Review of Substation Busbar Component Reliability

TB 930

(WG.B3.49)

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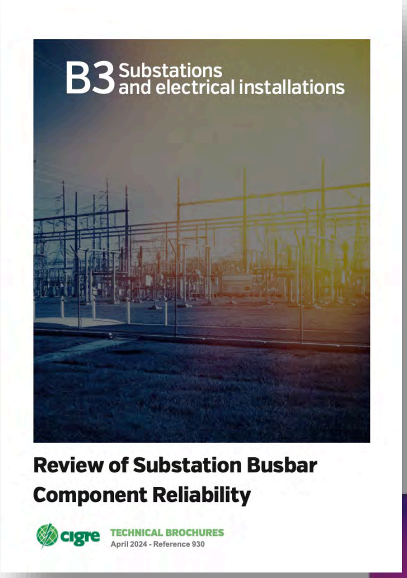
Why read this Technical Brochure?

- ➢ The grid is evolving and changing with renewables
- ➢ Increased rate of component ageing noted, including electrical contacts due to:
  - Volatility in loads and generation
    - o Increased grid Wind and Solar
    - o Decreased Coal, Oil, Gas, Nuclear power
  - Consumers are changing:
    - o E-Mobility, Data-Centres, AI, Industrial decarbonization….
- ➢ Consequences for the grid:
  - More grid extension – greenfield and brownfield projects, additional transmission
  - Digital substation retrofit
  - Remedial and proactive grid management is required



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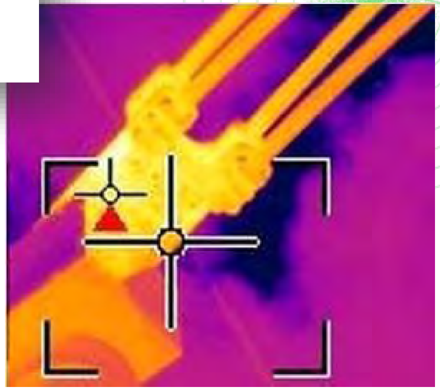
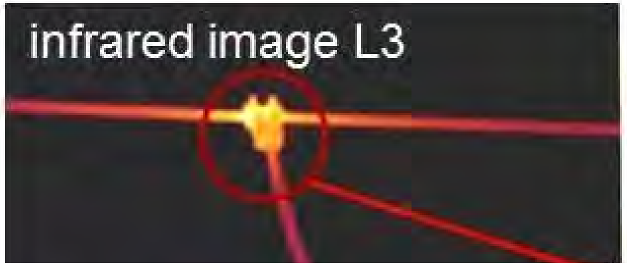
259 pages





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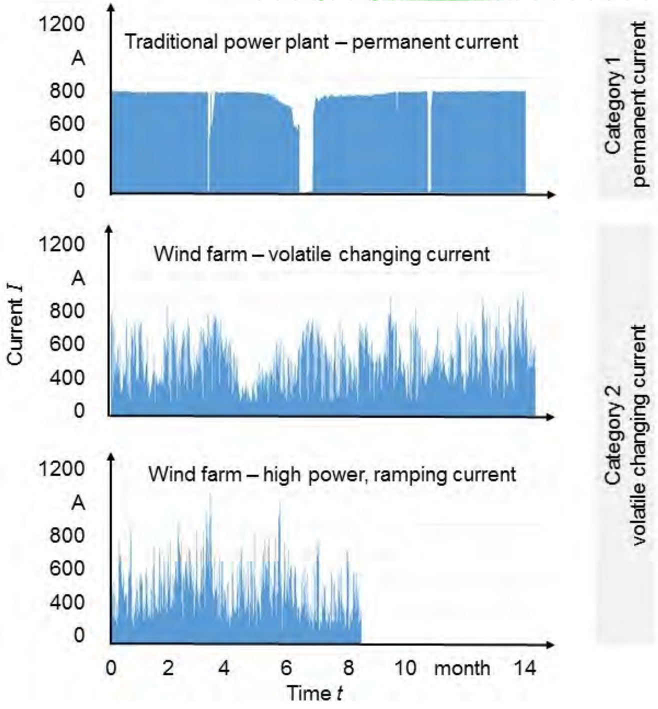
Why read this Technical Brochure?

