Substation Busbar and Conductors

Design Standard

DOCUMENT HIERARCHY

This document resides within the Planning component of Western Power’s Asset Management System (AMS).

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Record of endorsement, approval, stakeholders, and notification list is provided in EDM# 34232838 appendix

RESPONSIBILITIES

Western Power’s Engineering & Design Function is responsible for this document.

CONTACT

Western Power welcomes your comments, questions, and feedback on this document, which can be emailed to standards.excellence@westernpower.com.au

Contents

Revision Details

Version	Date	EDM Version	Summary of change
0	June 2013	1.0	First issue.
1	August 2019	2.0	Updated to new AMS format. Updated with AS2067 requirements. Supersedes NADS – Transmission Substation Aerial Conductors, Busbars and Fittings.
2	May 2021	5.0	Updated Gfault requirements
3	March 2023	6.0	Review of referenced Mathcad calculation files. Issues register items 7 and 8 addressed. Laminates section updated.
4	January 2024	7.0	Standards Online Update
5	January 2025	8.0	Revised Tables 7.1 and 7.2
6	January 2025	9.0	Updated copyright in footer.
7	February 2025	10.0	Updated copyright

1 Introduction

Busbars and conductors are used within substations to connect transformers, feeders, switchboards, capacitor banks, station supply transformers, dynamic reactive compensation plant, and other primary equipment.

The purpose of this Engineering Design Instruction (EDI) is to assist engineers in designing substations.

1.1 Purpose and scope

This Engineering Design Instruction outlines the design requirements for high voltage busbars and conductors.

This design instruction:

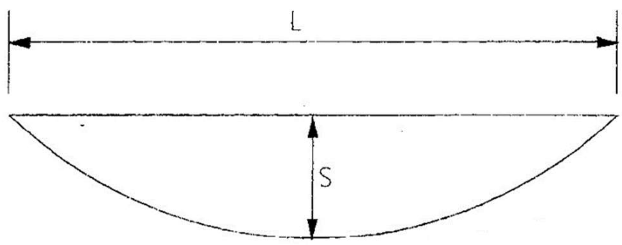
- Includes low level aerial (non-tensioned) stranded conductors, tubular busbars & laminations.
- Includes high level (tensioned) overhead aerial conductors (eg Terminals) and landing spans
- Includes bolted/welded/crimped connections and expansion joints.
- Includes legacy low level (tensioned) aerial stranded conductors eg Geraldton 132 kV
- Includes conductor selection for standards/templates.
- Excludes bus ducts, indoor switchboard busbars, cables & aerial bundled conductors (ABC)

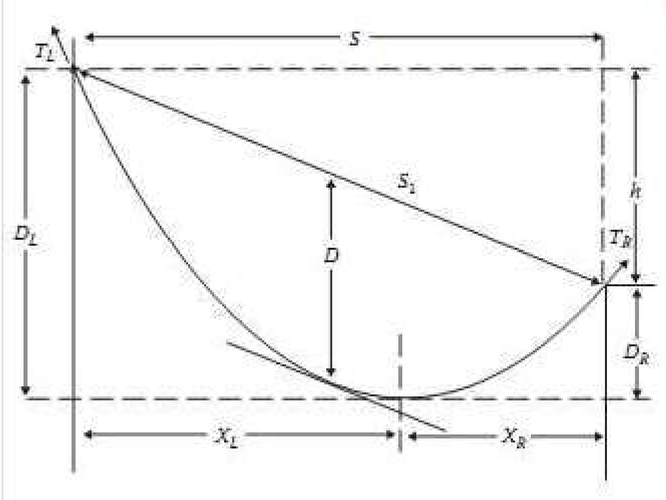
1.2 Acronyms

Acronym	Definition

1.3 Definitions

Term	Definition
Adiabatic	Heating process occurring in a very short time such that heat is not lost to the surroundings eg heat gain of a conductor during a short circuit
Aeolian vibration	A natural forced vibration caused by wind flowing over a conductor
Conductor breaking load (CBL)	The calculated minimum breaking load of a stranded conductor determined in accordance with the relevant standard eg AS 1531 A4. For WP conductor CBL refer to Appendix B below. Formerly called ultimate tensile strength (UTS).
Connector	A device that connects two conductors together. Connectors may be bolted or compression.

Corona	Luminous discharge due to ionisation of the air surrounding an electrode caused by a voltage gradient exceeding a critical value
Design life	Assumed period for which the asset is to be used for the intended purpose with anticipated routine maintenance but without substantial repair
Drag coefficient	For typical wind speeds, a dimensionless constant denoting the drag resistance of a conductor in air flow
Every day tension (EDT)	Static conductor tension at the everyday temperature (15° C) in “still air” ie maximum wind speed 7 m/s
IACS	International Annealed Copper Standard. 100% conductivity = 0.15328 Ω.g/m^2 at 20 C
Laminar wind	Smooth wind flow, not turbulent & prevalent in early morning in winter [AS/NZS 7000 Z3]
Lamination	A stack of aluminium or copper strips connected to termination palms at each end. In the case of an aluminium lamination the ends of the strips are welded to solid aluminium palms.
Limit state	A state beyond which the structure (conductor?) no longer satisfies the design performance requirements
Magnetic field constant	μ_0 = 4 x 10^{-7} Henries per metre [AS3865 2.2.2.5]
Resonance	The tendency of a conductor to oscillate at a greater amplitude at some frequencies than at others. Small periodic driving forces can produce large amplitude oscillations
Return period	Mean statistical interval in years between successive recurrences of a climatic action of a defined magnitude. The inverse of return period gives the probability of exceeding the action in one year.
Reynolds number	Non-dimensional parameter that relates the size of an object to the flow conditions it experiences. Low Re (< 10^5) indicates laminar airflow
Roughness average (R_a)	The arithmetic mean of the absolute departures of a profile (eg termination palm surface) from the mean line of the measurement
Sag	The deviation of a conductor from the straight line between the terminations Where endpoints are level:  S = Sag L = Conductor Span Where endpoints are not level:

	 S = Horizontal Conductor Span D = Conductor Sag at midspan
Serviceability limit state	A state beyond which specified service criteria are no longer met
Strouhal number	A dimensionless number describing oscillating flow mechanisms eg vortex shedding frequency
Terminal palm static load	Mechanical load imposed by gravity & ultimate wind on the conductor eg $G + W_p$
Terminal palm dynamic load	Mechanical conductor load = static + electromagnetic (SC) eg $1.25G_C + 0.25W_u + F_{SC}$
Terrain category	Indicates wind turbulence intensity based on the average ground roughness up to 10 km upwind of the site [AS/NZS 1170.2 4.2.1]
Vibration limit state	Maximum conductor stress causing fatigue failure at the end of the design life
Vortex shedding	An oscillating flow as air travels past a cylindrical object at laminar velocity

1.4 Symbols

Symbol	Definition
θ	angular deviation, radian
T	torsion, Nmm
E	Young’s elastic modulus, ratio of stress over strain, N/mm^2
G	shear modulus, modulus of rigidity, N/mm^2
J	first polar moment of area, mm^4
C	temperature, Centigrade
A	current, amp
k	kilo
G	ground safety clearance, 2440 mm

N	non-flashover distance, mm
H	horizontal safety clearance, mm
V	vertical safety clearance, mm
S	section safety clearance, mm
f	frequency, Hertz

1.5 References

References which support implementation of this document

Table 1.1 References

Reference No.	Title

2 Supporting Documentation[1]

3 Compliance[2]

This Engineering Design Instruction complies with all higher-level Western Power technical documents and relevant Australian Standards.

This Engineering Design Instruction should encompass all requirements of the relevant Australian Standards which are current at the time of issue. These relevant Australian Standards are listed in Table 3.2 below. A period will be set when the standard needs to be reviewed. If significant changes occur on an Australian Standard which affects safety, then an out of cycle review can be completed.

Table 3.1 Relevant Documentation

Document Title
Network Standard – Transmission Network Configuration and Planning

1 See Western Power Internal Document
2 See Western Power Internal Document

The relevant Australian Standards are listed below in Table 3.2.

Table 3.2 Australian Standards

Standard Number	Standard Title
AS 1154.1	Insulator & conductor fittings for overhead power lines – Performance, material, general requirements & dimensions
AS/NZS 1170.2	Structural design actions – wind actions
AS 1531	Conductors – bare overhead – aluminium & aluminium alloy
AS/NZS 1664	Aluminium structures – limit state design
AS/NZS 1665	Welding of aluminium structures
AS/NZS 1746	Conductors – bare overhead – hard-drawn copper
AS/NZS 1865	Aluminium & aluminium alloys – drawn wire, rod, bar & strip
AS/NZS 1866	Aluminium & aluminium alloys – extruded rod, bar, solid & hollow shapes
AS 1867	Aluminium & aluminium alloys – drawn tubes
AS 2067	Substations & high voltage installations exceeding 1 kV a.c.
AS/NZS 2344	Limits of electromagnetic interference from overhead a.c. powerlines & high voltage equipment installations in the frequency range 0.15 to 1000 MHz
AS 2947	Insulators – porcelain & glass for overhead power lines – voltages greater than 1000 V a.c. – test methods" Note parts 1 & 4
AS 3607	Conductors – bare overhead – aluminium & aluminium alloy – steel reinforced
AS 4169	Electroplated coatings – tin & tin alloys
AS 4312	Atmospheric Corrosivity Zones in Australia
AS/NZS 4325	Compression mechanical connectors for power cables with copper or aluminium conductors
AS 4398	Insulators – ceramic or glass station post for indoor or outdoor use – voltages > 1000 V a.c.
AS 62271.301	High voltage switchgear & control gear Part 301: dimensional standardization of terminals
AS 62217	Polymeric insulators for indoor and outdoor use with a nominal voltage > 1000 V – General definitions, test methods and acceptance criteria
AS/NZS 7000	Overhead line design – detailed procedure

Table 3.3 IEC Standards

Standard Number	Standard Title
IEC 60865-1 (2011)	Short circuit currents – calculation of effects – Part 1: Definitions & calculation methods
IEC TR 60865-2 (2015)	Short circuit currents – calculation of effects – Part 2: Examples of calculation
IEC TR 61597	Overhead electrical conductors – Calculation methods for stranded bare conductors

4 Functional Requirements

This Engineering Design Instruction is intended to be used by Substation Engineering staff and by companies completing outsourced design work for Western Power, as it outlines the Western Power requirements pertaining to Busbars and Conductors for transmission substations.

5 Safety in Design[3]

Safety in Design (SID) must be considered when completing all substation design work. SID focuses on making the design safer and easier to understand, with the aim to eliminate and mitigate potential hazards during the design phase of a project.

Some examples of Safety in Design in busbars and conductors design include:

- Using standard conductors where possible to maintain standard construction installation practices.
- Taking into account existing conductor sizes before specifying new conductor (i.e. stranded copper conductor is used in many brownfield sites). Specifying the right fittings is essential to prevent potential construction and installation issues.
- Looking out for existing long conductor spans terminated onto substation assets (i.e. overhead spans onto line disconnectors). These existing terminations cause high stress on the equipment palms and should be modified when possible.
- Site visits to accurately measure existing busbar heights for improved constructability. Any slight deviation in expected busbar height will affect busbar fittings and lengths, which may lead to longer outage requirements and fabrication rework.
- Designs to aim for level busbar to avoid angled busbars. Angled busbars are difficult to install and can lead to construction issues. Where the ground slopes along the length of the busbar, small changes in ground level can be accommodated by varying the amount of protrusion of footings out of the ground. Where the slope is too great for this method, the busbars may be stepped by use of adaptor plates etc. at fixed or expansion joints in the busbar.

All projects are required to have a SID Hazard Management Register to include evidence of all measures implemented to eliminate or reduce risks.

[3] See Western Power Internal Document

6 Overview of the Main Design Elements

6.1 Overview[4]

Processes that capture the key design elements required to select an appropriate conductor and arrangement /design are included below. This includes the calculation of the forces exerted on plant or supports while checking for the correct termination.

Note that, where possible, a standard approved conductor arrangement (as shown on standard/template drawings) should be used.

