Transmission Line Reference Book
345 kV and Above/Second Edition

Electric Power Research Institute
This document is copyrighted material.

Alaska Resources Library and Information Services (ARLIS) is providing this excerpt in an attempt to identify and post all documents from the Susitna Hydroelectric Project.

This book is identified as APA no. 379 in the Susitna Hydroelectric Project Document Index (1988), compiled by the Alaska Power Authority.

It is unable to be posted online in its entirety. Selected pages are displayed here to identify the published work.

Transmission Line Reference Book

345 kV and Above/Second Edition

Prepared by

Project UHV
Technical Resource Operation
Large Transformer Division
General Electric Co.
Pittsfield, Massachusetts

Transmission Engineering
Electric Utility Systems Engineering Department
Energy Systems and Technology Division
General Electric Co.
Schenectady, New York

Electric Power Research Institute
3412 Hillview Avenue, Palo Alto, California
Notice

This report was prepared by General Electric Company as an account of work sponsored by the Electric Power Research Institute, Inc. (EPRI). Neither EPRI, members of EPRI, General Electric Company, nor any person acting on behalf of any of them: (a) makes any warranty, express or implied, with respect to the use of any information, apparatus, method, or process disclosed in this report or that such use may not infringe privately owned rights; or (b) assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method, or process disclosed in this report.

Keywords

EHV-UHV
Conductors
Corona
Audible Noise
Electric Fields

Ordering Information

Requests for copies of this book should be directed to Research Reports Center (RRC), Box 50490, Palo Alto, CA 94303, (415) 965-4081. There is no charge for reports requested by EPRI member utilities and affiliates, contributing nonmembers, U.S. utility associations, U.S. government agencies (federal, state, and local), media, and foreign organizations with which EPRI has an information exchange agreement. On request, RRC will send a catalog of EPRI reports.
Editor
J. J. LaForest

Editorial Committee
M. G. Comber
L. E. Zaffanella

Authors
Chapter 1  Project UHV: A Transmission Research Facility
J. R. Doyle and L. E. Zaffanella
Chapter 2  EHV-UHV Transmission Systems
F. J. Ellert, S. A. Miske, Jr., and C. J. Truax
Chapter 3  Electrical Characteristics of EHV-UHV Conductor Configurations and Circuits
J. R. Doyle, J. J. LaForest, and T. S. Lauber (Rensselaer Polytechnic Institute)
Chapter 4  Corona Phenomena on AC Transmission Lines
M. G. Comber, D. W. Deno, and L. E. Zaffanella
Chapter 5  Radio Noise
M. G. Comber and R. J. Nigbor
Chapter 6  Audible Noise
M. G. Comber, R. J. Nigbor, and L. E. Zaffanella
Chapter 7  Corona Loss
M. G. Comber and L. E. Zaffanella
Chapter 8  Field Effects of Overhead Transmission Lines and Stations
D. W. Deno and L. E. Zaffanella
Chapter 9  Insulation — Design Criteria
J. D. Brown, F. A. Fisher, W. Neugebauer, and J. Panek
Chapter 10  Insulation for Power Frequency Voltage
K. J. Lloyd and H. M. Schneider
Chapter 11  Insulation for Switching Surges
K. J. Lloyd and L. E. Zaffanella
Chapter 12  Lightning Performance of Transmission Lines
J. G. Anderson
Chapter 13  Planning and Electrical Design of Transmission Lines
D. W. Deno, L. L. Garver, and J. J. LaForest
Quick Reference Chart for Major Design Items

To facilitate the use of this book by experienced line designers, a portion of the contents of Chapter 13, Sections 13.9 and 13.8, is presented below for quick reference. Section 13.9 summarizes the main design topics covered by this Second Edition, and Section 13.8 summarizes general circulation performance items useful for design. Each topical summary directs the reader to specific design sections elsewhere in the book.

### Design Topics: Line

<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching Surge Insulation</td>
<td>614</td>
</tr>
<tr>
<td>Lightning Insulation</td>
<td>615</td>
</tr>
<tr>
<td>Insulation for Contamination</td>
<td>616</td>
</tr>
<tr>
<td>Ground Electric Field</td>
<td>617</td>
</tr>
<tr>
<td>Magnetic Induction</td>
<td>618</td>
</tr>
<tr>
<td>Audible Noise</td>
<td>619</td>
</tr>
<tr>
<td>Radio Interference</td>
<td>620</td>
</tr>
<tr>
<td>Television Interference</td>
<td>621</td>
</tr>
<tr>
<td>Corona Loss</td>
<td>621</td>
</tr>
<tr>
<td>Ground Wire Design (60 Hz)</td>
<td>622</td>
</tr>
</tbody>
</table>

