7.4 Factors Influencing Space Charge Fields and Corona Losses 204
7.5 Empirical Methods 206
Appendix 7A Some Computational Aspects of Unipolar and Bipolar Space Charge Fields 209
7A.1 Tracing the Flux Lines of Space-Charge-Free Fields 209
7A.2 Numerical Solution of Nonlinear Two-Point Boundary Value Problems 211
REFERENCES 213

8. Radio Interference and Audible Noise **217**
8.1 Introduction 217
8.2 Analysis and Characteristics of RI 218
8.2.1 Unipolar Line 219
8.2.2 Bipolar Line 219
8.2.3 RI Characteristics 222
8.3 Analysis and Characteristics of AN 224
8.4 Empirical Methods for RI and AN 225
8.4.1 Radio Interference 226
8.4.2 Audible Noise 227
8.5 Hybrid AC/DC Transmission Lines 228
8.5.1 Electric Field and Space Charge Environment 229
8.5.2 Evaluation of Corona Performance 230
REFERENCES 233

PART 4. TESTING AND DESIGN CONSIDERATIONS

9. Measurement Methods and Test Techniques for Corona Performance Evaluation **237**
9.1 Introduction 237
9.2 Corona Test Methods 238
9.2.1 Laboratory Cages 238
9.2.2 Outdoor Test Cages 240
9.2.3 Outdoor Test Lines 242
9.2.4 Operating Lines 244
9.3 Determination of Corona Onset Gradient 245
9.3.1 Tests on Conductors 245
9.3.2 Tests on Hardware 246
9.4 Measurement of Corona Losses 247
9.4.1 AC Corona Losses 248
9.4.2 DC Corona Losses 251
9.5 Measurement and Interpretation of RI and AN on Short Lines 252
9.5.1 RI from Short Single-Conductor Lines 252
9.5.2 RI from Short Multi-Conductor Lines 261

9.5.3 AN from Short Lines 263
9.6 Instrumentation and Measurement Methods for RI 264
9.6.1 Instrumentation 264
Meter Response to Periodic Pulses 266
Meter Response to Random Pulse Trains 267
9.6.2 Measurement Methods 270
9.7 Instrumentation and Measurement Methods for AN 271
9.7.1 Instrumentation 271
9.7.2 Measurement Methods 273
9.8 Measurement of Parameters Defining DC Electric Field and Space Charge Environment 274
9.8.1 Electric Field 274
Ground Level Field-Mill 275
Above Ground Field-Mill 277
9.8.2 Ion Current Density 279
9.8.3 Unipolar Charge Density 280
9.8.4 Other Parameters 281
9.8.5 Measurement Methods 282
REFERENCES 283

10. Design Considerations **289**
10.1 Introduction 289
10.2 Influence of Corona Losses on Line Design 290
10.3 Design Criteria for RI 292
10.4 Design Criteria for AN 295
10.5 Design Criteria for DC Electric Fields and Ion Currents 298
10.6 Consideration of Corona Effects in the Overall Transmission Line Design 300
REFERENCES 304

INDEX **307**