The conductors and connections must satisfy safety, electrical, strength, serviceability, robustness & durability requirements as stated in Australian standards or WP/industry practice. The supporting primary plant (CTs, CBs...) terminal palms must be evaluated with respect to all loads (actions) and combination of loads (actions). Electrical/structural design iterations may be required to limit termination palm loads to acceptable values. Overloading of termination palms may lead to premature primary plant failure.

Conductor & busbar design compliance shall be assessed by comparing the proposed conductor arrangement with an approved standard/template primary arrangement. If the proposed conductor arrangement matches the template (eg the same fault level, same primary plant, same plant spacing, same conductors, same phase centres & so on) then design compliance shall be noted in the project Substation Design Report (SDR).

Approved primary layouts are available for 132 kV zone substations and 132 kV & 330 kV 'breaker & a half' terminals.

The use of tubular busbar in lieu of stranded conductor where a stranded conductor length between barrels would exceed 4m is preferred. The exception to this is for the connection between the current transformers and transformer bushings in a zone substation, where stranded conductor may be used for longer connections, provided calculated equipment terminal forces are less than that permitted for the equipment.

6.2 Design processes

An overview of the conductor design processes are provided in three flow charts:

- Low level stranded (non-tensioned) conductor design
- Tubular conductor design
- High level stranded (tensioned) conductor design

For vertical droppers from overhead conductors to electrical equipment, the bending force at the lower fixing point and the dropper displacement needs to be calculated. The required calculations are defined in IEC60865-1 Section 6.3.

4 See Western Power Internal Document

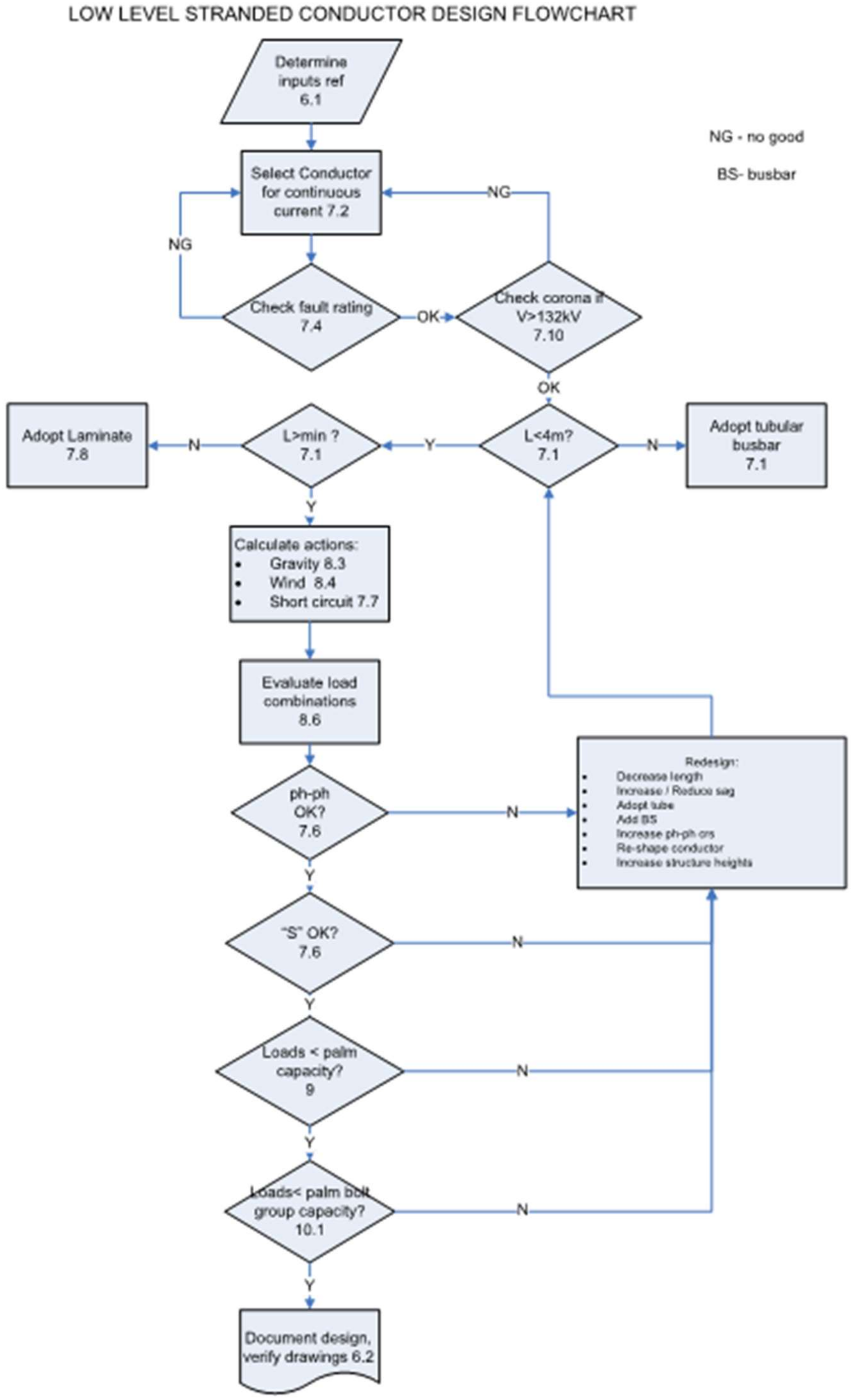

LOW LEVEL STRANDED CONDUCTOR DESIGN FLOWCHART
Determine inputs ref 6.1
NG - no good
BS- busbar
Select Conductor for continuous current 7.2
NG
NG
Check fault rating 7.4
OK
Check corona if V>132kV 7.10
OK
Adopt Laminate 7.8
N
L>min ? 7.1
Y
L<4m? 7.1
N
Adopt tubular busbar 7.1
Y
Calculate actions:
• Gravity 8.3
• Wind 8.4
• Short circuit 7.7
Evaluate load combinations 8.6
Redesign:
• Decrease length
• Increase / Reduce sag
• Adopt tube
• Add BS
• Increase ph-ph crs
• Re-shape conductor
• Increase structure heights
ph-ph OK? 7.6
N
Y
"S" OK? 7.6
N
Y
Loads < palm capacity? 9
N
Y
Loads< palm bolt group capacity? 10.1
N
Y
Document design, verify drawings 6.2

Figure 6.1

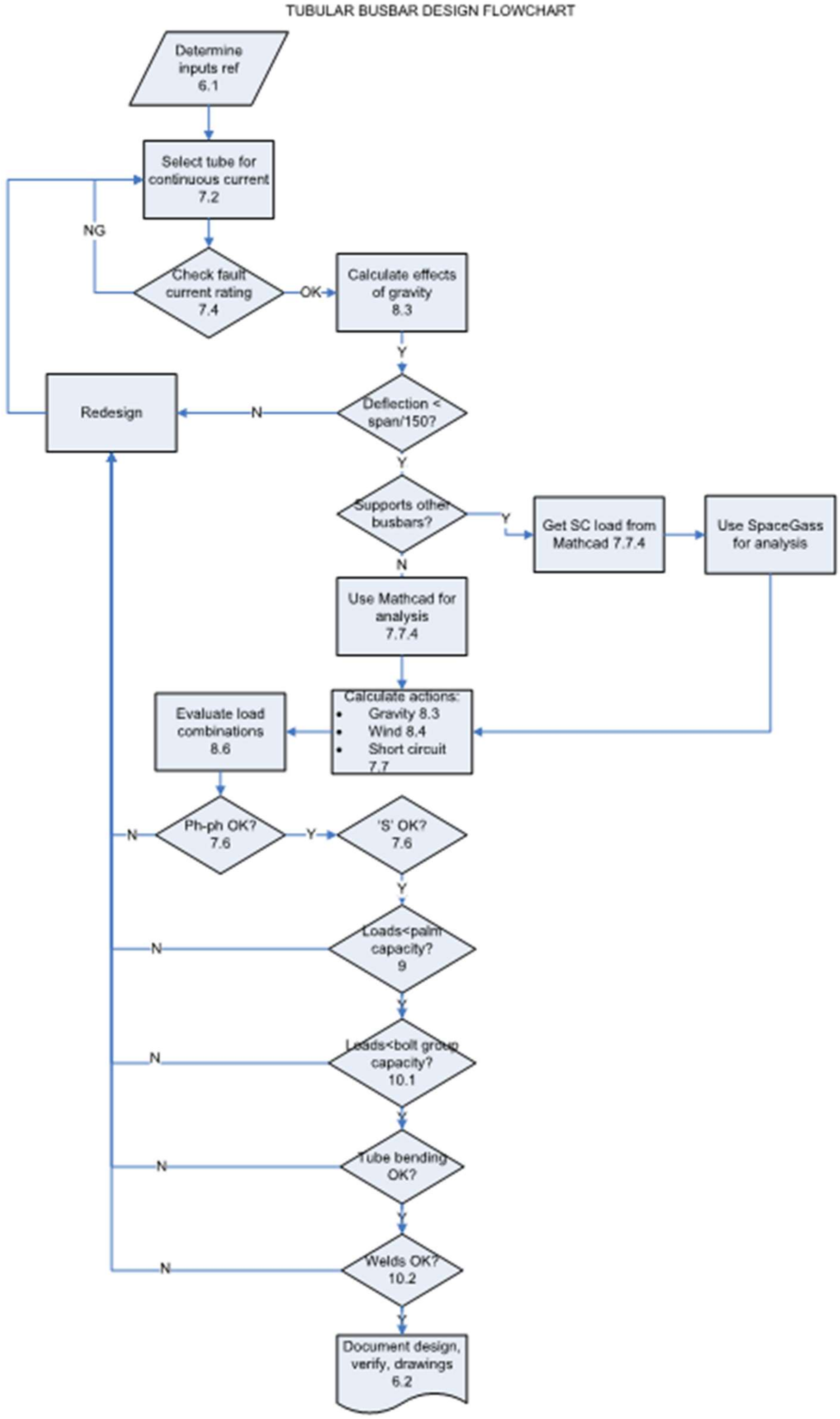

TUBULAR BUSBAR DESIGN FLOWCHART
Determine inputs ref 6.1
Select tube for continuous current 7.2
NG
Check fault current rating 7.4
OK
Calculate effects of gravity 8.3
Y
Redesign
N
Deflection < span/150?
Y
Supports other busbars?
Y
Get SC load from Mathcad 7.7.4
Use SpaceGass for analysis
N
Use Mathcad for analysis 7.7.4
Calculate actions:
Gravity 8.3
Wind 8.4
Short circuit 7.7
Evaluate load combinations 8.6
N
Ph-ph OK? 7.6
Y
'S' OK? 7.6
Y
N
Loads<paint capacity? 9
N
Loads<bolt group capacity? 10.1
N
Tube bending OK?
N
Welds OK? 10.2
Document design, verify, drawings 6.2

