

# Contact Lines for Electric Railways

Planning  
Design  
Implementation

Friedrich KieRling,  
Rainer Puschmann,  
Axel Schmieder

PUBLICIS

**TOC**

# Contents

<b>1</b>	<b>Traction power supply systems</b>	<b>31</b>
1.1	Functions of traction power supply.	31
1.2	Traction power supply networks	31
1.2.1	Types of traction power supply systems.	31
1.2.2	Basic structure of the traction power supply.	34
1.2.2.1	Traction power generation	34
1.2.2.2	Traction power distribution	35
1.2.3	Direct current traction networks.	36
1.2.4	AC 16,7 Hz single-phase traction networks.	37
1.2.4.1	Traction power generation.	37
1.2.4.2	Types of 16,7 Hz traction power networks	38
1.2.5	50 Hz single-phase AC traction networks.	40
1.3	16,7 Hz traction power supply of the German Railway (DB).	43
1.3.1	Energy generation.	43
1.3.2	Energy transmission and contact line supply.	43
1.3.3	Standard 16,7 Hz substations of the German Railway.	44
1.3.3.1	Function and types of standard substations.	44
1.3.3.2	110 kV open air equipment.	45
1.3.3.3	15 kV indoor equipment.	48
1.3.3.4	Auxiliaries' supply.	50
1.3.3.5	Protection.	51
1.3.3.6	Supervisory control and data acquisition system (SCADA).	53
1.3.3.7	Buildings and supporting structures.	56
1.3.4	Power system control.	57
1.3.4.1	Development, functions and design.	57
1.3.4.2	Local control units and remote control lines.	58
1.3.4.3	Remote control technology of the SCADA.	59
1.3.4.4	Converters, remote control nodes and satellite control centres	60
1.3.4.5	Master control centres.	60
1.3.4.6	Transmission control and network command centres.	61
1.4	AC 25 kV 50 Hz traction power supply of the Madrid-Seville line.	61
1.4.1	Line supply and connection.	61
1.4.2	Substations and their components.	63
1.5	DC 750 V traction power supply of the Ankaray underground railway system.	64
1.5.1	Line supply and switching.	64
1.5.2	Substations and components.	65
1.6	References.	67

<b>2</b>	<b>Requirements and specifications</b>	<b>69</b>
2.1	Requirements on contact lines	69
2.1.1	General	69
2.1.2	Mechanical Requirements	70
2.1.3	Electrical requirements	70
2.1.4	Environmental requirements	71
2.1.5	Requirements of operation and maintenance	71
2.2	Requirements resulting from the track, line and operating conditions	72
2.2.1	Requirements and demands made on contact lines	72
2.2.2	Operating requirements	72
2.2.2.1	Main-line, long-distance traffic	72
2.2.2.2	Local-area traffic	74
2.2.3	Requirements due to track-related factors	75
2.2.3.1	Main-line, long-distance traffic	75
2.2.3.2	Urban and local-area traffic	76
2.2.4	Requirements due to the railway line location	76
2.2.4.1	Main line long-distance traffic	76
2.2.4.2	Local-area traffic	77
2.2.5	Requirements relating to the gauge	77
2.2.5.1	Main-line long distance traffic	77
2.2.5.2	Local-area traffic	80
2.3	Climatic conditions	83
2.3.1	Temperatures	83
2.3.2	Wind velocities	84
2.3.3	Ice accumulation	86
2.3.4	Active substances in the air	86
2.3.5	Lightning voltage surges	86
2.4	Specifications due to the pantograph	87
2.4.1	Design and functions	87
2.4.2	Properties of collector strips	90
2.4.3	Contact forces between the pantograph and the overhead contact line	91
2.4.3.1	Basics for static contact force	91
2.4.3.2	Aerodynamic contact force	92
2.4.3.3	Dynamic contact force	93
2.5	Specifications on reliability and safety	94
2.5.1	Standards	94
2.5.2	Loading and strength	94
2.5.3	Insulation co-ordination	95
2.5.4	Protection against electric shocks	97
2.5.4.1	General protection against electric shocks	97
2.5.4.2	Protection against electric shocks by direct contact	98
2.5.4.3	Protection against electric shocks by indirect contact	99
2.5.4.4	Protection against electric shocks caused by the track potential	101
2.6	Environmental compatibility	102

