3.0 Life Cycle Costing .................................................. 56
  3.1 Introduction......................................................... 56
  3.1.1 The Future Value of Money – Net Present Value...... 56
  3.1.1.1 Monthly Payments........................................ 59
  3.1.2 Loading............................................................. 60
  3.1.3 Lifetime.............................................................. 60
  3.1.4 Sensitivity Analysis............................................ 60
  3.2 Application to an Electrical Installation..................... 60
  3.2.1 Installation Design............................................. 61
  3.2.2 Installation Costs............................................... 61
  3.2.3 Recurring Costs.................................................. 61
  3.2.3.1 Maintenance Costs....................................... 61
  3.2.3.2 Energy.......................................................... 61
  3.2.4 End of Life Costs............................................... 68
  3.3 Conclusion........................................................... 68

4.0 Short-Circuit Effects.............................................. 69
  4.1 Introduction......................................................... 69
  4.2 Short-Circuit Heating of Bars................................... 69
  4.3 Electromagnetic Stresses......................................... 70
    4.3.1 Estimating the Forces Between Parallel Sets of Bars... 72
    4.3.1.1 Round Bars................................................... 72
    4.3.1.1.1 Triangular Array....................................... 73
    4.3.1.1.2 In-Line Array.......................................... 74
    4.3.1.2 Bars of Rectangular Section.......................... 74
  4.4 Mounting Arrangements.......................................... 76
    4.4.1 Maximum Permissible Stress................................ 76
    4.4.1.1 Moment of Inertia........................................ 77
    4.4.2 Deflection...................................................... 78
    4.4.3 Natural Frequency........................................... 78

5.0 Busbar Profiles .................................................... 79
  5.1 Introduction......................................................... 79
  5.2 Reasons for Using Profiles..................................... 79
    5.2.1 Skin Effect Reduction....................................... 79
    5.2.2 Weight and Cost Saving.................................... 79
    5.2.3 Integrated Fixings and Mountings........................ 80
    5.2.4 Retention of Intellectual Integrity....................... 80
  5.3 Economics of Profiles........................................... 80
  5.4 Practical Profiles.................................................. 80
    5.4.1 Manufacturing Process..................................... 80
    5.4.1.1 EN 13605..................................................... 80
    5.4.2 Design for Manufacturing................................... 84
    5.4.2.1 Wall Thickness............................................ 84
    5.4.2.2 Avoid Sharp Corners..................................... 84
    5.4.2.3 Symmetry.................................................... 84
    5.4.2.4 Be Compact................................................ 85
    5.4.2.5 Avoid Deep Narrow Channels.......................... 85
    5.4.2.6 Avoid Hollow Chambers................................ 85
    5.4.3 Functional Design............................................. 85
5.5 Electrical Design Considerations ........................................ 85
5.5.1 Skin Effect .................................................................. 85
5.5.2 Thermal Dissipation ...................................................... 86
5.5.3 Jointing and Mounting ................................................... 87
5.5.4 Short Circuit Performance -
  Moment of Inertia .................................................................. 88
5.6 Calculation of Moment of Inertia of Complex Sections .... 88

6.0 Jointing of Copper Busbars .................. 90
  6.1 Introduction ................................................................. 90
  6.2 Busbar Jointing Methods .............................................. 90
  6.3 Joint Resistance ........................................................... 91
    6.3.1 Streamline Effect .................................................... 92
    6.3.2 Contact Resistance ................................................ 94
    6.3.2.1 Condition of Contact Surfaces ............................ 94
    6.3.2.2 Effect of Pressure on Contact Resistance .......... 94
  6.4 Bolting Arrangements .................................................. 98
    6.4.1 Joint Efficiency ....................................................... 99
  6.5 Clamped Joints ............................................................. 101
  6.6 Degradation Mechanisms ............................................. 101
    6.6.1 Oxidation .............................................................. 101
    6.6.2 Corrosion .............................................................. 102
    6.6.3 Fretting ................................................................. 102
    6.6.4 Creep and Stress Relaxation .................................... 102
    6.6.5 Thermal Expansion ................................................ 102
  6.7 Conclusion ................................................................. 102

Annex: Coatings ............................................................... 103
  A1.0 Introduction ............................................................... 103
  A2.0 Reasons for Coating ................................................ 103
    A2.1 Coating to Provide Electrical Insulation .................. 103
    A2.2 Coating to Inhibit Corrosion .................................... 103
    A2.2.1 Metal Coatings .................................................... 103
    A2.2.2 Non-Metallic Coatings ......................................... 103
    A2.3 Coating to Increase Current Rating ......................... 103
    A2.4 Coating for Cosmetic Purposes ............................... 104
    A2.5 Coating to Improve Joint Performance ................. 104
  A3.0 Methods of Coating .................................................. 104
    A3.1 Factory Application Methods ................................. 104
    A3.1.1 Extrusion ........................................................... 104
    A3.1.2 Powder Coating .................................................. 105
    A3.2 On-Site Application Methods ................................... 105
    A3.2.1 Heat-Shrinkable Sleeve ...................................... 105
    A3.2.2 Painting ............................................................. 105
    A3.2.2.1 Alkyd Paints .................................................. 105
    A3.2.2.2 Two-Part Epoxy ............................................. 105
  A4.0 Inspection and Maintenance ............................... 105