Figure 6.2

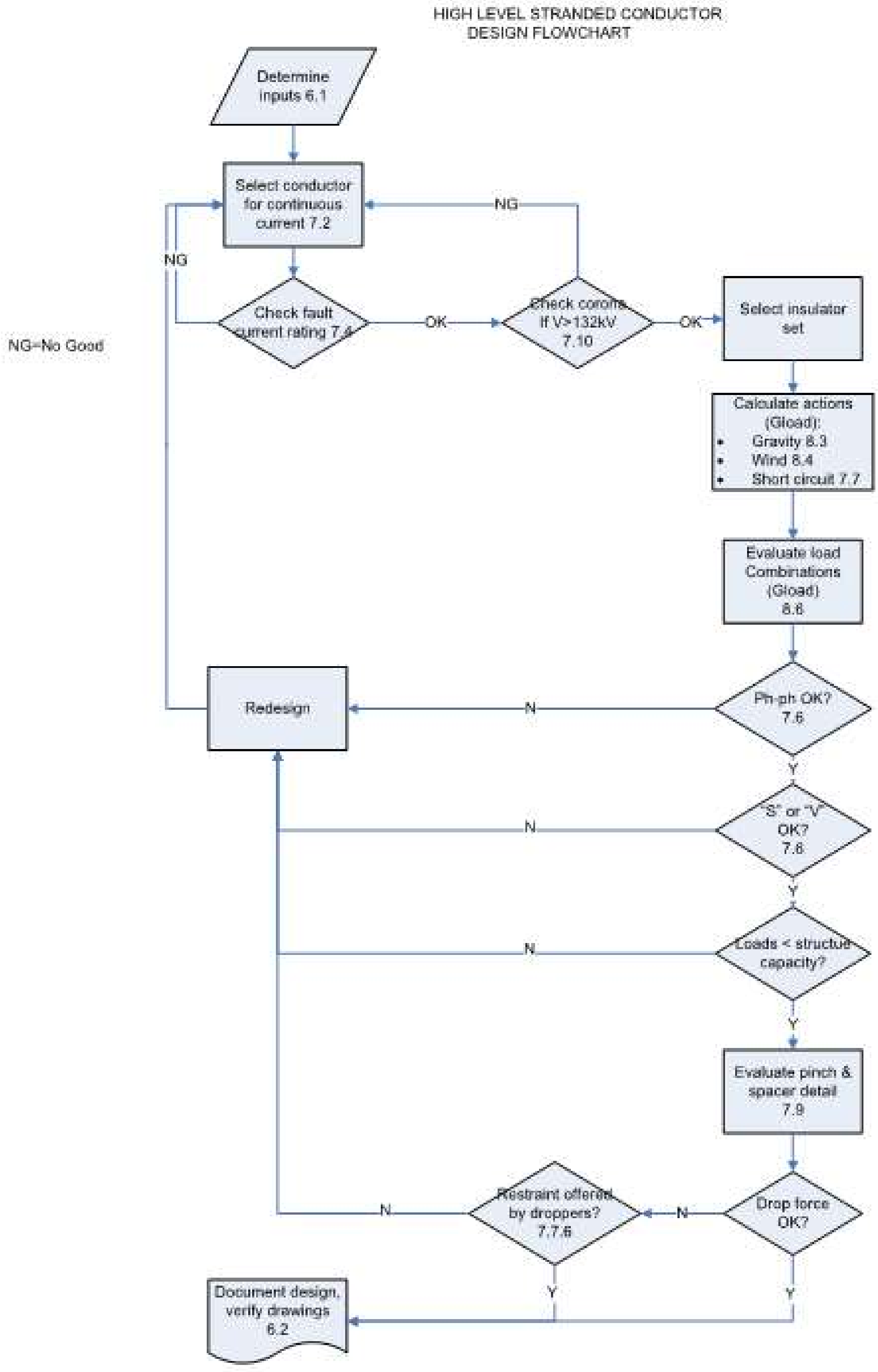

HIGH LEVEL STRANDED CONDUCTOR
DESIGN FLOWCHART
Determine inputs 6.1
Select conductor for continuous current 7.2
NG
NG
Check fault current rating 7.4
OK
Check corona If V>132kV 7.10
OK
Select insulator set
NG=No Good
Calculate actions (Gload):
Gravity 8.3
Wind 8.4
Short circuit 7.7
Evaluate load Combinations (Gload) 8.6
Redesign
N
Ph-ph OK? 7.6
Y
"S" or "V" OK? 7.8
N
Y
Loads < structure capacity?
N
Y
Evaluate pinch & spacer detail 7.9
Restraint offered by droppers? 7.7.6
N
N
Drop force OK?
Y
Y
Document design, verify drawings 6.2

Figure 6.3

6.3 Design Inputs[5]

- Design continuous current
- Fault current from the Network Standard - Transmission Network Configuration and Rating (To be provided by Grid Transformation)
- Operating voltage → minimum electrical clearances
- Three-dimensional conductor geometry from primary layouts
- Primary plant drawing, installation/operating manual, maximum termination palm load & special requirements such as over-pressure devices eg voltage transformer head expansion bellow
- Outage/recall constraints (may influence the conductor solution)
- Testing constraints eg dropper to facilitate surge arrester (SA) primary injection testing
- Maintainability & operability requirements
- EMF, RI, corona constraints eg quad conductor on the NT-NBT 91 line adjacent Pearce airbase

6.4 Design Deliverables[6]

- Conductor design calculations
- Three-dimensional force vectors on primary plant termination palms or gantries
- Sag-tension chart for high level (tensioned) conductors. Once calculated, sag-tension tables should be included on the relevant electrical elevation drawing to assist with stringing of the overhead conductors.
- Conductor design summary/references in the SDR
- Conductor arrangement & detail drawings
- Bolting & welding details
- Material lists

7 Electrical Design

Consideration shall be given to conductor design criteria such as electrical clearances (including for deflected conductor shape), current ratings, earthing, primary plant termination palm capacity, corona, electro-magnetic fields, radio interference, outage constraints, fittings, thermal effects, and so on.

7.1 Conductor selection

Substation conductor selection shall be based on standard approved primary template arrangements where possible. Otherwise initial conductor selection shall be per the following:

- Laminations between closely spaced plant where stranded conductor lengths would be less than those given in Table 7.6 below, or

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5 See Western Power Internal Document

6 See Western Power Internal Document

- Stranded all aluminium conductor (AAC) between low level plant where conductor length (between compression fitting barrels) is 4 m or less (connections between the CTs and TX in zone substations may use stranded conductor for longer spans if calculated forces permit), or
- Tubular aluminium busbar between low level plant where the above two criteria are exceeded
- Stranded AAC for high-level tensioned overheads or low-level tensioned conductors (the latter is no longer used)

For improved corrosion performance in coastal areas or locations subject to industrial pollution, all aluminium alloy conductor (AAAC/1120) shall be used instead of standard AAC in areas identified as having a corrosivity category of C4 or above, as defined in AS4312. Equivalent conductor sizes are Phosphorus for Triton and Sulphur for Venus.

7.2 Standard Substation Conductors[7]

Tables 7.1 and 7.2 list the standard conductor arrangements for the various circuit types within Terminal and Zone substations to meet circuit ratings stipulated in the Transmission Network Planning Criteria.

Notes:

a. 330 kV and 220 kV conductors are sized for corona in addition to current carrying capacity

b. The use of alternative conductors should be avoided as this creates difficulties for construction and maintenance due to having to supply or stock non-standard fittings & tools

Krypton is the standard overhead earth conductor used within Terminals.

Table 7.1 Preferred Terminal Conductor Arrangements

<table>
<tr><th colspan="2"></th><th colspan="6">Standard Terminal Ratings</th></tr>
<tr><th colspan="2" rowspan="2">System Voltage</th><th rowspan="2">330kV</th><th rowspan="2">220kV</th><th colspan="3">132kV</th><th rowspan="2">66kV</th></tr>
<tr><th>330/132kV</th><th>220/132kV</th><th>132/66kV</th></tr>
<tr><td rowspan="3">Normal Current (A) and Conductor Arrangement</td><td>(a) Busbar rating</td><td>3150
160 x 10 AL TUBE</td><td>2500
160 x 10 AL TUBE</td><td>3150
160 x 10 AL TUBE</td><td>2500
160 x 10 AL TUBE</td><td>2500
160 x 10 AL TUBE</td><td>1250
80 x 6 AL TUBE</td></tr>
<tr><td>(b) 1½ CB bay rating</td><td>2500
3 x Venus
100 x 10 AL TUBE</td><td>1250
2 x Venus</td><td>2800
3 x Venus
100 x 10 AL TUBE</td><td>2500
3 x Triton</td><td>1600
2 x Triton</td><td>1250
2 x Triton</td></tr>
<tr><td>(c) Line / Transformer circuit rating</td><td>2000
2 x Venus</td><td>1250
2 x Venus</td><td>2800 3 x Venus
100 x 10 AL TUBE</td><td>2500
3 x Triton</td><td>1600
2 x Triton</td><td>1250
2 x Triton</td></tr>
</table>

[7] See Western Power Internal Document

Table 7.2 Preferred Zone Substation Conductor Arrangements

		Standard Zone Substation Ratings						
System Voltage		132kV	66kV	33kV	22kV			11kV
					33MVA TX	66 MVA TX (dual secondary)	Operated at 6.6kV or 11kV	
Normal Current (A) and Conductor Arrangement	(a) Busbar rating	1600 100 x 10 AL TUBE	1250 80 x 6 AL TUBE	1250 80 x 6 AL TUBE	1250 80 x 6 AL TUBE	1250 80 x 6 AL TUBE	2500 100 x 10 AL TUBE	2500 100 x 10 AL TUBE
	(b) Line/feeder circuit rating	1600 2 x Triton	1250 2 x Triton	630 1 x Triton	630 1 x Triton	630 1 x Triton	800 1 x Triton	800 1 x Triton
	(c) **Transformer circuit rating**	**630** **1 x Triton**	**630** **1 x Triton**	**1250** **2 x Triton**	**1250** **2 x Triton**	**1250** **2 x Triton**	**2500** **3 x Triton**	**2500** **3 x Triton**

Table 7.3 and Table 7.4 show the ratings of the stranded conductors and commonly used aluminium tube used within substations.

Table 7.3 SWIS Substation rating data for commonly used stranded conductor.

Conductor ID (AMP Tx)	**Stranding**	**Name**	**Summer Rating** (A)
A101	19/3.25	KRYPTON	497
AA12	37/3.75	TRITON	889
AA14	61/3.75	VENUS	1,208

Table 7.4 SWIS Substation rating data for commonly used aluminium tube

Description	**Size** (mm) [outside diameter (O.D) x wall thickness]	**Summer Rating** (A)
Al Tube 6063-T5	160 x 10	5,271
Al Tube 6063-T5	100 x 10	3,304
Al Tube 6063-T5	80 x 6	2,142

7.3 Alloy Selection and Design Parameters[8]

Below is a summary of design recommendations for applications involving the use of aluminium tubes, plates, rods, bars & laminations as used in Western Power's transmission substations.

[8] See Western Power Internal Document

Table 7.5 Recommendations for applications of aluminium conductors

Aluminium Alloys	Recommended Aluminium Grade and Temper Designation	Recommended Size (mm)	Minimum Inside Bending Radii (mm)	Applications
Plate and Sheet	6061-T6	12 and 20 [Thickness]	30 50 [At raised temperatures (150- 200°C)]	Palm terminals, sealing plates etc.
Tubes	6063-T5	50 x 4 60 x 6 80 x 6 100 x 10 160 x 10 [outside diameter x wall thickness]	175 250 500 500 800 [Cold forming]	Busbars, corona rings, etc.
Rods	6063-T5	20 [Diameter]	20 [At raised temperatures (150 - 200°C)]	Earthing stirrup, corona ring component, etc.
Bars and Strips	6063-T6	12 [Thickness]	30 [At raised temperatures (150- 200°C)]	Palm terminals, adaptor palms, etc.
Laminations	1350-0	0.8		Expansion joints

All aluminium plates must be bent at raised temperatures of between 150 and 200 degrees.

7.4 Current Ratings[9]

Fault ratings & withstand times for WP substation operating voltages are given in Network Standard -Transmission Network Configuration and Rating. Note that the fault ratings are root mean square (r.m.s.) values.

If special conductor current ratings are required, then consult with the Principal Engineer of Substation Design.

Fault rating is based on the adiabatic condition - the short circuit thermal rating calculation assumes no heat is lost to the surrounding air [ref AS 7000 4.1.5]

Standard current ratings are derived from the IEC R10 series of numbers - 0.8, 1, 1.25, 1.6, 2, 2.5, 3.15, 4 & 5 eg CB ratings – 800 A, 1000 A, 1250 A, 1600 A, 2000 A

Bolted connection continuous current ratings are based on contact surface maximum current densities:

[9] See Western Power Internal Document

- Aluminium = 0.17 A/mm^2
- Copper = 0.32 A/mm^2

.: Current rating (A) = net contact area (mm^2) x surface current density (A/mm^2).

Asset Management Performance - Transmission (AMP Tx, supersedes TRIS) wind speeds for substation rating calculations are 1.0 m/s for stranded & tube and 0.5 m/s for flat bar & laminations. Maximum ambient temperature is taken as 46º C. These values are applicable throughout the SWIS.

Skin effect has been calculated when cross sectional area (CSA) > 600 mm^2 [IEC 60865].