- 2.6.1 General . . . . . 102
- 2.6.2 Environmental relevance of electric traction . . . . . 102
- 2.6.3 Land Usage . . . . . 103
- 2.6.4 Nature and bird protection . . . . . 103
- 2.6.5 Aesthetics . . . . . 103
- 2.6.6 Electric and magnetic fields . . . . . 104
- 2.7 Physical characteristics of materials in contact line installations . . . . . 104
- 2.8 References . . . . . 107
- 3 Traction contact line systems and overhead contact line designs 109**
- 3.1 Terminology . . . . . 109
- 3.2 Overhead contact line types . . . . . 111
  - 3.2.1 Basic characteristics . . . . . 111
  - 3.2.2 Wires and stranded conductors . . . . . 112
    - 3.2.2.1 Types of wires and stranded conductors . . . . . 112
    - 3.2.2.2 Contact wires . . . . . 112
    - 3.2.2.3 Steel wires . . . . . 114
    - 3.2.2.4 Stranded conductors . . . . . 114
    - 3.2.2.5 Synthetic ropes . . . . . 115
  - 3.2.3 Trolley-type contact lines . . . . . 115
    - 3.2.3.1 Definition and application . . . . . 115
    - 3.2.3.2 Single-point suspension with fixed anchored contact wire . . . . . 115
    - 3.2.3.3 Pendant-type suspension with and without automatic tensioning . . . . . 116
    - 3.2.3.4 Bridle-type suspension . . . . . 116
    - 3.2.3.5 Elastic supports . . . . . 117
  - 3.2.4 Trolley-type contact line with stitch suspension . . . . . 117
  - 3.2.5 Overhead contact lines with catenary suspension . . . . . 118
    - 3.2.5.1 Basic design . . . . . 118
    - 3.2.5.2 Contact lines with droppers at the supports . . . . . 118
    - 3.2.5.3 Contact line with offset support droppers . . . . . 119
    - 3.2.5.4 Contact line with stitch suspension . . . . . 119
    - 3.2.5.5 Contact line with inclined suspension . . . . . 121
    - 3.2.5.6 Contact line with elastic dropper elements . . . . . 122
    - 3.2.5.7 Contact line with auxiliary catenary wire, compound contact line . . . . . 122
  - 3.2.6 Horizontal catenary overhead contact lines . . . . . 123
- 3.3 Conductor rails . . . . . 124
  - 3.3.1 Third rail installations . . . . . 124
  - 3.3.2 Types of conductor rail . . . . . 126
  - 3.3.3 Construction and operation of conductor rail installations . . . . . 127
- 3.4 Overhead conductor rail installations . . . . . 129
- 3.5 References . . . . . 132

<b>4 Design of contact lines and cross-span equipment</b>	<b>135</b>
4.1 Overhead contact line equipment	135
4.1.1 Basic design	135
4.1.2 Selection of the overhead contact line design	137
4.1.3 Selection of conductor cross sections and tensile forces	138
4.1.4 Selection of span lengths	139
4.1.5 Selection of system height	140
4.1.6 Design of contact lines in tunnels	141
4.1.7 Adoption of contact wire pre-sag	142
4.1.8 Selection of dropper spacing	142
4.1.9 Use of a stitch wire	143
4.1.10 Selection of tensioning section length	143
4.1.11 Design of connected and insulated overlaps	148
4.1.12 Design of overhead contact line equipment and its components	149
4.1.12.1 Configuration of overhead contact line equipment	149
4.1.12.2 Midpoint anchors	150
4.1.12.3 Automatic flexible tensioning	151
4.1.12.4 Fixed terminations	154
4.1.12.5 Dropper	155
4.1.12.6 Electrical connections	155
4.1.12.7 Electrical sectioning	156
4.1.12.8 Design of neutral sections and phase separations	157
4.2 Cross-span equipment	159
4.2.1 Introduction	159
4.2.2 Hinged cantilevers	160
4.2.3 Cantilevers across several tracks	164
4.2.4 Head-spans	164
4.2.4.1 Application	164
4.2.4.2 Design principles	165
4.2.4.3 Detailed structural design	166
4.2.5 Portal structures	167
4.2.6 Contact line pull-offs	169
4.2.7 Cross-span equipment in tunnels	169
4.3 Traction power lines	169
4.3.1 Definitions	169
4.3.2 Routing and supporting of traction power lines	171
4.4 Signals for electric traction	172
4.5 Guards to prevent accidental contact	173
4.6 Components and elements	173
4.6.1 Overhead line disconnectors	173
4.6.2 Insulators	175
4.6.2.1 Purpose and loadings	175
4.6.2.2 Insulating materials	176
4.6.2.3 Designs and applications	176