### Design Topics: Station

<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transient Voltage Insulation</td>
<td>623</td>
</tr>
<tr>
<td>Insulation for Contamination</td>
<td>624</td>
</tr>
<tr>
<td>Corona Performance</td>
<td>624</td>
</tr>
<tr>
<td>Corona Shields</td>
<td>625</td>
</tr>
<tr>
<td>Ground Electric Field</td>
<td>625</td>
</tr>
</tbody>
</table>

### Circuit Performance Items

<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compensation</td>
<td>606</td>
</tr>
<tr>
<td>Stability</td>
<td>606</td>
</tr>
<tr>
<td>Line Loading</td>
<td>607</td>
</tr>
<tr>
<td>Routing</td>
<td>608</td>
</tr>
<tr>
<td>Transposition</td>
<td>609</td>
</tr>
<tr>
<td>Transmission-Line Protection</td>
<td>610</td>
</tr>
<tr>
<td>Power-Line Carrier</td>
<td>611</td>
</tr>
<tr>
<td>Environmental Measurements</td>
<td>612</td>
</tr>
<tr>
<td>Line Parameters</td>
<td>613</td>
</tr>
</tbody>
</table>
## Contents

### Foreword

Chapter 1  **Project UHV: A Transmission Research Facility**  
1.1 Introduction  
Chapter 2  **EHV-UHV Transmission Systems**  
2.1 Introduction  
2.2 Load Growth and Transmission System Evolution  
2.3 Factors Affecting EHV-UHV Transmission Growth  
2.4 EHV-UHV Transmission System Characteristics  
2.5 EHV-UHV Line Design — Principal Areas to Be Considered  
2.6 Optimization of Transmission Systems  

### Chapter 1

#### Project UHV: A Transmission Research Facility

- **Introduction**  
- **Description of Project UHV Facilities**
  - 900-kV Surge Arresters
  - Precision Capacitor
  - Single-Phase Cascade Operation
  - Switching Surge Operation
  - Three-Phase UHV Test Line
  - Insulator Strings
  - Corona Testing Cage
  - Insulator Contamination Research

#### Instrumentation for Data Acquisition

- Data Acquisition Computer
- Instrumentation Systems

### References

- **Preliminary References**  
- **Technical References**
  - Historical Load Growth  
  - Forecast Load Growth  
  - AC Transmission Line Growth  

### Chapter 2

#### EHV-UHV Transmission Systems

- **Introduction**  
- **Role of Transmission**
- **General Transmission Design Criteria**

#### Load Growth and Transmission System Evolution

- **Historical Load Growth**
- **Forecast Load Growth**
- **AC Transmission Line Growth**

#### Factors Affecting EHV-UHV Transmission Growth

- **Load Growth**
- **Generation Siting**
- **Fuel Costs and Availability**
- **Reliability**
- **Electric**
- **Environment**

#### EHV-UHV Transmission System Characteristics

- **Stability Considerations**
- **Series Compensation**
- **Shunt Compensation**
- **Power Transmission Capability**

### Chapter 3

#### Electrical Characteristics of EHV-UHV Conductor Configurations and Circuits

- **Introduction**
- **Conductor Surface Gradients**
- **Electrostatic Induction**
- **Electromagnetic Induction**

#### Reactance and Resistance of Bundle Conductors

- **Introduction**
- **Types of Conductors and Conductor Materials**
- **Inductive Reactance**
- **Capacitive Reactance**
- **Surge Impedance and Surge Impedance Loading**
- **Resistance**
- **Ground Wires**
- **Equivalent Single Conductor**

#### Transmission-Line Unbalance

- **Electric Static Unbalance**
- **Single-Circuit Electromagnetic Unbalance**
- **Unbalance in Parallel Double-Circuit Untransposed Lines**

#### Induced Voltages on Parallel Lines

- **Electrostatic Induction on the De-energized Circuit**
- **Electromagnetic Induction on the De-energized Circuit**

#### Summary

Appendix 3.1  **Calculation of Electric Fields**

Appendix 3.2  **Inductive Reactance of Bundled Conductors**

Appendix 3.3  **Capacitive Reactance of Bundled Conductors**
Appendix 3.4 Conductor Table Calculations 148
Appendix 3.5 Transmission-Line Parameters (>60 Hz) 150
Appendix 3.6 Unbalance Factor Equations 165
References 167