7.5 Current Rating of Busbar in Oil filled Cable Box

For copper busbar in an oil filled Transformer cable box with non-circulating oil, the approximate current rating can be calculated as follows:

- For rectangular copper bar convert to a circular rod having the equivalent cross-sectional area (CSA)
- For circular rod go to the next step
- Maximum current $I_{max} = 25\ r^{1.72}$ (where 'r' is the rod radius)
- Example: rectangular bar with CSA = 486 mm^2 → equivalent circular rod with r ~ 12.4 mm → ~ 1900 amps

7.6 Electrical Clearances

- Conductor arrangements shall comply with Ground (G), Non-flashover (N), Section (S) safety & phase-phase clearances as outlined in Engineering Design Instruction – Safety & maintenance clearances.
- Type tested primary plant may have reduced phase-phase centres eg CBs. The reduced conductor centres will lead to increased short circuit forces & reduced phase-phase clearances.
- Busbar centres usually match disconnector phase centres except for terminal 1.5 CB "A" & "B" busbars eg for 330 kV busbars, phase centres = 4500 mm (not 5800 mm)
- A 50 % reduction of phase – phase clearance is allowed during a 'design' short circuit. A 25 % reduction of phase – phase clearance is allowed for a 'design' wind [AS 2067]. These reductions may influence decisions regarding stranded conductor sag selection & maximum allowable spans.
- Allowance shall be made for conductor swing angle due to "everyday" wind load [see Definitions above]. One way of improving phase to earth clearances for stranded conductor passing underneath a gantry beam is to adopt a "V" disc insulator set or a station post insulator in lieu of a single vertical disc insulator set (usually with steel plate weights). The latter is typical WP practice. Some guidance is provided in AS/NZS 7000 Appendix R albeit in the context of suspension insulator sets & poles/towers. Note that short circuit also causes conductor swing.

7.7 Short Circuit

7.7.1 General[10]

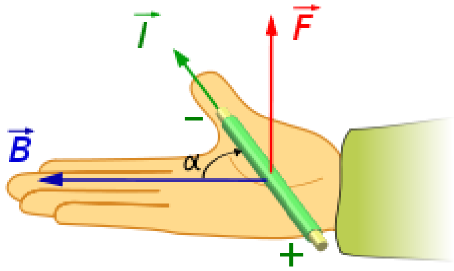

Figure 7.1 Fleming's 'Right hand rule' depicting the direction of EMF

- Terminal & zone substation design fault levels are given in Network Standard – Transmission Network Configuration & Ratings
- Short circuit force depends on the following variables:
  - Short circuit current
  - Voltage phase
  - Time constant, T (eg 45 ms)
  - Type of fault (eg 1 phase, 2 phase to earth..)
  - Clearance time
  - Concurrent forces (eg wind)
- The DC component requirements should be checked for individual sites, and particularly for specialised applications. Applications that are likely to require consideration are power stations, sites close to power stations, bus-section breakers for busbars with series reactors installed.
- The severity of the short circuit force is affected by high-speed single phase auto reclose (HSSPAR) which may be used on the fringe of the SWIS or other strategic locations. The second shot may occur after 150 ms.
- IEC 60865-1 (2011) and AS 2067 (2016) supersede AS 3865-1991 & IEC 865-1986
- AS/NZS 7000 Appendix C covers short circuit on Lines, which may be a useful reference with respect to landing spans
- Typical primary protection clearing times [AS/NZS 7000 Table U2]. Actual clearance times are available from WP Transmission Protection Design.
- Asymmetric time constant (dc component) for WP is 45 ms. Fully (DC) offset faults are only experienced for lightning strikes or re-closures onto faults / maintenance earths where the point on wave is worst case [AS 62271.100 Annex I]

7.7.2 Inputs

- Short circuit current rating $I_{r.m.s.}$ – standard circuit ratings are given in the Network Standard – Transmission Network Configuration & Ratings

10 See Western Power Internal Document

- Phase centres – may vary for different primary plant. Reduced phase centres are allowed by AS 2067 if the primary plant has passed an impulse test. Eg a 145 kV DIS = 2.4 m & 145 kV CB = 1.85 m (reduction based on impulse test)
- Minimum phase to phase clearance
- Conductor type
- Number of conductors per phase
- Length of the total current path – this may include ‘busbars’ internal to CBs/CTs & the phase arms of disconnectors.
- Stranded conductor flexible length – ie the length of conductor between connector barrels, less the ‘stiff’ length/s at one or both ends
- Dropper details – number, location, length

7.7.3 Calculations – General

The effects of short circuits shall be calculated using IEC 60865-1 Edition 3.0 (2011) except for non-tensioned stranded conductor less than 4 m length. Different methodologies are used for rigid conductor arrangements (busbars) & flexible conductor arrangements (stranded conductor) to reflect the differing dynamic response of the 2 arrangements.

Two-phase to earth faults generally provide worst case terminal palm loads. A calculation for say the red & white phases will return the same values as for the white & blue phases. The resulting asymmetric loading on say a ‘pi’ structure will be more onerous than the symmetric loading due to a three-phase short circuit. Although the magnitude of the loads per phase for 2 & 3 phase faults are similar, for a three-phase fault the white phase load is negated by opposing magnetic attractions from the red & blue phases on opposite sides.

7.7.4 Calculations – Tubular Busbar[11]

The calculation of mechanical effects of short-circuit current is based on IEC 60865-1 Edition 3.0 (2011). For the structure loads caused by fault current flow in the busbar, the ratio of natural frequency of the busbar and the electrical system frequency determines the dynamic effects of the short-circuit force. Refer to IEC 60865-1 Section 5.

Two short circuit current path scenarios shall be modelled:

- With current flowing along the main busbar as predicted
- With current flowing along the main busbar, down the verticals & then along the horizontal portions of the cross-overs or tee-offs as depicted

See Section 7.7.4.1 and Section 7.7.4.2

7.7.4.1 With current flowing along the main busbar as depicted

- Short circuit current (I_{sc}) is shown flowing left to right in the red & white phases. Reversal of the current flow would not affect the analysis.
- Since the short circuit current flow is in the same direction the red & white phases are attracted to each other as shown by the uniformly distributed loads (UDL)

[11] See Western Power Internal Document

- For the red phase the short circuit load is in the positive Z (+Z) direction
- Worst case load combination requires wind to be in the transverse direction (+/-Z)
- For the white phase the short circuit load is in the negative Z (-Z) direction
- The longitudinal direction denotes 'along the main bus' or +/- X
- The transverse direction denotes 'across the main bus' or +/- Z
- If possible, the fixed joint (FX) on the main busbar should be located on a busbar support rather than a disconnector. However, this is not always possible!

7.7.4.2 With current flowing along the main busbar, down the verticals & then along the horizontal portions of the cross-overs or tee-offs as depicted

- The short circuit current path is selected to maximise the length of loaded busbar
- Short circuit loads are uniformly distributed assuming both adjacent phases have equal current flow
- Where only one phase has short circuit current flow & the adjacent phase has not (eg the red phase with triangular load shape) load curtailment may be considered
- The vertical legs of the tee-off or cross-over busbars are usually spaced at √2 times the main/circuit busbar phase centres, assuming the main/tee-off phase centres are equal. Short circuit loads in the tee-off verticals are reduced by a factor of √2 because of the greater separation. For ease of input into SpaceGass the load is resolved into 2 orthogonal components. For example, if the short circuit load in the main/tee-off busbars is 500 N/m then each tee-off vertical orthogonal component (x & z axes) would be 250 N/m.
- There is no adjacent parallel busbar for the first portion of the red phase tee-off horizontal busbar near the bend. That is that portion of the red phase busbar does not have a corresponding white phase busbar nor its current. Assuming curtailment (ie the load diminishes), a triangular load shape is shown.
- The wind direction shown (+Z) will tend to push the tee-off busbars into the circuit DIS (say) expansion joints (EX). This will be compounded by short circuit load in the red phase main busbar. A check should be made that the tee-off busbar does not hit the disconnector head.
- Conversely an opposite wind direction (-Z) would exacerbate white phase movement due to short circuit load. The white phase tee-off busbar will tend to pull out of the expansion joint (EX). A check should be made that the tee-off busbar does not exit the expansion bracket. Standard busbar expansion joint (EX) penetrations are given in Table 22.
- If possible the fixed joint (FX) on the main busbar should be located on a busbar support rather than a disconnector. However, this is not always possible eg when the busbar is supported by disconnectors at both ends because one end must be fixed & the other must have an expansion joint!

7.7.5 Calculations - Low Level Stranded Conductors[12]

For flexible conductors, the tensile forces caused by the swing-out and drop-back of main conductor and pinch effect between sub-conductors during the short-circuit are calculated and

[12] See Western Power Internal Document

compared with the permitted loading of the support structure/insulator/primary plant palm/connector.

Flexible conductor arrangements are covered in IEC 60865-1 Section 6. However, it appears that the IEC methodology pertains more to longer spans such as overhead/landing spans. Typically, WP over-head/landing spans & long droppers are between 8 m & 80 m.

It is not clear whether the design of short stranded conductor spans commonly used in substation low level primary arrangements are adequately covered by IEC 60865-1 Section 6. Short conductors are not 'pin ended', instead generally projecting from the barrel of rigid compression fittings. Thus, a short portion of the stranded conductor near the fitting is 'stiff' not flexible. The stiff length for WP standard conductors has been empirically determined:

Table 7.6 Stranded all aluminium conductor (AAC) details

Name	Strands (No./dia. In mm)	Diameter (mm)	Mass (N/m)	Stiff length (m)	Min. length between barrels (m) **	Min. length between barrels (m) ##
Krypton	19/3.75	16.3	4.3	0.4	1.0	1.2
Triton	37/3.75	26.3	11.1	0.5	1.2	1.5
Venus	61/3.75	33.8	28.1	0.6	1.6	2.0

** single plane bending ## double plane bending

For minimum conductor sag or hog refer to Section 8.2 below.

For low level stranded conductor short circuit calculations, three conductor lengths may require assessment:

- Transverse load length acting on one terminal palm:
  - 50% flexible length + stiff length + compression fitting length
- Transverse load length acting on the primary plant:
  - as above for both sides + primary plant internal 'busbar' length (eg CT head length)
- Tension load length acting on one terminal palm:
  - flexible length

For short stranded conductors (length between compression barrels < 4 m) the transverse (ie perpendicular to conductor) short circuit force shall be calculated using the following empirical formula[13]:

$F_{sc,\ trans} = 0.2\ k_{stranded}\ I_{r.m.s.}^{2} / a_c$ where:

- $F_{sc,\ trans}$ – in N/m
- $k_{stranded}$ = 1.6 (dimensionless)
- $I_{r.m.s.}$ – r.m.s. fault current rating (kA)
- a_c – phase to phase centres (m)

Note that IEC 60865-1 also adopts $I_{r.m.s.}$ for stranded conductor.

13 R.J. Cakebread & H.J. Brown 'Integrated mechanical design loading for open type EHV substation structures & equipment' Electra No. 60

Tension short circuit force (ie in-line with the conductor) for short stranded conductor shall be determined by using the parabolic formula:

$F_{sc, tens} = F_{sc, trans} [L_{flex}]^2 / (8 S)$ where:

- $F_{sc, tens}$ – longitudinal force (N)
- L_{flex} = flexible length (m)
- S – flexible conductor sag or hog (m)

Note that the parabolic tension formula above is far simpler than the hyperbolic tension formula (which involves cosh..) & is only a couple of percent less accurate for short spans (L < 300 m).

For short stranded conductors, the point load due to minor droppers (eg VTs & SAs) may be ignored.

7.7.6 Calculations - Stranded Droppers[14]

Locations of long dropper upper fixing points and the slack (sag) of the droppers are to be closely examined to avoid droppers being stretched during the swing-out of the overhead span due to short-circuit , so that the primary plant palms at the bottom of the dropper will not be damaged. The bending force at the lower fixing point, and the displacement of the dropper need to be calculated in accordance with IEC60865-1. Refer to the stranded dropper Worked Example Section 11.2.

7.7.7 Calculations – High Level Stranded Conductors[15]

The calculation of mechanical effects of short-circuit current is based on IEC 60865-1 Edition 3.0 (2011) Section 6.