4.6.2.4	Electrical and mechanical rating . . . . .	177
4.6.2.5	Selection and application . . . . .	178
4.6.3	Clamps and connection fittings . . . . .	180
4.6.3.1	Purpose and rating . . . . .	180
4.6.3.2	Materials. . . . .	180
4.6.3.3	Overhead contact line equipment . . . . .	183
4.6.3.4	Hinged tubular cantilever. . . . .	185
4.6.3.5	Head span structure. . . . .	188
4.7	Systemisation of the overhead contact lines and their components. . . . .	190
4.8	Implemented contact line systems. . . . .	192
4.8.1	Mass transit systems. . . . .	192
4.8.2	Main line systems. . . . .	198
4.8.2.1	Overhead lines for DC 3 kV. . . . .	198
4.8.2.2	Overhead contact lines for AC 15 kV 16,7 Hz. . . . .	202
4.8.2.3	Overhead contact line for AC 25 kV 50 Hz. . . . .	208
4.9	References. . . . .	215
<b>5</b>	<b>Calculations for overhead contact line equipment</b>	<b>219</b>
5.1	Assumptions concerning loads and stresses. . . . .	219
5.1.1	Basic principles. . . . .	219
5.1.2	Dead loads. . . . .	219
5.1.3	Tensile forces and their components. . . . .	221
5.1.3.1	Tensile forces acting on conductors and wires. . . . .	221
5.1.3.2	Components of the tensile forces acting on conductors. . . . .	224
5.1.4	Wind loads. . . . .	229
5.1.5	Ice loads. . . . .	231
5.2	Sag. . . . .	232
5.2.1	Single trolley-type contact line. . . . .	232
5.2.1.1	Supports at equal height . . . . .	232
5.2.1.2	Supports at different heights. . . . .	233
5.2.1.3	Catenary suspended contact lines. . . . .	234
5.3	Physical state change equations. . . . .	236
5.4	Deflection due to wind. . . . .	240
5.4.1	Deflection due to wind on tangent track. . . . .	240
5.4.2	Deflection due to wind and contact wire stagger in curves. . . . .	241
5.4.2.1	Contact wire offset in still air. . . . .	241
5.4.2.2	Contact wire offset under wind load. . . . .	242
5.4.3	Deflection of overhead contact line equipment due to wind. . . . .	243
5.5	Longitudinal spans and tensioning section lengths. . . . .	247
5.5.1	Relevance of span and tension lengths. . . . .	247
5.5.2	Maximum possible spans. . . . .	247
5.5.2.1	Significant parameters. . . . .	247
5.5.2.2	Working range of pantograph head. . . . .	248
5.5.2.3	Lateral movement of the vehicle. . . . .	248

5.5.2.4	Contact wire limit position with deflection by wind . . . . .	250
5.5.2.5	Determination of longitudinal span lengths. . . . .	252
5.5.3	Calculating tensioning section lengths (tension lengths). . . . .	253
5.6	References. . . . .	255
<b>6</b>	<b>Planning of overhead contact line systems</b>	<b>257</b>
6.1	Objective and process. . . . .	257
6.2	Fundamentals and initial data . . . . .	260
6.2.1	General. . . . .	260
6.2.2	Technical requirements. . . . .	260
6.2.3	Planning documents. . . . .	260
6.2.3.1	Introduction. . . . .	260
6.2.3.2	New lines. . . . .	263
6.2.3.3	Existing lines. . . . .	265
6.2.3.4	Alterations. . . . .	265
6.2.3.5	Tracks and topography. . . . .	265
6.2.3.6	Circuit diagram . . . . .	266
6.3	Contact wire stagger and horizontal forces. . . . .	267
6.4	Determination of span lengths. . . . .	273
6.5	Tensioning section lengths. . . . .	274
6.6	Overlapping Sections. . . . .	276
6.7	Contact line above points. . . . .	277
6.7.1	Introduction. . . . .	277
6.7.2	Designation and drawing of track points. . . . .	277
6.7.3	Principles of overhead contact line wiring at track points. . . . .	281
6.7.4	Fitting-free area . . . . .	281
6.7.5	Arrangement of intersecting contact line wiring at points. . . . .	282
6.7.6	Definition of supports for crossing contact wires at track points . . . . .	284
6.7.7	Height of contact wires in points area. . . . .	287
6.7.8	Example for point wiring. . . . .	289
6.7.9	Tangential point wiring. . . . .	292
6.8	Route obstacles for wiring. . . . .	294
6.8.1	General. . . . .	294
6.8.2	Points. . . . .	295
6.8.3	Signals and signal visibility. . . . .	295
6.8.4	Railway crossings. . . . .	295
6.8.5	Engineering structures. . . . .	296
6.8.6	Electrical separations at stations and on open track. . . . .	300
6.9	Layout plan . . . . .	300
6.9.1	Objective and information. . . . .	300
6.9.2	Overhead contact line system symbols . . . . .	301
6.9.3	Contact line equipment supports and pole locations. . . . .	301
6.9.4	Single poles. . . . .	306
6.9.5	Head-span structures . . . . .	307