Tables

Table 1 Properties of Typical Grades of Copper and Aluminium .................. 7
Table 2 Properties of 100% IACS Copper ........................................... 7
Table 3 Implied Properties of 100% IACS Copper ............................... 8
Table 4 Comparison of Creep Properties of HC Copper and Aluminum ................. 12
Table 5 Comparison of Fatigue Properties of HC Copper and Aluminium ..... 12
Table 6 Minimum Bend Radius of HC Copper and Aluminium ................. 13
Table 7 Self-extinguishing Arches in Copper and Aluminium Busbars ...... 13
Table 8 Discount Factors for Various Discount Rates ............................. 57
Table 9 Maximum Working Current for a Range of Busbar Sizes .......... 62
Table 10 Resistance and Power Loss at 500 Amps ................................ 62
Table 11 Energy Cost Per Metre for Various Widths of Copper Bars at 500 A Load 63
Table 12 Present Value (€) per Metre of Bar ..................................... 67
Table 13 Power Factor and Peak Current ........................................ 71
Table 14 Tolerances for Dimensions b and h for \( b_{\text{max}} \)
    or \( h_{\text{max}} < 20:1 \) .................................................. 82
Table 15 Tolerances for Dimensions b and h for \( b_{\text{max}} \)
    or \( h_{\text{max}} > 20:1 \) .................................................. 82
Table 16 Thickness Tolerances .................................................. 82
Table 17 Coefficient for Twist Tolerance ....................................... 84
Table 18 Maximum Sizes of Profile According to Two Manufacturers .... 84
Table 19 Nut Factors for Different States of Lubrication .................... 96
Table 20 Proof Strength and Coefficient of Thermal Expansion for Copper and Typical Bolt Materials 96
Table 21 Typical Thread Characteristics ..................................... 97
Table 22 Typical Busbar Bolting Arrangements ................................ 99

Figures

Figure 1 Effect of small concentrations of impurities on the
  resistivity of copper ...................................................... 8
Figure 2 Effect of cold rolling on mechanical properties and
  hardness of high conductivity copper strips ...................... 10
Figure 3 Typical creep properties of commercially pure
  copper and aluminium .................................................. 12
Figure 4 Heat dissipation by convection from a vertical surface
  for various temperature rises above ambient .................... 16
Figure 5 Convection loss from typical bar sections ...................... 17
Figure 6 Heat dissipation by radiation from a surface assuming relative emissivity of 0.5 and surroundings at 30°C .... 18
Figure 7 Radiation loss from typical bar sections ...................... 19
Figure 8 Convection and radiation losses at various
  temperatures ............................................................... 20
Figure 9 Total heat losses for a single bar of various
  heights against temperature rise .................................... 20
Figure 10 Total heat losses for each bar of a parallel pair of
  various heights against temperature rise ....................... 21
Figure 11  Parameter $p$ versus cross-sectional area in mm$^2$ for typical copper at 80°C..........................23
Figure 12  Resistivity of typical HC copper (101.5% IACS) as a function of temperature............................25
Figure 13  Skin depth of typical HC copper (101.5% IACS) at 50 Hz, 60 Hz, 400 Hz as a function of temperature...25
Figure 14  dc resistance of typical HC Copper (101.5% IACS) versus area at 20°C and 80°C..........................26
Figure 15  Plots of shape factor versus $\gamma$......................................................29
Figure 16  Factor $A$ for round bars as a function of $\gamma$................................................30
Figure 17  Proximity factor, $S_p$, for single phase systems with parallel round bars...........................................31
Figure 18  Mean proximity factors for flat arrangement of round bars carrying balanced three phase currents...32
Figure 19  Mean proximity factors for delta arrangement of round bars carrying balanced three phase currents...33
Figure 20  Shape factor for tubes..................................................................................35
Figure 21  Shape factor for tubes with low values of shape factor..............................................35
Figure 22  Shape factor for tubes..................................................................................36
Figure 23  The shape factor computed from the Bessel function formula using $\nu(\nu_d/\omega)$ as the frequency parameter...36
Figure 24  Shape factor as a function of the ratio $\mu/R$..................................................37
Figure 25  Factor $A$ versus $\beta = \nu/a$ for values of $g = t/b$........................................38
Figure 26  Proximity factor for single phase tubes as function of the factor $A$ for values of $\eta = s/2a = s/d$........38
Figure 27  Proximity factor for single phase tubes.........................................................39
Figure 28  Factor $A$ for proximity loss factor as a function of $g = t/b$ for various values of $\beta = t/a$..............40
Figure 29  Proximity factor, $S_p$, for round bars at various spacings designated by $\eta$.................................41
Figure 30  $R_{sc}/R_{sc}$ as a function of the parameter $\nu^2/R_{sc}$........................................43
Figure 31  $R_{sc}/R_{sc}$ as a function of the parameter $\nu^2/R_{sc}$........................................43
Figure 32  Shape factor, $R_{sc}/R_{sc}$, as a function of the parameter $\nu^2/R_{sc}$........................................44
Figure 33  Shape factor versus $2b/\nu$ for various values of $b/\nu$........................................44
Figure 34  Plots of the shape ratio $S_{sc}$ versus the ratio $\frac{2}{a}$ for various values of $\frac{1}{s} = \frac{1}{s}$ for anti-parallel currents......47
Figure 35  Shape factor $S = \frac{2}{a}$ as a function of the separation $s$ for various values of $\frac{1}{s} = \frac{1}{s}$ with $\nu_{sc}$ in $\mu\Omega/m$ and $f/n Hz$.................................................................49
Figure 36  Linear plots of $R_{sc}/R_{sc}$ versus $p$ where $p = 1.5853\sqrt{\frac{1}{s}}$ with $\nu_{sc}$ in $\mu\Omega/m$ and $f/n Hz$..............................52
Figure 37  Quasi logarithmic plots of $R_{sc}/R_{sc}$ versus $p$ where $p = 1.5853\sqrt{\frac{1}{s}}$ with $\nu_{sc}$ in $\mu\Omega/m$ and $f/n Hz$..............................55
Figure 38  Power loss versus width for 6.3 mm thick copper bars.........................................................63
Figure 39  Cost of energy loss per metre versus width for 6.3 mm thick copper bars........................................64
Figure 40  Total cost per metre versus bar width for 5000 hours operation at 500 A........................................64
Figure 41  Total cost per metre of bar versus bar width for a range of operating times.................................65