In summary the design process involves determining the optimal initial tension which results in the short circuit and drop forces being approximately equal. Where multiple sub conductors are used, the optimal spacer spacing is then determined by ensuring the pinch forces are equal or less than the short circuit and drop forces.

7.8 Laminations[16]

Laminations are used to maintain the continuity of the current path across an expansion joint (EX) or in lieu of conductor when the conductor length (between compression fitting barrels) is less than the minimum (refer to Table 7.6).

Outdoor laminations are usually made from thin sheets (WP thickness 0.56mm, 0.8mm, or 1.0mm / PLP thickness 1.2 mm – use of either is acceptable) of soft ductile aluminium alloy 1350-0. This ensures the flexibility to endure the frequent thermal movement of the associated busbar or operational vibration of disconnectors or circuit breakers. The surplus length of the laminations must exceed the calculated movement of the assembly. Generally, the lamination length is approximately 125% of the straight distance between palms, but this should be confirmed by drawing to ensure a reasonable laminate profile is obtained.

[14] See Western Power Internal Document
[15] See Western Power Internal Document
[16] See Western Power Internal Document

If the lamination assembly length (ie palm + laminations + palm) is large, then the palm lengths shall be maximised so that the maximum lamination length is 600 mm. It is prudent to avoid laminations 'flop' whereby the laminations change shape & electrical clearances are compromised. Long laminations are to be avoided.

Where lamination assemblies accommodate phase centre differences (eg between circuit breakers & disconnectors/current transformers) care shall be exercised to avoid torsional effects on the less robust primary terminal palm. For example, one would usually locate the lamination assembly crank on the CB end rather than the CT end. The CB terminal palm is often more robust than that on the CT. Also, the phase to phase clearances are maximised & short circuit forces minimised.

Care should be taken when detailing the weld between the thin laminations (eg 0.56 mm thick) & the thick palms. The palms should be double bevelled & vee butt welded to the laminations to ensure full electrical continuity.

Laminations oriented 'on the flat' resist horizontal short circuit forces well ie the laminations are loaded in the strong axis. If the laminations are oriented 'on edge' (ie loaded on the weak axis), then large deformations of the flexible laminations may occur during a short circuit. The terminal palms should be checked for the induced tension forces.

Laminations made of copper are sometimes used. These do not have palms. Instead the laminations are bolted directly on to the primary plant termination palm/bolted connection palm. To distribute the bolt clamping forces on to the thin copper laminations, thick copper keeper plates are used. Examples may be found in old air insulated outdoor 22 kV yards where copper tube busbars were used. Ideally copper connections should be tinned to control corrosion.

The ratings for Aluminium laminations shown in Tables 14A, 14B, and 14C are for 0.56mm, 0.8mm, and 1.0mm thick aluminium strips respectively. Grade 1350-0 (replaces Grade 1445), based on a horizontal (flat) configuration (worst case), an equivalent bar thickness equal to the sum of the lamination's thickness, and a 90 °C maximum temperature, and climatic zone 1 & 2 ambient temperatures.

Table 7.7 0.56mm Aluminium lamination current ratings

Preferred Current Rating	**No. of Lams (0.56mm thick)**	**Palm Width** (mm)	**Lamination Width** (mm)	**Gap Between Lamination stacks** (mm)	**Recommended Palm Thickness** (mm)	**Rating Summer** (A)
800*	6	100	100	-	12	857
1000*	10	100	100	-	12	1117
1250*	14	100	100	-	12	1608
1600*	20	130	100	-	12	1605
2000*	32	130	100	-	20	2219
2500	2 x 28	180	50	70	20	2641
3150	2 x 42	180	50	70	25	3400

Table 7.8 0.8mm Aluminium lamination current ratings

Preferred Current Rating	No. of Lams (0.8mm thick)	Palm Width (mm)	Lamination Width (mm)	Gap Between Lamination stacks (mm)	Recommended Palm Thickness (mm)	Rating Summer (A)
800*	6	100	100	-	12	1037
1000*	7	100	100	-	12	1130
1250*	9	100	100	-	12	1303
1600*	15	130	100	-	12	1750
2000*	21	130	100	-	20	2136
2500	2 x 19	180	50	70	20	2589
3150	2 x 29	180	50	70	25	3372

Table 7.9 1.0mm Aluminium lamination current ratings

Preferred Current Rating	No. of Lams (1.0mm thick)	Palm Width (mm)	Lamination Width (mm)	Gap Between Lamination stacks (mm)	Recommended Palm Thickness (mm)	Rating Summer (A)
800* / 1000*	6	100	100	-	12	1175
1250*	8	100	100	-	12	1384
1600*	12	130	100	-	12	1750
2000*	17	130	100	-	20	2152
2500	2 x 15	180	50	70	20	2568
3150	2 x 24	180	50	70	25	3446

** Note: where one lamination stack is used either side of a busbar this value can be doubled*

Proprietary laminates (e.g. from PLP) may also be used. Refer to the manufacturers information for required size and number of laminations for required rating.

If alternative laminates not listed above are proposed to be used the Substation Design Principal Engineer should be contacted in order to determine a rating for the proposed laminate.

Table 7.10 below gives lamination short circuit current ratings for 0.56mm thick laminates. Equations for Aluminium lamination short time current rating are based on Dean’s equation.

Table 7.10 **Short time current ratings for Aluminium Laminations**

Required Rating	Number of Laminations
50 kA 1 sec	7
40 kA 1 sec	6
31.5 kA 1 sec	5
25 kA 1 sec	4
25 kA 3 sec	6
16 kA 3 sec	4
6 kA 1 sec	1

These ratings represent the most used lamination grade. Ratings for laminations with differing grades, width, or thickness can be calculated using the equations located in the Supporting Documentation Register.

Figure 7.2 below shows commonly used flexible lamination configurations.

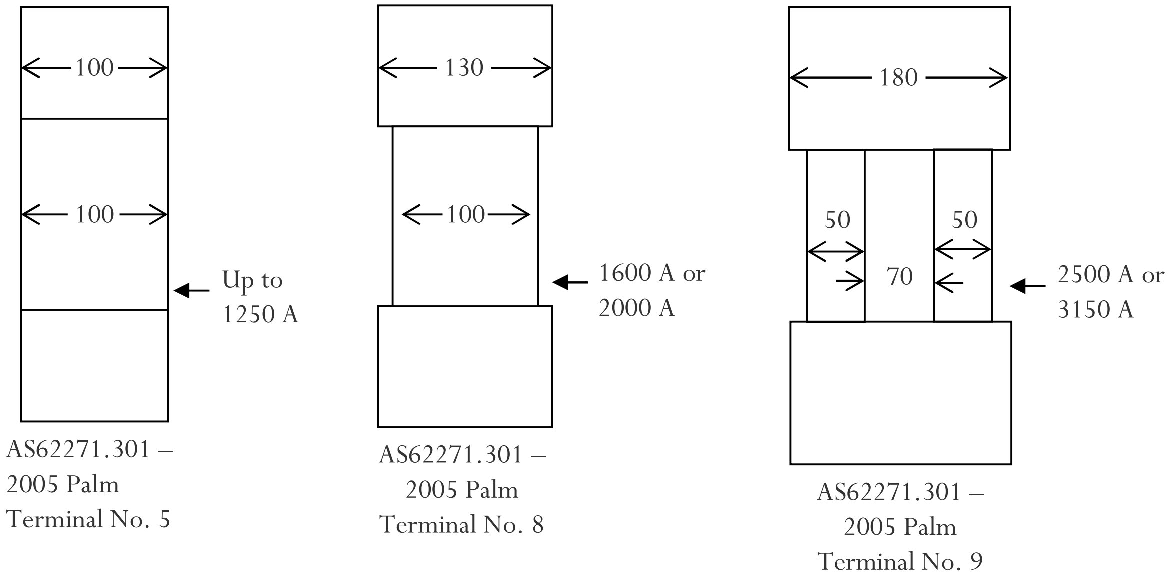

Figure 7.2 Flexible Lamination Configurations (AS62271.301 - 2005 palm sizes)

7.9 Pinch [17]

Standard sub-conductor distances are 70 mm, 125 mm & 380 mm (the later mainly for droppers & overheads).

As a guide, spacers should be installed with a maximum separation of 1.5m for short connections between primary plant.

[17] See Western Power Internal Document

7.10 Corona

The corona performance of standard template substation arrangements appears to be satisfactory. However small substation sites may require specialist corona design input.

Refer to AS 2067 (2016) s2.2.6.

Further information follows:

- Corona mitigation is required for voltage > 132 kV
- Rule of thumb: For 330kV, adopt twin conductor & a minimum stranded conductor diameter = 33.8 mm (Venus). For 220kV, adopt twin conductor & a minimum stranded conductor diameter = 33.8 mm (Venus).
- Corona usually occurs during rain or fog when the surface voltage gradient exceeds 16 kV/cm. Lightly tensioned disc strings such as landing spans & possibly between substation gantries may produce spark discharges [AS/NZS 7000 H1].
- Surface voltage gradient is influenced by voltage, number of sub-conductors, size of conductors, phase spacing, conductor surface finish (eg smooth, corroded…)
- For radio interference voltage (RIV) information refer to AS 1154.1 Appendix D. The relationship between corona & RIV is given in AS 1154.1 Figure D1.
- For CTs - RIV < 2500 µV at $1.1U_m/\sqrt{3}$ [AS60044.1]
- Television interference voltage (TIV): the recent (2013) conversion to digital television technology has made television reception much less susceptible to corona-generated interference
- Audible noise – the principle source is water drops on the conductor surface
- Corona rings reduce the voltage gradient

7.11 Electrostatic Induction

This phenomenon may be significant above 200 kV.

The electrostatic induction design limit is 5 mA. Thresholds for spark discharges are given in AS/NZS 7000 Table H1. Refer also to AS/NZS 7000 H2.

In order to prevent electro-static charge buildup on metallic objects within substations, all metallic objects (steel structures, marshalling boxes etc.) are effectively earthed.

7.12 Electro Magnetic Fields[18]

The limits to be met at the boundary of Western Power substations are detailed in the Network Standard – Transmission and Distribution Line Easements and Restriction Zones

- For health reasons exposure of workers or the public to EMF is limited by proximity or time
- EMF may also induce dangerous voltages in adjacent parallel conductors, pipelines or metallic fences. This may be modelled in CDEGS (earthing software used by WP)

[18] See Western Power Internal Document

- Load or fault current flowing in conductors may generate high voltages in parallel metallic circuits
- From the Technical Rules: electromagnetic interference caused by equipment forming part of the transmission and distribution system must not exceed the limits set out in Tables 1 and 2 of Australian Standard AS 2344 (1997)
- Telecommunication EMF limits are given in Australian Standard HB 102
- Limits for pipelines are given in AS/NZS 4853

8 Structural Design

8.1 Design Life[19]

The WP substation design life is 50 years. Busbar & conductor design shall consider the following:

- In benign environments stranded conductors may last 80 years
- In more aggressive environments the end of conductor design life may be reached in 20 years
- Design life is influenced by maintenance, environment, temperature & loading factors
- Ref Siemens Tech Topics No. 15 “Expected life of electrical equipment” eg design life of insulation from Arrhenius equation ln k = ln A – (Ea/r) / T generally design life halves for each 10 degrees Centigrade temperature rise

8.2 Sag[20]

For low level (non-tensioned) stranded conductors:

- Adopt a sag (or hog) greater than 5% of the stranded conductor ‘flexible’ length, subject to electrical clearances
- The objective is to reduce tension forces & reduce transfer of operational forces from CBs or DIS onto adjacent primary plant eg CTs

For high-level (tensioned) stranded conductors, sag-tension charts should be produced to provide the installation contractor the design sag and tension for a range of ambient temperatures that may be experienced on the day of stringing, typically a range of 5 to 40 degrees. This information should be shown on the electrical elevation drawing of the conductor span.