6.9.6	Multiple-track cantilevers. . . . .	307
6.9.7	Portals. . . . .	307
6.9.8	Tunnel supports. . . . .	307
6.9.9	Electrical connections. . . . .	307
<b>6.9.10</b>	<b>Return current circuits and protective earthing. . . . .</b>	<b>308</b>
6.9.11	Signals for electric traction. . . . .	311
<b>6.9.12</b>	<b>Establishing layout plans. . . . .</b>	<b>311</b>
<b>6.10</b>	<b>Transverse profile diagram. . . . .</b>	<b>312</b>
<b>6.10.1</b>	<b>Objective and information. . . . .</b>	<b>312</b>
<b>6.10.2</b>	<b>Types of poles and their classification. . . . .</b>	<b>312</b>
<b>6.10.3</b>	<b>Pole geometry. . . . .</b>	<b>315</b>
<b>6.10.4</b>	<b>Transverse switching lines, disconnectors on poles. . . . .</b>	<b>315</b>
<b>6.10.5</b>	<b>Determination of pole lengths. . . . .</b>	<b>315</b>
<b>6.10.6</b>	<b>Cantilevers. . . . .</b>	<b>318</b>
<b>6.10.7</b>	<b>Pole and foundation selection. . . . .</b>	<b>319</b>
<b>6.10.8</b>	<b>Head-span structures. . . . .</b>	<b>320</b>
<b>6.10.9</b>	<b>Portals. . . . .</b>	<b>323</b>
<b>6.11</b>	<b>Longitudinal profiles. . . . .</b>	<b>325</b>
<b>6.11.1</b>	<b>Contents. . . . .</b>	<b>325</b>
<b>6.11.2</b>	<b>Dropper arrangement. . . . .</b>	<b>325</b>
<b>6.11.3</b>	<b>Contact wire height reductions. . . . .</b>	<b>326</b>
6.11.4	Traction power line longitudinal profile. . . . .	326
6.11.5	Minimum clearances to overhead lines and traction feeder lines . . . . .	327
<b>6.11.6</b>	<b>Traction power lines. . . . .</b>	<b>328</b>
6.11.6.1	Introduction. . . . .	328
6.11.6.2	Line attachment to poles. . . . .	328
6.11.6.3	Clearance verification. . . . .	329
<b>6.12</b>	<b>Project documentation. . . . .</b>	<b>335</b>
<b>6.13</b>	<b>Computer supported configuration. . . . .</b>	<b>336</b>
<b>6.13.1</b>	<b>Objectives. . . . .</b>	<b>336</b>
<b>6.13.2</b>	<b>Structure and modules. . . . .</b>	<b>337</b>
<b>6.13.3</b>	<b>Data management. . . . .</b>	<b>337</b>
<b>6.13.4</b>	<b>Hardware and software. . . . .</b>	<b>339</b>
<b>6.13.5</b>	<b>Application. . . . .</b>	<b>339</b>
<b>6.14</b>	<b>References. . . . .</b>	<b>340</b>
<b>7</b>	<b>Cross-span structures, poles and foundations</b>	<b>341</b>
<b>7.1</b>	<b>Loading assumption. . . . .</b>	<b>341</b>
7.1.1	Introduction. . . . .	341
7.1.2	Permanent loads. . . . .	341
7.1.3	Variable loads. . . . .	342
7.1.3.1	General. . . . .	342
7.1.3.2	Wind loads. . . . .	342
7.1.3.3	Ice loads. . . . .	344



7.1.3.4	Simultaneous action of wind and ice . . . . .	345
7.1.4	Loadings due to erection and maintenance. . . . .	345
7.2	Transverse support equipment and poles. . . . .	345
7.2.1	Transverse support equipment. . . . .	345
7.2.1.1	Types of support equipment . . . . .	345
7.2.1.2	Swivel cantilevers. . . . .	345
7.2.1.3	Cantilever across several tracks. . . . .	346
7.2.1.4	Flexible transverse support equipment . . . . .	347
7.2.1.5	Portal structures. . . . .	347
7.3	Poles. . . . .	348
7.3.1	Types of poles. . . . .	348
7.3.2	Loading assumptions. . . . .	349
7.3.3	Structural design and materials. . . . .	350
7.4	Rating of cross-span supports. . . . .	352
7.4.1	Introduction. . . . .	352
7.4.2	Cantilevers. . . . .	353
7.4.2.1	Loading and internal forces and moments. . . . .	353
7.4.2.2	Rating based on Eurocodes. . . . .	355
7.4.3	Flexible cross-supporting structures. . . . .	357
7.4.3.1	Introduction. . . . .	357
7.4.3.2	Loading, internal forces and sag of head span wires. . . . .	357
7.4.3.3	Height of installation, determination of pole lengths. . . . .	359
7.4.3.4	Loadings and internal forces of cross-span wires. . . . .	360
7.4.3.5	Rating of head-span wires, cross-span wires and supports. . . . .	360
7.4.4	Horizontal registration arrangements. . . . .	361
7.5	Rating of poles. . . . .	363
7.5.1	Introduction. . . . .	363
7.5.2	Determination of pole length. . . . .	363
7.5.3	Loadings and internal forces and moments. . . . .	363
7.5.4	Rating of cross sections. . . . .	366
7.5.4.1	Introduction. . . . .	366
7.5.4.2	Lattice steel poles. . . . .	366
7.5.4.3	Double channel poles. . . . .	369
7.5.4.4	H-beam poles. . . . .	370
7.5.4.5	Steel reinforced concrete poles. . . . .	372
7.5.4.6	Deflection. . . . .	374
7.6	Subsoil. . . . .	376
7.6.1	Introduction. . . . .	376
7.6.2	Undisturbed soil. . . . .	376
7.6.2.1	Classification. . . . .	376
7.6.2.2	Non-cohesive, rolling soils. . . . .	377
7.6.2.3	Cohesive soils. . . . .	377
7.6.2.4	Organic soils. . . . .	377
7.6.3	Rock. . . . .	378