- Connector costs are typically 0,5 to 1% of total substation cost
- Price tends to overrule quality, testing & technical improvement
- Supplier price pressure leads to:
  - → ‘cheaper’ products
  - → reduced component lifetime
- <1% of substation value can result in total substation failure
  - → Potential revenue loss in millions caused by a connector costing hundreds of €
- Increased loads & changing loading profiles leading to changes in ageing characteristics & potential failures
- No specific IEC standard for the design, manufacture or testing of the wide range of substation connectors



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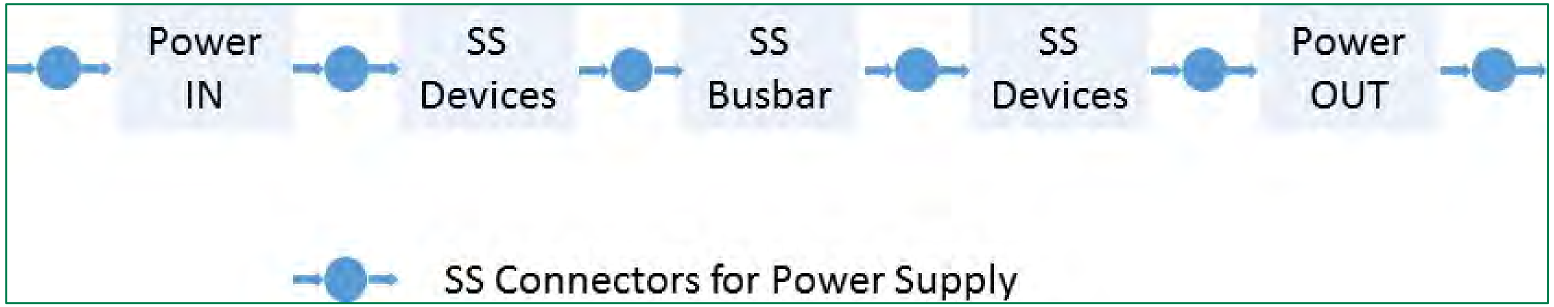
1. Introduction