Figure 42  Total cost per metre against current density for a range of operation times.................................66
Figure 43  Estimated working temperature versus width of bar (mm) for 500 A load........................................66
Figure 44  Cost per metre ($€$) against bar width for a) 20 000 hours operation without discount and b) 2000 hours per year for 10 years at 5% discount.............................................67
Figure 45  Short-circuit current waveform........................................................................71
Figure 46  Three phase system with spacings D (mm), (a) triangular array (b) inline array.............................................73
Figure 47  Factor $K$ for calculating the force between two bars of rectangular section.........................................75
Figure 48  Form factor $K_t$, (a) low values of $\alpha/\beta$ (long sides facing each other) (b) high values of $\alpha/\beta$..................................................................75
Figure 49  Typical copper profiles................................................................................79
Figure 50  A non-typical profile indicating the dimensions used in the standard...........................................81
Figure 51  Measurement of straightness........................................................................83
Figure 52  Measurement of flatness..............................................................................83
Figure 53  Measurement of twist....................................................................................83
Figure 54  Profile cross-section showing mounting lugs and slots for bolt-head..............................................85
Figure 55  $R_{sc}/R_{sc}$ as a function of the parameter $\nu^2/R_{sc}$ with $f/n Hz$ and $R_{sc}$ in $\mu\Omega/m$.................................86
Figure 56  Thermal image of two profiles under load...................................................................................87
Figure 57  Hole-free joints..............................................................................................87
Figure 58  Calculation of moment of inertia of a complex shape....................................................................88
Figure 59  Parameters used in the calculation of moment of inertia of each element........................................89
Figure 60  A typical bolted joint....................................................................................90
Figure 61  A simple clamped joint................................................................................90
Figure 62  A riveted joint..............................................................................................91
Figure 63  A soldered joint............................................................................................91
Figure 64  A welded joint............................................................................................91
Figure 65  An overlapped joint.....................................................................................91
Figure 66  Streamline effect in overlapped joints.....................................................................................92
Figure 67  Bolt placement in overlapped joints.....................................................................................93
Figure 68  Overlap joint between bars with angled ends.............................................................................93
Figure 69  The effect of pressure on the contact resistance of a joint..................................................................95
Figure 70  Possible bolting techniques for copper busbars...........................................................................98
Figure 71  Joint with a longitudinal slot........................................................................98

Disclaimer

While this publication has been prepared with care, Copper Development Association, European Copper Institute and other contributors provide no warranty with regards to the content and shall not be liable for any direct, incidental or consequential damages that may result from the use of the information or the data contained.

Copyright © Copper Development Association and European Copper Institute.