7.6.4	Soil	fill	378
7.6.5	Soil investigation		378
7.6.6	Methods of obtaining soil samples		378
7.6.6.1	Introduction		378
7.6.6.2	Investigation boring		379
7.6.6.3	Investigation by probes		379
7.6.7	Probing		380
7.6.7.1	Introduction		380
7.6.7.2	Driven probes in accordance with DIN 4094		380
7.6.7.3	Standard Penetration Test		381
7.6.8	Evaluation of soil investigation		381
7.6.9	Soil characteristics		382
7.6.10	Practical application		382
7.7	Foundations		385
7.7.1	Basis of design		385
7.7.2	Block foundations without steps		385
7.7.3	Block foundations with steps		388
7.7.4	Driven pile foundations		391
7.7.5	Anchor foundations		395
7.8	Example		397
7.8.1	Data of contact line		397
7.8.2	Design according to recent European standards		398
7.8.2.1	Loadings		398
7.8.2.2	Design of pole		399
7.8.2.3	Cantilever		401
7.8.3	Foundation		403
7.9	References		405
<b>8</b>	<b>Contact line designs for special applications</b>		<b>409</b>
8.1	Introduction		409
8.2	Maintenance installations		409
8.3	Tunnel seals		411
8.4	Separation between electrification systems		412
8.4.1	Introduction		412
8.4.2	System separation sections on open lines		412
8.4.3	Stations with two power supply systems		414
8.5	Movable bridges		415
8.5.1	Introduction		415
8.5.2	Contact line design		416
8.5.2.1	Folding bridges		416
8.5.2.2	Swivelling bridges		418
8.5.2.3	Lifting bridges		420
8.5.3	Electrical connections and signalling		422
8.6	Level crossings of lines fed by differing power supply systems		423

8.6.1	Crossing between mainline railways and tramways. . . . .	423
8.6.2	Crossings between light-rail and trolley bus lines. . . . .	424
8.7	Contact line design above level crossings. . . . .	426
8.7.1	Arrangements for standard height transports. . . . .	426
8.7.2	Arrangements for oversize transports with permanently increased contact wire heights. . . . .	427
8.7.3	Arrangement of gaps within the overhead contact line. . . . .	428
8.7.4	Temporary lifting of contact line by movable cantilevers. . . . .	429
8.7.4.1	General. . . . .	429
8.7.5	Temporary lifting or removing of the contact lines by manual procedures	431
8.8	Container terminals, loading and checking tracks, railway lines in mines . .	432
8.8.1	Swiveling contact lines. . . . .	432
8.8.2	Circuit diagrams for loading and checking tracks. . . . .	433
8.8.3	Swivelling stopes and laterally arranged overhead contact lines. . . .	434
8.9	References. . . . .	436
<b>9</b>	<b>Interaction of pantographs and overhead contact lines</b>	<b>439</b>
9.1	Introduction. . . . .	439
9.2	Technical principles. . . . .	439
9.2.1	Propagation of transversal impulses along the length of a contact wire under tension. . . . .	439
9.2.2	Behaviour of the taut contact wire when subjected to a constant force applied at a point moving along it. . . . .	441
9.2.3	Contact wire uplift at high speeds. . . . .	442
9.2.4	How a concentrated mass reflects transversal impulses travelling along a contact wire. . . . .	445
9.2.5	How a dropper reflects transversal impulses travelling along a contact wire. . . . .	447
9.2.6	Doppler factor. . . . .	449
9.2.7	Natural frequencies of an overhead contact line. . . . .	451
9.2.8	Dynamic characteristics of typical overhead contact line designs . . . .	451
9.3	Simulation of interaction of overhead contact lines and pantographs . . . .	453
9.3.1	Purpose and objectives. . . . .	453
9.3.2	Model of the pantograph system. . . . .	454
9.3.3	Contact line system models. . . . .	456
9.3.3.1	Basic considerations. . . . .	456
9.3.3.2	Modelling with the aid of the finite-element method [0.16]. . . . .	457
9.3.3.3	Analytical solution in the frequency area [0.14]. . . . .	457
9.3.3.4	Method using frequency-dependent finite elements. . . . .	457
9.3.3.5	Modelling on the basis of d'Alambert's wave equations [0.5] . . . . .	458
9.3.4	Overhead contact line installation models using frequency-dependent finite elements. . . . .	458
9.3.4.1	Mathematical description. . . . .	458
9.3.4.2	Natural frequency calculation example. . . . .	462