The standard approach is to tension the conductors such that the maximum sag at maximum conductor operating temperature (85 degrees) is 5% of the span length. Electrical clearances are determined at this maximum sag and it must not be exceeded. However, it is permissible to increase the static conductor tension, which can in some cases be beneficial by reducing the drop force following a short circuit. Short circuit calculations should be performed to determine if an increase in static conductor tension (and hence reduction is sag) is beneficial.

Sagging tensions are covered in AS/NZS 7000 Appen S9 & Appen T12 (dynamometer).

19 See Western Power Internal Document
20 See Western Power Internal Document

Note that excessive sag may reduce electrical safety clearances under.

8.3 Gravity

- Sometimes called dead load (DL)
- Acts vertically downward (in Spacegass software '–Y' direction)
- Consists of the self-weight of conductor, spacers, droppers, busbars & fittings
- Portable earth sets (not generally applicable to 330 kV since permanent earth switches are fitted to disconnectors, except for the line side of surge arresters).

Table 8.1 Masses of aluminium busbars, conductors, fittings & portable earths

Description	**Mass** kg/m
160 mm OD x 10 mm wall thickness	12.72
100 mm OD x 10 mm wall thickness	7.63
80 mm OD x 6 mm wall thickness	3.77
60 mm OD x 6 mm wall thickness	2.75
Venus 61/3.75 AAC	1.86
Triton 37/3.75 AAC	1.13
Krypton 19/3.25 AAAC/1120	0.43
Compression fitting	~ 1 kg each
Spacer	~ 1 kg each
Portable Earth 150 mm^2 Cu PVC cable	0.6
Portable Earth 95 mm^2 Cu PVC cable	0.4

8.4 Wind

8.4.1 Background

For all wind related loading calculations, refer to Engineering Design Instruction – Substation Foundations and Structures

8.4.2 Vibration

Long light-weight aluminium busbars may be prone to wind induced vibration. Laminar air flow at low wind speed is the main cause.

Standard WP busbar drawings include a stranded aluminium conductor damper to reduce vibration effects. This conductor is welded to the busbar tube at one end and free at the other end. It is recommended that damping conductors are installed in all tubular busbars, regardless of length.

Table 8.2 Damper types

Busbar Size (mm)	Damper
80 O.D. x 6 w.t.	Triton
100 O.D. x 10 w.t.	Triton or Venus (see note)
160 O.D. x 10 w.t.	Venus

Note: For 100x10 tubular bus, use the same conductor as used in the rest of the substation as damping wire. For example, for 330kV yards, use Venus as damping wire in 100x10 tube. For 132kV yards use Triton.

Further information about vibration is provided in Section 11.

8.5 Seismic[21]

For all seismic related loading calculations, refer to Engineering Design Instruction – Substation Foundations and Structures

8.6 Load Combinations[22]

Loads are factored & combined to reflect realistic loading events. The factored load combination must be less than the primary plant termination palm factored capacity.

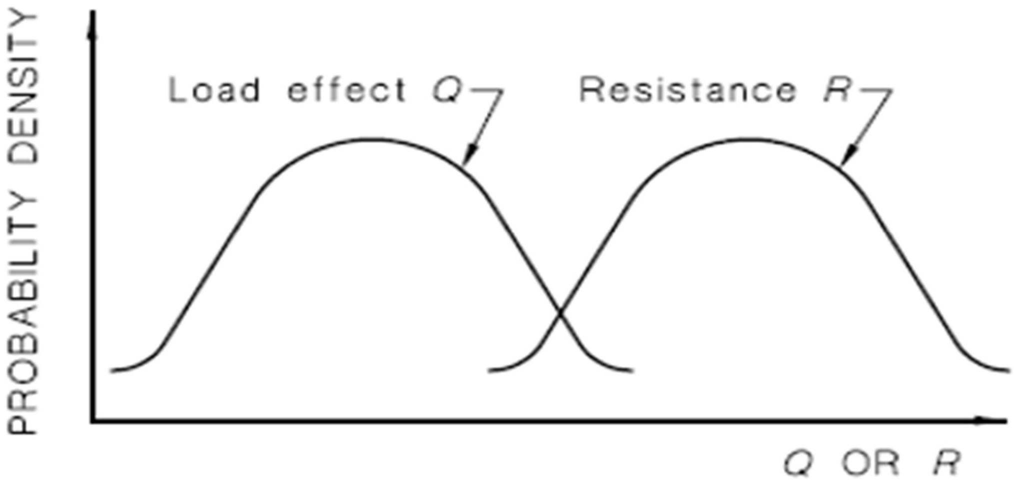

Figure 8.1 Schematic probabilities of load & resistance effects

AS 2067 (2016) Table 2.1 provides load combination factors for substation design.

Other relevant points are provided as follows:

- For transmission line design - $\phi R_n > W_n + 1.25F_t + 1.1G_s + 1.25G_c + 1.25F_{sc}$ [AS 7000 C2]

[21] See Western Power Internal Document
[22] See Western Power Internal Document

- Strength reduction factors – porcelain SPI ø = 0.8, conductor ø = 0.9 [AS/NZS 7000 Table 6.2]
- Coordinate system - longitudinal (in-line with the circuit, direction X), vertical (direction Y) & transverse (perpendicular to the circuit, direction Z)
- The target reliability index for aluminium structures is ß = 2.5 [AS/NZS 1664.1 Commentary]
- ASCE #113 section 3.3 suggests 1.1G because conductor DL may be calculated with greater certainty than DL for building elements

8.7 Tubular Busbar[23]

Structural design of aluminium tubular busbar shall comply with AS 1664. Standard WP tubes are 80 O.D. x 6 w.t., 100 O.D. x 10 w.t. & 160 O.D. x 10 w.t. Factored elastic bending stress capacity for those tubes are:

- Welded ø F_L = 84 MPa (tension or compression, in the heat affected zone [HAZ])
- Non-welded ø F_L = 191 MPa (tension or compression)

Refer to worked example in section 11 below.

Table 8.3 Some structural properties of WP aluminium busbars

Tube size	Moment of inertia Z (mm^3)	Factored bending capacity øM (kNm)
Welded - ø F_L = 84 MPa		
80 x 6	24 x 10^3	2.01
100 x 10	58 x 10^3	4.87
160 x 10	166.4 x 10^3	13.97
Non-welded - ø F_L = 191 MPa		
80 x 6	24 x 10^3	4.58
100 x 10	58 x 10^3	11.07
160 x 10	166.4 x 10^3	31.78

- Typically, WP substation tubular busbar design is governed by factors other than tube stress, as follows:
- Deflection limits for gravity action. The WP busbar serviceability deflection limit shall be less than or equal to span / 150
- Phase to phase clearance for lower voltages with high fault level eg Mungarra 11 kV – 900 mm phase centres at 40 kA r.m.s.
- Primary plant terminal palm limitations such as:
  - Busbars spanning between 2 disconnectors. One end must be a fixed connection (FX) which may attract high bending moment & thus exceed the torsional capacity of the DIS terminal palm or contact functionality.
  - Large tube with a long span which causes a high vertical gravity load on a disconnector. This is more likely in a 330 kV mesh yard.
  - Restriction of thermal movement of the busbar due to a ‘sticky’ expansion connection (EX) may cause contact alignment challenges during DIS

[23] See Western Power Internal Document

construction/commissioning In order to overcome this, it is recommended that for heavy and/or long tubular busbar spans, roller box type expansion fittings are used rather than the simple tube resting on a hole in aluminium plate.

9 Plant Capacity

9.1 Primary plant termination palms

Manufacturers of primary plant shall provide static & dynamic termination palm capacity limits. Busbar & conductor designs shall not exceed those limits.

Static loads consist of the combined conductor loads including wind. Dynamic loads consist of the static load plus the short circuit load.

Termination palms are sensitive to overload for various reasons:

- Oil seals may be damaged leading to leaks, increased maintenance, flash-over or explosion
- Disconnector current carrying contacts may suffer misalignment & subsequent arcing

The following sections outline primary plant termination palm capacities affecting conductor design.

9.2 Connectors[24]

The strength capacity of connectors, such as compression fittings, bolted tees & dead-ends, shall be considered when designing conductors:

- Compression fittings are generally preferred over bolted fittings unless ease of disconnection is required – refer to WP Construction/Maintenance (Kewdale) eg "bolted run compression tee" fittings for droppers
- "non-tension" fittings are only tested to 0.6/1.2 kN according to AS 1154.1. That is less than most plant termination palm capacities! By contrast AS/NZS 4325 T3 states that the tensile test value for stranded aluminium conductor = 40A where 'A' equals conductor CSA eg Triton 37/3.75 tension = 408 x 40 = 16.3 kN
- Maximum aluminium temperature after a short circuit test = 200 ºC [AS 1154.1 4.6.1.2]
- Compression fitting ductility – the minimum required aluminium elongation = 12% [refer NBT report on cracked compression terminations]
- Alloy/Brinell hardness for fittings for AAC – 1350 / 18-24 HB 10/500 [AS 1154.1 s8.1.10.2.2]
- Class B connectors may be used for systems where SC is restricted by protective devices [AS/NZS 4325]
- Connector mechanical test T_{alum} = 40 x A or T_{Cu} = 60 x A (maximum 20,000 N) where 'A' is cross sectional area (mm^2) [AS/NZS 4325 Table 3]
- Connector thermal test – current at which connector steady temperature is 100 ºC whilst adjacent conductor steady temperature is 120 ºC [AS/NZS 4325 6.3]
- Compression fitting barrel sizes are given in AS 1154.1 Table 8.1

[24] See Western Power Internal Document

- Compression dead ends (rather than heliform [armour grip]) are used for Substation tensioned conductors
- Compression fittings have been used by WP for tubular aluminium busbar eg some 100 mm O.D. busbars

9.3 Transformer Bushings[25]

- Conductor loads on Tx bushings shall be minimised. A comprised bushing may fail catastrophically which could jeopardise the Tx. Lead times for Tx or bushing replacement are significant.
- The bushing inclination angle affects the allowable termination palm load ie as the bushing deviates from the vertical more self-capacity is consumed in resisting bending due to gravity. Refer to the ABB (type GOE) Tx bushing brochure [ref ABB website].

9.4 Disconnectors[26]

- Take care to minimise the transfer of operating forces from the DIS to adjacent primary plant. This may be achieved by adopting a tubular busbar with expansion joint, a curved flexible stranded conductor or a lamination.
- Disconnectors & earth switches (ES) shall be able to close & open while subjected to the rated static mechanical termination palm load [AS 62271.102 Table 3]
- The manufacturer's drawing shall show the maximum termination palm capacity. Although the DIS station post insulators have high strength, the DIS palm capacity is limited by allowable deflections of the load contacts (to minimise damaging arcing).
- Disconnectors are covered by AS 62271.102
- IEC 60694 provides guidance on DIS operation (10.3), mechanical aspects (11.2) & temperature limits (11.3)
- IEC 60865-1 has information on the DIS structure spring constant

9.5 Circuit Breakers[27]

- Take care to minimise the transfer of operating forces from the CB to adjacent primary plant. This may be achieved by adopting a tubular busbar with an expansion joint, a curved flexible stranded conductor or a lamination.
- AS 62271.100 states the minimum termination palm capacity:
  - <= 72 kV – 1500 N
  - >= 145 kV – 3000N

9.6 Current Transformers[28]

- Care shall be exercised when designing conductor connections onto CTs so as to minimise forces on termination palms – overloading may cause oil leaks from the palm seals

[25] See Western Power Internal Document
[26] See Western Power Internal Document
[27] See Western Power Internal Document
[28] See Western Power Internal Document

- CTs are covered by AS 60044.1

9.7 Voltage Transformers[29]

- Inductive VTs are covered by AS 60044.2
- Capacitive VTs are covered by AS 60044.5
- Pressure relief expansion bellow (if provided) – allow conductor slack and headroom so that bellow movement is not restricted during a short circuit

9.8 Surge Arresters[30]

- Porcelain versus polymeric – WP has now (2012) adopted polymeric surge arrestors because they are safer (ie porcelain surge arresters may explode, throwing out sharp porcelain projectiles at high velocity)
- Additional busbar supports may be required adjacent to porcelain SAs where long droppers occur eg terminal yards. Especially where 132 kV primary plant is used within a 330 kV layout.
- Surge Arresters are covered by AS 1307.2 (R2015) and IEC 60099-4
- Refer to the manufacturer's information for mechanical strength:
  - Specified Short-term Load (SSL) for wind gusts & short circuit eg ABB TEXLIM Q-C polymer SSL = 40 kNm
  - Specified Long-term Load (SLL) for conductor gravity loads eg ABB TEXLIM Q-C polymer SLL = 21 kNm
  - Axial tension

9.9 Station Post Insulators[31]

- For busbar supports supporting 2 spans of tubular busbar, adopt fixed-fixed (FX-FX) or expansion-expansion (EX-EX) busbar joints where possible, to minimise torsion effects on the SPI
- Depending on the voltage, standard WP SPI cantilever strengths vary between 6 & 16 kN. Note some station post insulators are designed to be mounted at one end only so care must be taken when designing and installing as cantilever strength is reduced if installed incorrectly.
- Note that AS 7000 uses a capacity reduction factor ø = 0.8 for porcelain. That is, one may only 'load up' a SPI to 80% of its failure load eg øR = 8 kN for a 10 kN rated SPI.
- Tests & characteristics of insulators are covered by IEC 60168 & IEC 60273 respectively

29 See Western Power Internal Document
30 See Western Power Internal Document
31 See Western Power Internal Document

10 Connections

10.1 Bolted Joints

10.1.1 General[32]

Bolted joints enable rapid site assembly of conductor components.