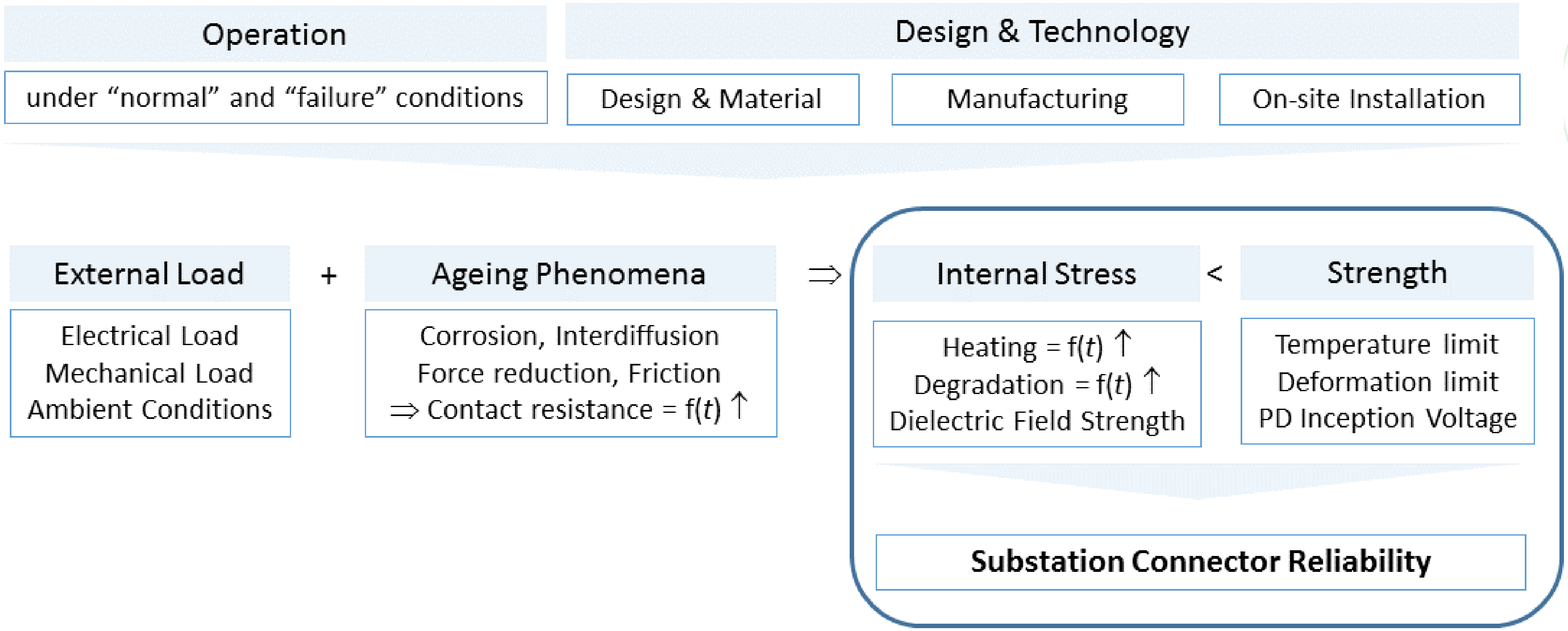
Introduction

1. GENERAL RELIABILITY EXPECTATION



$$VD = MTBF/(MTBF + MTTR + Offline)$$

VD	**- Availability factor**
MTBF	**- Mean Time between Failure**
MTTR	**- Mean Time to Repair**
Offline	**- Offline Time**



$$VDa = VD1 * VD2 * \ldots * VDn$$

n - Number of links in the chain

2. Properties of electrical contacts and degradation mechanism

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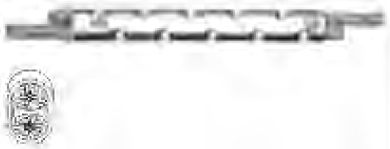
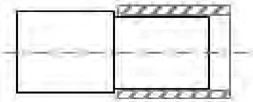
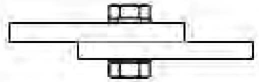
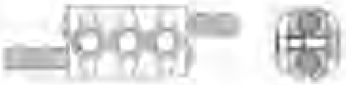
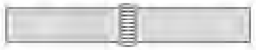
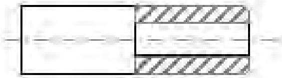
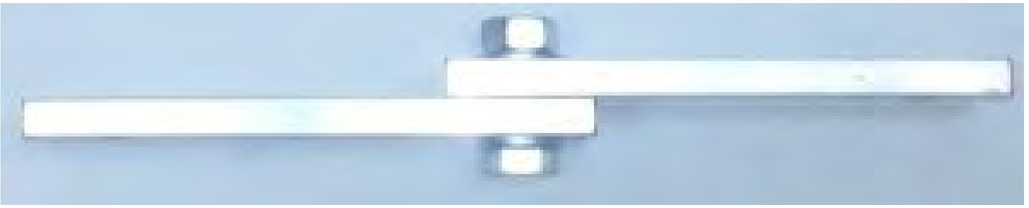
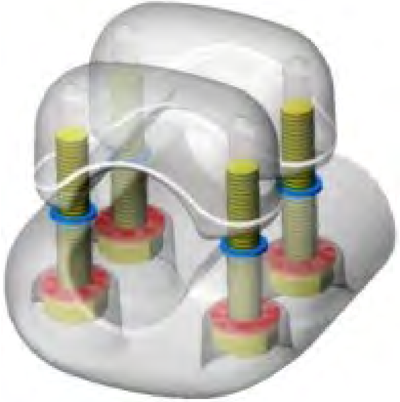
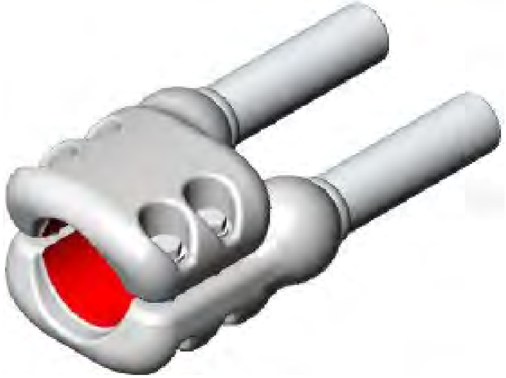
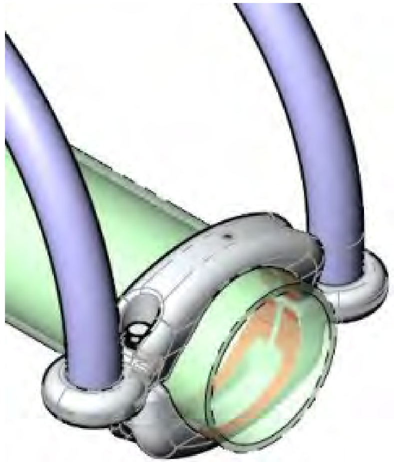
Function		Examples			
Conjugate and frictional	functional integration between current carrying and joint forcing elements	Full-tension and non-tensioned, hexagon **press connector and cable lugs** 	Full-tension **notch type connectors** 	**helically formed rod fittings** as line splices for stranded conductors 	**Shrinked** cylindrical bus bar connections 
	Separate force storage elements	**Bolted** bas bar connection 	Non-tensioned **connecting clamps** 	Full tension connectors **wedge-/cone tension clamps** 	
Cohesively		**Welded/solded connections** for flexible and thermal linear expansion tapes 	**Metal spraying** for local connecting areas on bus bars 		