Chapter 4 Corona Phenomena on AC Transmission Lines 169
4.1 Introduction 169
4.2 Mechanism of Corona 169
Gas Discharge Processes 169
The Townsend Avalanche Process 170
DC Corona Modes 170
AC Corona 175
4.3 Corona Loss Concept 175
Field Without Corona 175
Field in the Presence of Corona — Corona Current 175
Corona Loss in Fair Weather 176
4.4 Effect of Surface and Atmospheric Conditions 180
Fair-Weather Corona Sources 180
Corona Due to Particles Near the Conductor 181
Effect of Water on the Conductor 181
Effect of Air Density, Humidity, and Wind 181
Effect of Surface Conditions 182
Surface Treatment — Measurements and Results 185
4.5 Evaluation of Corona Effects from Single-Phase and Three-Phase Tests 187
Measurement and Analysis Using Single-Phase Test Facilities 187
Corona Generation and Surface Gradient 187
Generation Quantities 188
Audible Noise-Generated Power 189
Radio Noise Generation Function 189
Measurement and Analysis Using Three-Phase Test Facilities 191
4.6 Influence of Corona Currents on Switching-Surge Overvoltages 192
Project EHV Test Program 192
Project UHV Test Program 195
4.7 Ozone 199
Introduction 199
Ambient Concentration 199
Acceptable Levels 199
Measurements at Project UHV 200
Ozone Measurements in Other Locations 202
Calculations of Incremental Ozone Concentration 202
Other Corona Products 203
References 203

Chapter 5 Radio Noise 205
5.1 Introduction 205
5.2 Radio Noise Measurement 205
The Radio-Noise Meter 206
Weighting Circuits 206
Meter Response — Bandwidth and Pulse Repetition Rate 208
Actual Band-Pass Characteristics 210
Antenna Systems 210
Measurement of Transmission-Line Noise 211
5.3 Design Considerations 211
Characterization of Transmission-Line Radio Noise 212
Effect of Line Geometry and Conductor Surface Conditions 212
Noise Tolerability Criteria 213
5.4 Calculation of Transmission Line RL 217
Generation and Propagation of RL 217
RL Generation Data 222
Determination of Propagation Characteristics 225
RL Design Curves 229
Comparison of the Reference Book RL Calculation Method with Measured Data 245
RL Statistics 247
5.5 Television Interference 248
TVI Calculation Procedure 249
Example Calculation 250
Comparison of Calculations with Measurements 250
5.6 Radio Noise from Substations 251
Calculation of RL from Substations 251
RL Generation from Toroidal Grading Rings 252
Radio Noise of Insulator Strings 253
Ghosting and Blocking 253
Surface Treatment — Measurements and Results 253
5.7 Additional Topics 253
Effect of Water on the Conductor 253
Effect of Air Density, Humidity, and Wind 253
Radio Noise of Insulator Strings 253
Ozone Measurements in Other Locations 253
Calculations of Incremental Ozone Concentration 253
Effect of Surface Conditions 253
Ghosting and Blocking 253
Surface Treatment — Measurements and Results 253
5.8 Influence of Corona Currents on Switching-Surge Overvoltages 256
Project EHV Test Program 256
Project UHV Test Program 259
5.9 Ozone 259
Introduction 259
Ambient Concentration 259
Acceptable Levels 259
Measurements at Project UHV 260
Ozone Measurements in Other Locations 262
Calculations of Incremental Ozone Concentration 262
Other Corona Products 263
References 263

Chapter 6 Audible Noise 267
6.1 Introduction 267
6.2 Audible Noise Characteristics and Measurement 267
Characteristics of Transmission-Line Noise 267
Measures of Audible Noise 268
Instrumentation 269
Measurements 270
6.3 Design Considerations 270
Effect of Weather Conditions 270
Effect of Line Geometry and Conductor Surface Conditions 271
Assessing the Impact of Transmission-Line Audible Noise 272
6.4 Calculation of Transmission-Line Audible Noise 274
Introduction 274
Generation and Propagation of AN 275
AN Generation Data — Broad-Band Noise 278
Calculation of Audible-Noise Levels — Random Noise 281
Influence of Tower, Sag, and Ground Wires 283
Generalized 120-Hz Calculation

8.3 Calculation of Electric Fields

Introduction
Transmission-Line Induced Currents
Currents Induced on a Sphere Above Ground
Current Induced on a Round-Topped Hemisphere on a Ground Plane
Current Induced on a Cylinder Above Ground
Current Induced on a Half-Cylinder on a Ground Plane
Methods for Approximate Calculation of Current Induced on Objects Close to the Ground
Currents Induced in Large Objects
Currents Induced in TV and FM Antennas
Induced Current Summary Tables
Accuracy Expected in Calculating Induced Currents
Examples of Electric Induction Calculation
Single-Phase vs Three-Phase Induction
Electric Induction Calculation with Impedance to Ground
Statistical Impedance with Vehicles
Examples Calculations

8.4 Calculation of Magnetic Fields

General Method for Transmission Lines
Example Calculation

8.5 Measurement of Electric Fields

Techniques for the Measurements of the Unperturbed Electric Field
Measurements of the Electric Field on a Boundary Surface
Measurement of the Space Potential