10.1.2 Electrical Design of Bolted Joints[33]

Standard terminal palms to suit continuous current ratings shall be selected from AS 62271.301 Figure 1. Palm characteristics such as bolt hole diameter, minimum thickness & current rating are given in AS 62271.301 Table 1. Note that all WP primary plant (with the exception of cable sealing ends) is supplied with palm terminals or adapters, not cylindrical terminals. A pin to palm connector is required to connect standard terminal palms to cable sealing end cylindrical terminals.

The terminal palm continuous current ratings are based on the following parameters:

- Minimum palm material conductivity eg copper or aluminium of a suitable grade
- Palm surface finish “3.2” – roughness average (R_a) = 3.2 micrometers. Equivalent to ‘N8’ per ISO 4287 ‘Geometric Product Specifications (GPS)’
- Maximum temperature of bolted connections in air - bare copper/aluminium = 90 °C
- Contact pressure range 5.5 to 10 MPa [AS 62271.301 B2.1].
- Minimum bolt strength eg stainless steel gr. 70 or steel PC 8.8. Steel PC 4.6 is not recommended.
- Torques for lubricated bolts are given in AS 62271.301 Table B1 (steel) & Table B5 (stainless steel). Applies at any temperature > 0 °C
- Stainless steel locking plates to maintain bolt tension eg 1 mm thick stainless steel plate refer WP drg. SS1/8/0/317/1
- Use of large galvanised flat washers to limit the bearing pressure on the soft aluminium palms eg for M12 bolts the washer size is 13.5 ID x 44.5 OD. Refer to Table 19 below.
- Corrosion prevention by use of an electrical jointing compound with zinc particles eg Alminox
- Silver or nickel plated = 115 °C

10.1.3 Structural Design of Bolted Joints[34]

Fixed busbar connections (denoted ‘FX’ on primary drawings) attract bending moment due to busbar flexure in the horizontal plane, so bolt shear must be checked. Longer stranded conductors attract tension, so bolt shear must be checked. These actions are also accompanied by transverse reactions. Refer to the bolt group capacity Table 10.2 below & worked examples in section 11.3.

[32] See Western Power Internal Document
[33] See Western Power Internal Document
[34] See Western Power Internal Document

The WP standard substation primary connection bolt type is stainless steel grade 316 property class 70 (A4-70) per EN ISO 3506.

Stainless steel bolt design shall comply with The Steel Construction Institute "Design Manual for Structural Stainless Steel".

To transfer the large axial bolt forces into soft aluminium palms, large diameter 6 mm thick galvanised steel washers are required under both the bolt head & nut. These washers are not based on an Australian Standard – see Table 10.1 below.

Note PC4.6 steel bolts are not strong enough for thicker aluminium connections due to the high coefficient of expansion of aluminium relative to the steel bolt – so adopt PC8.8 galvanised steel or A4-70 stainless steel for bolting aluminium plate to station post insulators (SPI).

Table 10.1 WP Load Spreading Washers

Bolt size	**Large galv. washer size** (mm)
M12	44 O.D. x 13 I.D. x 6 thick.
M16	55 O.D. x 17 I.D. x 6 thick.

Table 10.2 Design capacities for stainless steel Gr. 316 Class A4-70 bolt groups

Bolt size	**No. bolts in group**	**Bolt centres** (mm)	**Shear capacity** (kN)	**In-plane moment capacity** (kNm)	**Tension capacity** (kN)	**Out-of-plane moment capacity** (kNm)
M12	4	50	94	3.32	215	5.36
M16	4	60	175	7.46	400	12
M16	6	60	264	14.4	600	12

Table10.3 Design capacities for steel PC 8.8/S bolt groups

Bolt size	**No. bolts in group**	**Bolt centres** (mm) **match SPI**	**Shear capacity** (kN)	**In-plane moment capacity** (kNm)	**Tension capacity** (kN)	**Out-of-plane moment capacity** (kNm)
M12	4	54	125	4.8	224	6
M16	4	90	237.2	15	416	18.7

The following graph shows capacity interaction for combined shear.

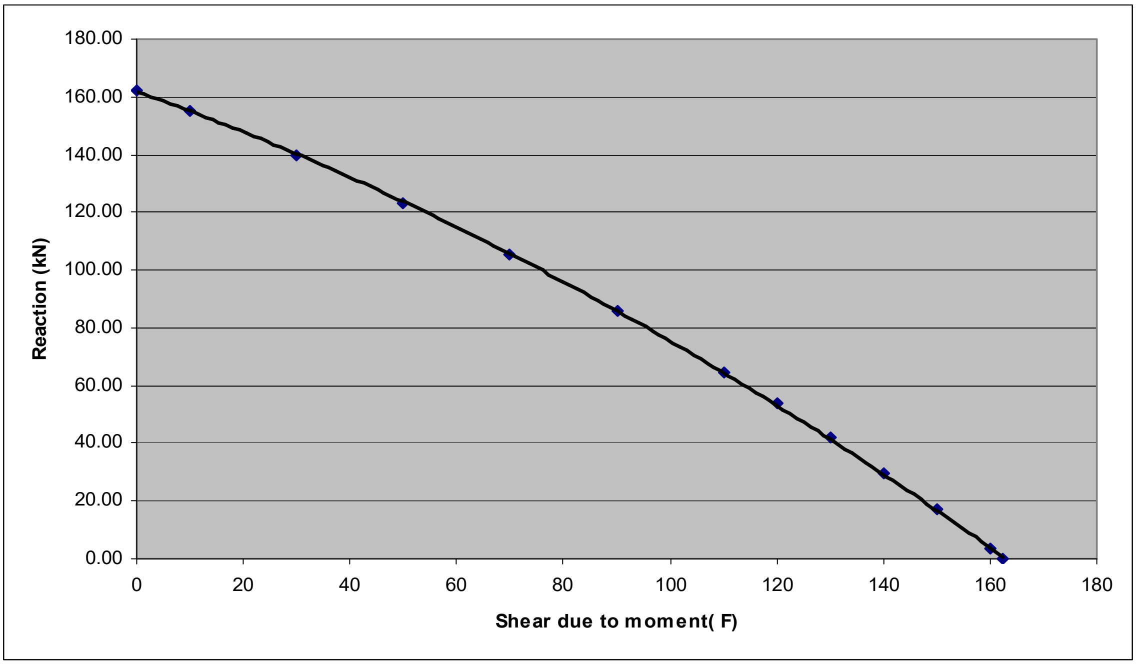

Figure 10.1 Graph shows capacity interaction for combined shear

See worked examples in Section 11.

10.2 Welds

- All aluminium weld designs shall follow AS 1665
- Welds for busbars & laminations shall be full penetration butt welds to ensure that the weld matches the electrical rating of the members being joined ie to maintain the full cross-sectional area across the weld.
- Welding of aluminium creates a heat affected zone (HAZ) which will locally reduce the strength of the aluminium within 25 mm of the weld. To enhance busbar strength at a splice location & provide a weld backing strip (to minimise burn through), a split aluminium sleeve 300 mm (eg PLP catalogue) long shall be snugly fitted internally prior to welding. Locate the splice away from the busbar maximum bending moments if possible eg locate the splice at the zero bending moment / point of contra-flexure.

10.3 Expansion Joints

Acceptable expansion joint details are depicted on standard WP substation drawings.

Consider the following when designing expansion joints:

- Friction coefficient may be reduced by adopting a nylon or Teflon seat, or preferably by using a roller box type expansion fitting. This may avoid the effect of 'sticking/release' on DIS set-up/performance. Long spans of large tubular busbar can cause large dead load reactions on DIS. Since long span busbars deflect a lot the tube may slope in the expansion bracket hole thus 'cutting into' the sharp edge of the bracket hole & cause binding. It is essential to specify a radius to the edges of the expansion bracket hole.

- Thermal movement eg for a 90 °C temperature range, 12.2 m long aluminium busbar the change in length $\Delta L = L \times \alpha \times \Delta T = 12200 \times 23.4 \times 10^{-6} \times 90 = 26$ mm
- Construction/erection tolerances eg AS 4100 recommends erection tolerances for structural steel
- Expansion bracket penetration shall be per the table below. These figures factor in thermal expansion, short circuit movement & typical construction tolerances.

Table 10.4 Busbar penetrations through expansion brackets (minimum)

Tube size	Minimum penetration (mm)
80 O.D. x 6 w.t.	80
100 O.D. x 10 w.t.	100
160 O.D. x 10 w.t.	160

- Locate a fixed busbar joint at the stronger of the two primary plant eg for a busbar between say a busbar support (BS – 10 kN) & a current transformer (CT – 2.5 kN), locate the fixed joint at the BS. The fixed (rigid) busbar joint attracts bending moment & more force than the expansion (free) joint, thus greater loads are transferred to the stronger primary plant/structure.
- On busbar supports do not mix FX & EX on the same SPI. Either adopt FX-FX or EX-EX on the same SPI to reduce torsional effects on the station post insulator.

11 Worked Examples

The following worked examples provide an insight into some aspects of busbar & conductor design.