9.3.4.3	Contact force calculation . . . . .	463
9.3.4.4	Examples for contact force calculations. . . . .	465
9.4	Measurements and tests. . . . .	466
9.4.1	Introduction. . . . .	466
9.4.2	Contact force measurements. . . . .	468
9.4.2.1	Basic principles. . . . .	468
9.4.2.2	Measuring technology. . . . .	468
9.4.2.3	Measured quantities. . . . .	472
9.4.2.4	Correction of the aerodynamic collector strip uplift. . . . .	475
9.4.2.5	Evaluation and assessment of the measurement results. . . . .	476
9.4.3	Measurement of the overhead contact line position and the thickness of the contact wire. . . . .	479
9.4.4	Assessment of dynamic characteristics of pantographs. . . . .	482
9.4.5	Measurement of contact wire uplift and dynamic contact line elasticity. . . . .	484
9.4.5.1	Stationary measurement of contact wire uplift. . . . .	484
9.4.5.2	Mobile measurement of the contact wire uplift. . . . .	486
9.4.5.3	Measurement of the dynamic elasticity of the overhead contact line. . . . .	486
9.5	Effect of the design parameters. . . . .	487
9.5.1	Introduction. . . . .	487
9.5.2	Criteria for overhead contact line installation designs. . . . .	487
9.5.2.1	Elasticity and uplift. . . . .	487
9.5.2.2	Dynamic criteria. . . . .	490
9.5.3	Overhead contact line design parameters. . . . .	492
9.5.3.1	Cross-sectional areas and tensile stress. . . . .	492
9.5.3.2	Span lengths and system height. . . . .	494
9.5.3.3	Pre-sag and stitch wires. . . . .	496
9.5.3.4	Effect of adjustment accuracy. . . . .	498
9.5.4	Pantograph design parameters. . . . .	499
9.5.4.1	Introduction. . . . .	499
9.5.4.2	Features of pantograph designs. . . . .	499
9.5.4.3	Trains running with multiple pantographs. . . . .	502
9.5.4.4	Collector strip and contact wire materials. . . . .	504
9.6	Conclusions. . . . .	507
9.6.1	Limits on the transmission of energy via overhead contact lines and pantographs. . . . .	507
9.6.2	Overhead contact line requirements. . . . .	509
9.6.3	Pantograph requirements. . . . .	509
9.6.4	Requirements concerning the interaction of overhead contact lines and pantographs. . . . .	511
9.7	References. . . . .	512
<b>10</b>	<b>Currents and voltages in traction power supply networks</b>	<b>517</b>
<b>10.1</b>	<b>Introduction. . . . .</b>	<b>517</b>
<b>10.2</b>	<b>Electrical characteristics of contact lines. . . . .</b>	<b>517</b>

10.2.1	Basic relations	517
10.2.2	Impedances	518
10.2.2.1	Components	518
10.2.2.2	Resistance per unit length	519
10.2.2.3	Inductance per unit length	522
10.2.2.4	Impedance per unit length	525
10.2.2.5	Measuring the impedances of contact lines	526
10.2.2.6	Calculated and measured impedances per unit length - comparisons	530
10.2.3	Track-to-earth leakage per unit length	534
10.2.4	Capacitances per unit length	536
10.3	Voltage regulation in contact line networks	538
10.3.1	basic requirements	538
10.3.2	Basic principles	539
10.3.3	Voltage drop calculations	541
10.3.3.1	Introduction	541
10.3.3.2	Single-end feed	541
10.3.3.3	Double-end feed	543
10.3.4	Other calculation algorithms	546
10.4	Operating currents	548
10.4.1	General	548
10.4.2	Traction currents of traction units	548
10.4.3	Currents in a contact line section	548
10.4.3.1	basic considerations	548
10.4.3.2	General-purpose railway lines	549
10.4.3.3	High-speed and heavy-traffic railway lines	551
10.5	Contact line circuits	552
10.5.1	Basic requirements on contact line circuits	552
10.5.2	Basic types of circuits	553
10.5.3	Contact line installation circuits used by the German railways, DB	555
10.5.4	Disconnectors	560
10.6	References	560
<b>11</b>	<b>Current-carrying capacity and protective provisions</b>	<b>563</b>
11.1	Current-carrying capacity of electric traction contact lines	563
11.1.1	Electric traction power load	563
11.1.1.1	Power requirements	563
11.1.1.2	Railways for general traffic	563
11.1.1.3	High-speed and heavy-duty railway lines	569
11.1.1.4	Short-circuit loads	571
11.1.2	Current-carrying capacity	576
11.1.2.1	Introduction	576
11.1.2.2	Differential equation describing the heating of contact wires	576
11.1.3	Current capacity in case of varying operational currents	577
11.1.3.1	Differential equation of contact line heating	577