8.6 Measurements of Magnetic Fields

8.7 Comparison Between HV Transmission-Line and Common Environment Electric and Magnetic Fields

8.8 Electric-Field Induction In Objects

Introduction
Transmission-Line Induced Currents
Currents Induced on a Sphere Above Ground
Current Induced on a Round-Topped Hemisphere on a Ground Plane
Current Induced on a Cylinder Above Ground
Current Induced on a Half-Cylinder on a Ground Plane
Methods for Approximate Calculation of Current Induced on Objects Close to the Ground
Currents Induced in Large Objects
Currents Induced in TV and FM Antennas
Induced Current Summary Tables
Accuracy Expected in Calculating Induced Currents
Examples of Electric Induction Calculation
Single-Phase vs Three-Phase Induction
Electric Induction Calculation with Impedance to Ground
Statistical Impedance with Vehicles
Examples Calculations

8.9 Magnetic Induction on Objects

Impedance Matrix with Ground Return
Shield Wire Currents
Induction in Conductive Objects Parallel to the Line

8.10 Electric-Field Induction in People

Induced Currents and Their Distribution
Electric Field Exposure Monitors
Exposure Measurements Within Field Ranges
Currents Induced by Spark Discharges
Transient Currents Induced by Switching Transients
People Response to Short-Term Exposure to Electric Fields

8.11 Biological Effects of Electric Fields on People and Animals

8.12 Magnetic Field Induction in People

8.13 Biological Effects of Magnetic Fields on People and Animals

References
8.14 Fuel Ignition
Introduction
Fuel Ignition Induced by Spark Discharge
Corona-Induced Fuel Ignition
Flashovers Caused by Fires

8.15 Trees and Poles in High-intensity Electric Fields
Introduction
Dead Tree-Tip Burning
Pole Fire with Grounded Hardware
Pole Fire Without Grounded Hardware
Mechanism Causing Wood Fires
Live Tree-Tip Corona Damage

8.16 Corona from Grounded Objects
Introduction
Measuring Techniques
Space Potential as the Independent Variable
Corona Current and Corona Power
Corona Onset
Radio Noise
Audible Noise
Ozone
Conclusions

8.17 Shielding Methods
Introduction
Shielding by a Horizontal Grid of Grounded Wires
Design Procedure
Shielding by a Vertical Grid of Grounded Wires
Shielding by Meshes of Grounded Wires
Natural Shields — Trees and Houses
Underbuilt Lower-Voltage Lines

Appendix 8.1 Calculation of Maximum Field

Appendix 8.2 Measurements of Electric Field with a Free-Body Meter

Appendix 8.3 Air Model Facility

Appendix 8.4 Transmission-Line Electric Induction Calculation with Matrices

Appendix 8.5 Magnetic Induction with Resistive Ground Return

References

Chapter 9 Insulation-Design Criteria

9.1 Introduction

9.2 Voltage Stress on Insulation
Introduction
System Voltage
Overvoltage

9.3 Characteristics of Overvoltages
Temporary Overvoltages
Switching Overvoltages
Switching of Reactive Circuits — Observed Phenomena
Fault Occurrence and Fault Clearing
Other Switching Operations
Recovery Voltage Across Breakers
Lightning-Querovoltages

9.4 Methods of Analysis
Introduction

9.5 Methods of Controlling Overvoltages
Introduction
Resistor Insertion
Breaker Timing Control
System Modification
Switching Restrictions
Line Discharge Resistors
Surge Arresters

9.6 Weather Considerations

9.7 Insulation Dielectric Strength
Withstand Voltage
Types of Insulation

9.8 Statistical Properties of Withstand Voltage

9.9 Stress vs Strength

Appendix 9.1 Resonant Voltages on Parallel, Reactor-Compensated Lines

Appendix 9.2 ABCD Method of Analysis

Appendix 9.3 Electrostatic Method of Analysis for Design Procedure

Appendix 9.4 Probability of Overvoltage Occurrence

References

Chapter 10 Insulation for Power Frequency Voltage

10.1 Introduction
Contamination Flashover on Transmission Systems
Research in the Field of Contamination Flashover

10.2 Survey of the Contamination Performance of Power Transmission Systems
Spot and Area Contamination
Types of Contaminants and Weather Conditions
Countermeasures

10.3 Contamination Test Methods
Introduction
Outline of Test Methods
Comparison of Test Methods

10.4 Research at Project UHV
Introduction
Insulators Tested
Power Sources for Testing
Influence of the Parameters of the Test Circuit
Factors that Affect Wetting Mechanisms
Investigation of Natural Wetting Conditions
Wetting Method and Contaminants Used at Project UHV
Flashover Probability of Contaminated Insulators
Performance of Various Types of Insulators in Short Strings
Performance of Insulators in Long Strings
Contamination Tests with Natural and Artificial Wetting Conditions
Nonlinearity of Flashover Strength with Insulator Length
Comparison of Electrical Strength for Different String Orientations