11.1 Low level single stranded conductor[35]

11.2 Vertical Dropper[36]

11.3 Natural frequency (busbar) [37]

11.3.1 Example Calculation - 100 OD x 10 wt x 8.5 m span[38]

11.3.2 Example Calculation - 100 OD x 10 wt x 10 m span[39]

35 See Western Power Internal Document
36 See Western Power Internal Document
37 See Western Power Internal Document
38 See Western Power Internal Document
39 See Western Power Internal Document

11.4 Zone Substation 132 kV – T2 tubular busbars[40]

11.4.1 Dead load[41]

11.4.2 Wind action[42]

11.4.3 Short Circuit[43]

11.4.4 Structural analysis (Spacegass) [44]

11.4.4.1 Check phase – phase clearance[45]

11.4.4.2 Check loads on circuit DIS[46]

11.4.5 Capacity of aluminium tube grade 6063-T6 [AS 1664.1] [47]

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40 See Western Power Internal Document
41 See Western Power Internal Document
42 See Western Power Internal Document
43 See Western Power Internal Document
44 See Western Power Internal Document
45 See Western Power Internal Document
46 See Western Power Internal Document
47 See Western Power Internal Document

Appendix A: Conductor Material Parameters [48]

Table A.1: Conductor material

Parameter	Aluminium 6101-T6	Copper HC	Stainless Steel 316
Density γ kg/m³	2700	8890	8000
Young's modulus E GPa	69	124	200
Rigidity modulus G GPa	~24	45	77
Ult. tensile strength MPa	200	200-250	
Yield tensile strength MPa	175 ^^	50-55	
Ult. shear strength MPa	186 / 207 Ξ		
Yield shear strength MPa	138		
Fatigue strength limit MPa	69 **	117 ##	
Coefficient of thermal expansion 10^{-6} m/m °C	23.4	16.6	16
Melting temp °C	645 [AS7000 AA1.2] 660 [Jensen, Alcoa]	1083 [Alcoa]	1375wiki 1510eng toolbox
Resistivity @ 20 °C μΩ.m	0.0283	0.0172	
Elongation %	10		
Poisson's ratio	0.35	0.35	0.30
Brinell hardness	15 BHW	35 10/100	200 10/3000/10
IACS %		101	
Emissivity ***	0.5	0.77	-
Solar absorption coeff ***	0.5	0.70	-
Electrode potentials V	-0.83	-0.20	-0.08 to -0.19

Notes to Table above:

HC – high conductivity IACS – International Annealed Copper Std

** how many cycles? (45 MPa / $50x10^6$ cycles) – see S-N curve in Appendix G below.

half hard $300x10^6$ cycles

^^ aluminium strengths based on 99% probability with 95 % confidence level

Ξ AS1664 / Alcoa

- Alum **6101-T6** has high conductivity, high strength & is commonly used for busbars in Aust [PLP]
- Copper high conductivity designation Cu-ETP (electrolytically refined tough pitch copper) per AS1279. Was called alloy 110A. UTS = 480 – 20d (wire diameter mm)

[48] See Western Power Internal Document

Table A.2: Properties of Material

Properties of Materials

Unit	Aluminium	Aluminium alloy 1120	Copper	Galvanised steel	Aluminium-clad steel
Density at 20°C					
kg/m^3	2700	2700	8890	7800	6590
Conductivity at 20°C					
% IACS	61	59	97	10.1	20.3
Resistivity at 20°C					
$\mu\Omega.m$	0.0283	0.0293	0.01777	0.17	0.085
Constant-mass temperature coefficient of resistance					
per °C	0.00403	0.00390	0.00381	0.0044	0.0036
Ultimate tensile stress					
MPa	160–185	230–250	405–460	1310–1390	1270–1340
Modulus of elasticity					
GPa	68	68	124	193	162
Coefficient of linear expansion					
per °C	23.0×10^{-6}	23.0×10^{-6}	17×10^{-6}	11.5×10^{-6}	12.9×10^{-6}

If further technical information is required, an Olex Technical Informative is available. Topics covered include:

Appendix B: Stranded Conductor Parameters

Some characteristics of WP standard substation stranded all aluminium conductors (AAC) are tabulated below:

Table B.1 Stranded Conductor Parameters

Parameter	Krypton	Triton	Venus
Stranding	19/3.25	37/3.75	61/3.75
Mass (kg/m)	0.433	1.13	1.86
Fault rating (kA / 1 sec)	19	49.2	81.2
Fault rating (kA / 3 sec)	11	28.4	46.9
Diameter (mm)	16.3	26.3	33.8
Area (mm^2)	157	408.7	673.7
Breaking load – CBL (kN)	37.4	62.9	98.3
Modulus of elasticity (GPa)	65	64	64

- Creep (permanent elongation) is a function of time, temperature, conductor stress & conductor constraints [AS/NZS 7000 Appendix V]. Applies to longer overheads
- Bird caging – torque in conductor [AS/NZS 7000 Z4.1] – can be caused by mis-alignment of a crimped palm onto a primary plant termination palm. An example of bird caging is shown below:

Figure B.1

Appendix C: Busbar Short Circuit Ratings

Table C.1 Short circuit thermal ratings for aluminium busbar components

Description	SC 1s (kA) uno	SC 3s (kA)
80 OD x 6 tube	163	94
100 OD x 10 tube	331	191
160 OD x 10 tube	551	318
100 x 12 flat	147	85
130 x 20 flat	220	127
180 x 20 flat	442	255
20 dia. rod	50 (for 0.5 s)	-

Appendix D: Short Circuit Explained

The following explanation of short circuit mechanical effects is taken from Copper Development Association (CDA) report #22.

When a busbar system is running normally the inter-phase forces are normally very small with the static weight of the busbars being the dominant component. Under short-circuit conditions this is very often not the case as the current rises to a peak of some thirty times its normal value, falling after a few cycles to ten times its initial value. These high transitory currents create large mechanical forces not only in the busbars themselves but also in their supporting system. This means that the support insulators and their associated steelwork must be designed to withstand these high loads as well as their normal structural requirements such as wind, ice, seismic and static loads. The peak or fully asymmetrical short circuit current is dependent on the power factor (cos θ) / network X/R of the busbar system and its associated connected electrical plant. The value is obtained by multiplying the r.m.s. symmetrical current by the appropriate factor given in balanced three-phase short-circuit stresses. If the power factor of the system is not known then a factor of 2.55 will normally be close to the actual system value especially where generation is concerned. Note that the theoretical maximum for this factor is $2\sqrt{2}$ or 2.828 where $\cos\theta = 0$. These peak values reduce exponentially and after approximately 10 cycles the factor falls to 1.0, i.e., the symmetrical r.m.s. short circuit current. The peak forces therefore normally occur in the first two cycles (40 ms) In the case of a completely asymmetrical current wave, the forces will be applied with a frequency equal to that of the supply frequency and with a double frequency as the wave becomes symmetrical. Therefore, in the case of a 50 Hz supply these forces have frequencies of 50 or 100 Hz.

The maximum stresses to which a bus structure is likely to be subjected would occur during a short circuit on a single-phase busbar system in which the line short-circuit currents are displaced by 180°.

In the case of a single-phase short-circuit, the forces produced are unidirectional and are therefore more severe than those due to a three-phase short-circuit, which alternate in direction.

In a three-phase system a short-circuit between two phases is almost identical to the single-phase case and although the phase currents are normally displaced by 120°, under short-circuit conditions the phase currents of the two phases are almost 180° out of phase. The effect of the third phase can be neglected.

In a balanced three-phase short-circuit, the resultant forces on any one of the three phases is less than in the single-phase case and is dependent on the relative physical positions of the three phases.

The short-circuit forces must be absorbed first by the conductor. The conductor therefore must have an adequate proof strength to carry these forces without permanent distortion. Copper satisfies this requirement as it has high strength compared with other conductor materials. Because of the high strength of copper, the insulators can be more widely spaced than is possible with lower-strength materials.

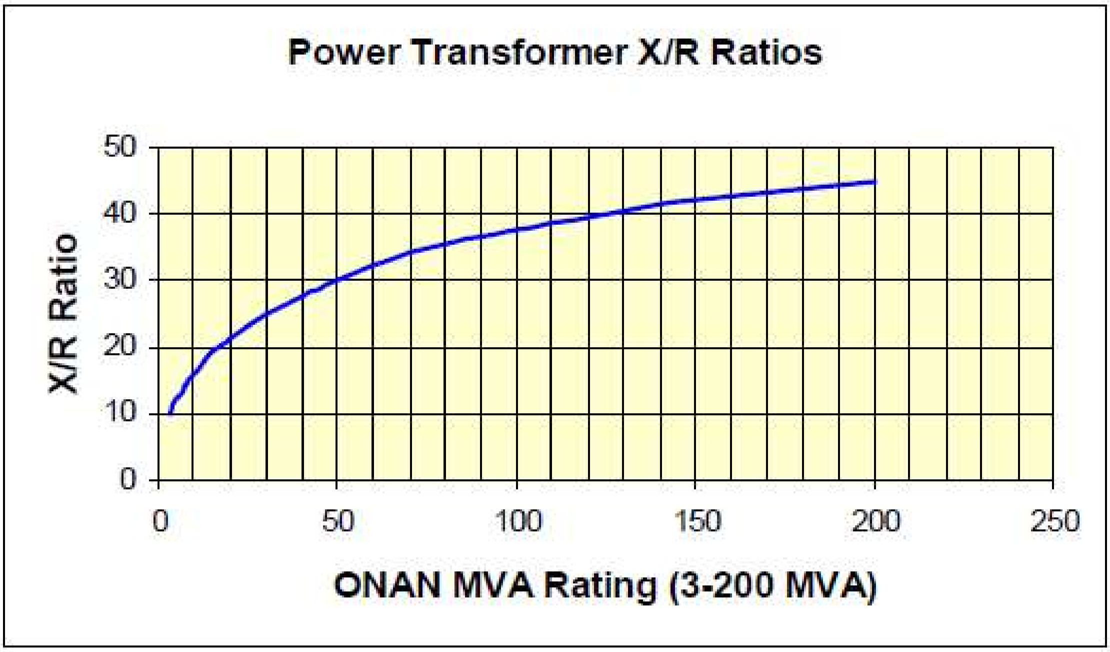
Power Transformer X/R Ratios
X/R Ratio
0
10
20
30
40
50
0
50
100
150
200
250
ONAN MVA Rating (3-200 MVA)

Figure D.1

Appendix E: Conductor Vibration

Calculating the magnitude of busbar vibration is problematic. Traditionally longer busbars are fitted with an internal stranded conductor to increase the mass/damping and the gap between the forcing & resonant frequency.

Laminar (smooth) air flow occurs at wind speeds between 0.5 to 7 m/s (25.2 kph) [ref AS 7000 1.4.43 & Z3]. Other references cite wind speeds of less than 20 m/s [IEEE Std 605] or 15 mph (6.7 m/s) [PLP]. These wind speeds are more prevalent in flat open terrain & areas with constant low velocity prevailing winds / low temperatures [AS/NZS 7000 8.2.7.3]

Below a speed of 0.5 m/s wind does not have enough energy to induce vibration. Velocities above 7 m/s are generally turbulent & do not induce vortex shedding. [AS/NZS 7000 Z3]

Vibration movement in air is less than 0.2 D (ie < 20% of busbar outside diameter). By contrast movement in water is ~ 1.0 D. The busbar movement occurs perpendicular to the wind direction in an up/down motion as illustrated below:

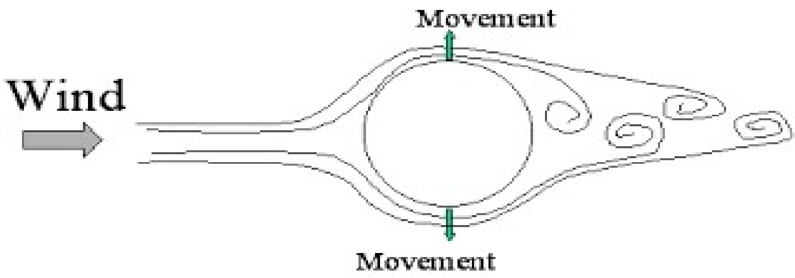

Figure E.1

The Strouhal number (S) is a dimensionless number describing oscillating flow mechanisms. For a cylindrical shape S = 0.185 (sometimes rounded to 0.2 eg AS 7000 formula).

Fixed & free ends influence busbar natural frequency.

If the natural frequency (f) of the busbar coincides with the shedding frequency of the vortices, large amplitude displacement response may occur, often referred to as the critical velocity effect. The asymmetric pressure distribution, created by the vortices around the busbar, result in alternating transverse forces. To calculate busbar natural frequency: determine end fixities in the vertical plane, calculate dead load (DL) deflection of the busbar (eg Defl. $\Delta = 5wl^4/(384EI)$ for a beam pinned vertically at both ends) & then $f \sim 18/\Delta^{0.5}$.

The recommended damping conductor mass is between 10 & 33% of tubular busbar mass eg 100 x 10 tube → damper mass = 0.76 to 2.5 kg/m eg 160 x 10 tube → damper mass = 1.27 to 4.2 kg/m. Some designers use 2 x damping wires 2/3 the length of the tube ie damping wire is doubled up in the middle 1/3 of the tube.

The damping wire opposes vertical movement of the busbar tube as it is fixed at one end of the tube and free at the other.

Avoid tubular bus natural frequency < 2.75 Hz [ref "Use of compression technology on busbars" D. Simpson EESA Conference 2003].

For stranded conductor, f = 0.185 v/d where ‘f ’ is frequency (Hz), ‘v’ is wind velocity perpendicular to conductor (m/s) & ‘d’ is the conductor outside diameter (m). Power dissipation of a vibration damper (eg Stockbridge) must be greater than the wind power (this only applies to the longer spans of Transmission lines.

Appendix F: Approval Record and Document Control[49]

[49] See Western Power Internal Document