11.1.3.2	Parameters affecting the current-carrying capacity of a conductor .	579
11.1.3.3	Current-carrying capacity of individual contact wires or conductors	585
11.1.3.4	Current-carrying capacity of overhead contact lines. . . . .	586
11.1.3.5	Current-carrying capacity of conductor rails. . . . .	588
11.1.3.6	Short-term current-carrying capacity and reference strength . . . .	589
11.1.3.7	Short-circuit current-carrying capacity. . . . .	590
11.1.3.8	Fusing current . . . . .	592
£-11.1.4	Thermal design calculations . . . . .	593
f	11.1.4.1 Maximum principle. . . . .	593
'"	11.1.4.2 Matching load and current-carrying capacity characteristics . . . .	593
11.2	Effect of the temperature on contact wire characteristics. . . . .	595
I	11.2.1 Introduction. . . . .	595
'	11.2.2 Metallurgical principles . . . . .	596
∴	11.2.3 Effect of heating on the tensile strength . . . . .	598
•	11.2.4 Effect of exposure to increased heat on tensile strength . . . . .	600
	11.2.5 Heating and reduction of contact wire tensile strength at locations subject to increased wear and at connection terminals. . . . .	603
	11.2.6 The tensile strength of contact wires at the contact wire collector strip interface. . . . .	605
	11.2.7 Conclusions. . . . .	607
11.3	Contact line protection and fault location. . . . .	608
	11.3.1 Purpose of protective provisions for contact lines. . . . .	608
	11.3.2 Protective provisions for overhead contact lines used by the D B . . . .	610
	11.3.3 Fault localisation. . . . .	615
11.4	References. . . . .	617
<b>12</b>	<b>Current return circuit and earthing</b>	<b>621</b>
12.1	Introduction. . . . .	621
12.2	Terms and Definitions. . . . .	622
	12.2.1 Introduction. . . . .	622
	12.2.2 Earth. . . . .	622
	12.2.3 Earth electrode. . . . .	623
	12.2.4 Soil resistivity and resistance to earth. . . . .	623
	12.2.5 Structure earth, tunnel earth, traction system earth . . . . .	623
	12.2.6 Earth potential and rail potential . . . . .	624
	12.2.7 Touch voltage. . . . .	624
	12.2.8 Accessible voltage. . . . .	624
	12.2.9 Overhead contact line zone and pantograph zone. . . . .	625
	12.2.10 Return circuit . . . . .	625
	12.2.11 Stray Current . . . . .	625
12.3	Basic principles. . . . .	626
	12.3.1 Return circuit. . . . .	626
	12.3.2 Rail potentials. . . . .	630
	12.3.2.1 General aspects. . . . .	630

12.3.2.2	Track-to-earth voltage in operational conditions. . . . .	632
12.3.2.3	Track-to-earth voltage in the case of short circuits. . . . .	634
12.3.3	Safety. . . . .	635
12.3.4	Security. . . . .	635
12.3.5	Stray current corrosion. . . . .	636
12.3.6	Common features of and differences between AC and DC railways . . .	636
12.3.7	Measurements. . . . .	638
12.4	Earth as a conductor. . . . .	638
12.4.1	Soil resistivity and conductivity. . . . .	638
12.4.2	Track-earth circuit . . . . .	640
12.4.2.1	General. . . . .	640
12.4.2.2	Track-earth circuit of DC systems. . . . .	641
12.4.2.3	Track-earth circuit of AC systems. . . . .	643
12.4.3	Earth electrodes in the vicinity of railways. . . . .	647
12.4.3.1	Earth resistance of electrodes and pole earthing. . . . .	647
12.4.3.2	Effective leakance per unit length. . . . .	650
12.5	Direct-current traction systems. . . . .	650
12.5.1	Design of the return circuit and earthing installations. . . . .	650
12.5.2	Safety of persons. . . . .	652
12.5.3	Stray current protection. . . . .	653
12.5.3.1	General information on stray current corrosion. . . . .	653
12.5.3.2	Effect of the polarity. . . . .	656
12.5.3.3	Protective measures against stray current corrosion. . . . .	657
12.5.4	Stray current collecting nets. . . . .	659
12.5.5	Design of DC installations with respect to return circuit and earthing .	660
12.5.5.1	Basic recommendations. . . . .	660
12.5.5.2	Railway-owned earthing systems. . . . .	661
12.5.5.3	Earthing measures for the three-phase power supply. . . . .	662
12.5.5.4	Traction substations. . . . .	662
12.5.5.5	Line sections in the open. . . . .	663
12.5.5.6	Passenger stations. . . . .	664
12.5.5.7	Signalling and telecommunications installations. . . . .	664
12.5.5.8	Depot and workshop area. . . . .	664
12.5.5.9	Tunnels. . . . .	666
12.5.5.10	Lightning protection. . . . .	668
12.5.5.11	Third party earthing installations. . . . .	668
12.5.5.12	Construction of DC earthing installations and provisions. . . . .	669
12.5.5.13	Verification measurements. . . . .	669
12.5.6	Practical experience with the Ankaray LRT system. . . . .	669
12.5.6.1	Description of the project . . . . .	669
12.5.6.2	Measurement of the resistance to earth. . . . .	670
12.5.6.3	Measurement of rail potentials. . . . .	670
12.5.6.4	Test of rail insulation. . . . .	670
12.5.6.5	Measurement of the potential between structure earth and earth .	670

- 12.5.6.6 Current through short-circuiting devices in the stations . . . . . 671
- 12.5.7 Maintenance. . . . . 671
- 12.5.8 Concluding recommendations. . . . . 672
- 12.6 Alternating current traction systems. . . . . 672
- 12.6.1 Design of the return circuit and earthing installations. . . . . 672
  - 12.6.1.1 General . . . . . 672
  - 12.6.1.2 Current return through rails and earth buried return conductors . 673
  - 12.6.1.3 Parallel return conductors. . . . . 674
  - 12.6.1.4 Auto-transformers. . . . . 676
  - 12.6.1.5 Booster transformers. . . . . 677
- 12.6.2 Requirements of return circuit and earthing installations. . . . . 677
  - 12.6.2.1 Personal safety. . . . . 677
  - 12.6.2.2 Interference. . . . . 680
- 12.6.3 Design of installations. . . . . 680
  - 12.6.3.1 Return circuit . . . . . 680
  - 12.6.3.2 Substations and stations. . . . . 682
  - 12.6.3.3 At-grade sections. . . . . 683
  - 12.6.3.4 Tunnel sections. . . . . 683
  - 12.6.3.5 Viaducts. . . . . 685
  - 12.6.3.6 Depot and workshop area . . . . . 685
  - 12.6.3.7 Signalling and telecommunications systems. . . . . 686
  - 12.6.3.8 Third-party installations. . . . . 686
  - 12.6.3.9 Lightning protection. . . . . 687
  - 12.6.3.10 Implementation. . . . .
  - 12.6.3.11 Verification measurements. . . . .
- 12.6.4 Return current conductors and earthing systems used by the DB . . . 689
  - 12.6.4.1 Track and rail bonds. . . . . 689
  - 12.6.4.2 Track release circuits, traction return current path and traction earth691
  - 12.6.4.3 Traction system earth connections of concrete structures. . . . . 693
- 12.6.5 Current return and earthing for the Madrid-Seville AC 25 kV high-speed line. . . . . 694
- 12.6.6 Concluding recommendations. . . . . 697
- 12.7 References. . . . . 698

**13 Electric traction contact lines as emitters of electromagnetic disturbance 703**

- 13.1 Introduction. . . . . 703
- 13.2 Coupling mechanisms. . . . . 704
- 13.3 Interference parameters. . . . . 704
  - 13.3.1 Overview. . . . . 704
  - 13.3.2 Operating currents and short-circuit currents. . . . . 705
  - 13.3.3 Higher harmonics. . . . . 706
    - 13.3.3.1 General . . . . . 706
    - 13.3.3.2 Single-phase AC railways. . . . . 706



13.3.3.3	Direct-current railways . . . . .	710
13.4	Interference due to single-phase AC railways . . . . .	711
13.4.1	Introduction . . . . .	711
13.4.2	Galvanic interference . . . . .	711
13.4.3	Inductive interference . . . . .	712
13.4.4	Capacitive interference . . . . .	717
13.5	Electric and magnetic fields in the vicinity of traction contact lines . . . . .	718
13.5.1	Basics . . . . .	718
13.5.2	Effects of electromagnetic fields on human beings . . . . .	718
13.5.3	Effect of fields on equipment . . . . .	719
13.5.3.1	Effects in general . . . . .	719
13.5.3.2	Persons with implanted cardiac pacemakers . . . . .	722
13.5.3.3	Information technology and electronic data processing equipment . . . . .	722
13.5.3.4	Electric railways as sources of radio-frequency interference . . . . .	722
13.6	Conclusions . . . . .	724
13.7	References . . . . .	725
<b>14</b>	<b>Erection and operation</b>	<b>729</b>
14.1	Basic definitions . . . . .	729
14.2	Erection . . . . .	729
14.2.1	Principles . . . . .	729
14.2.2	Production and testing standards for components . . . . .	729
14.2.3	Construction and assembly work . . . . .	731
14.2.3.1	Introduction . . . . .	731
14.2.3.2	Foundation and pole setting work . . . . .	732
14.2.3.3	Erection and adjustment of the overhead line supports and contact lines . . . . .	733
14.2.3.4	Installation of section insulators, cross-over contact lines, traction power supply lines and railway earthings . . . . .	736
14.2.4	Acceptance and commissioning . . . . .	737
14.3	Operate . . . . .	737
14.3.1	Training and instruction of staff . . . . .	737
14.3.2	Electrotechnical conduct standards and service guidelines . . . . .	738
14.3.3	Switching . . . . .	739
14.3.4	Irregularities and their recognition . . . . .	741
14.4	Wear and ageing . . . . .	741
14.4.1	Classification of components . . . . .	741
14.4.2	Concrete poles and foundations . . . . .	742
14.4.3	Steel poles, cantilevers and other support structures . . . . .	743
14.4.4	Traction power supply lines, messenger wires, droppers and connectors . . . . .	744
14.4.5	Contact wires . . . . .	745
14.4.6	Insulators . . . . .	747
14.4.7	Disconnectors and section insulators . . . . .	749
14.5	Maintenance . . . . .	750

14.5.1	Scope of maintance. . . . .	750
14.5.2	Reliability. . . . .	750
14.5.3	Diagnostics. . . . .	755
14.5.4	Statistical recording and analysis of faults. . . . .	759
14.5.5	Corrective maintenance. . . . .	761
1.6	Recycling and disposal. . . . .	762
B4.6.1	Dismantling. . . . .	762
14.6.2	Suitable preparation and disposal of materials for recycling. . . . .	763
1.7	Equipment for installation and maintenance. . . . .	763
14.7.1	Tools and equipment. . . . .	763
14.7.2	Special vehicles. . . . .	766
14.7.3	Measuring and diagnostic equipment. . . . .	774
18	Life cycle consideration. . . . .	774
19	References. . . . .	777
<b>Appendix 1: Standards and regulations</b>		<b>781</b>
<b>appendix 2: Frequently used abbreviations</b>		<b>791</b>
Index		<b>795</b>