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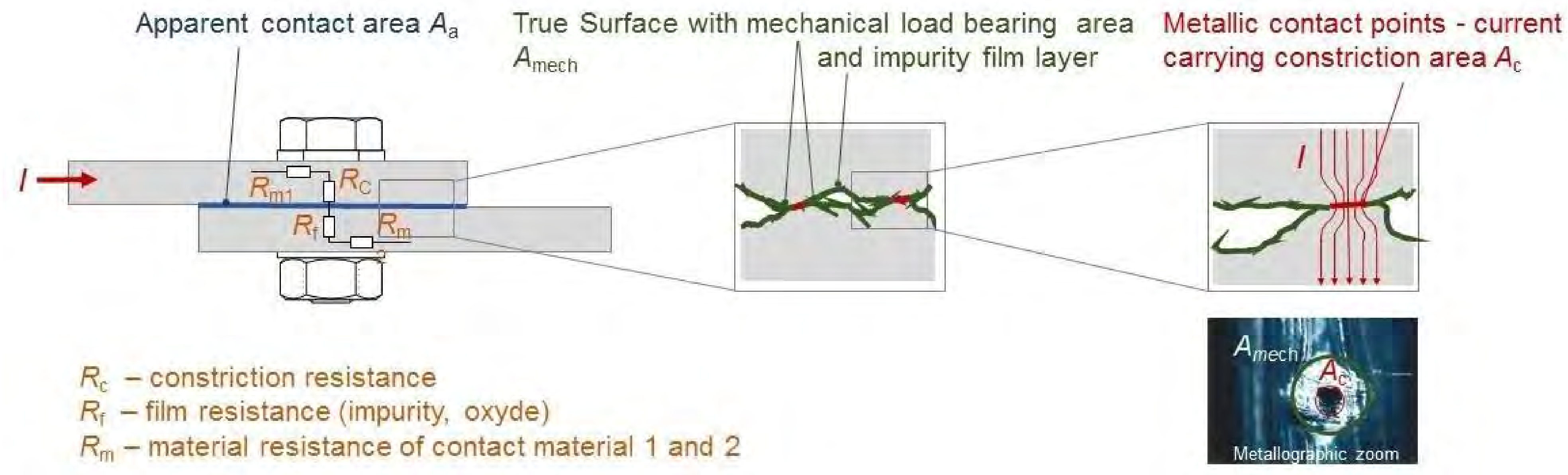
Contact Theory

- Installation is a critical factor in a connection’s performance and longevity
- Typically, only 2% of the total contact area is effectively current-carrying (micro contacts)
- Essential to create and maintain as many micro points as possible during the entire contact lifetime



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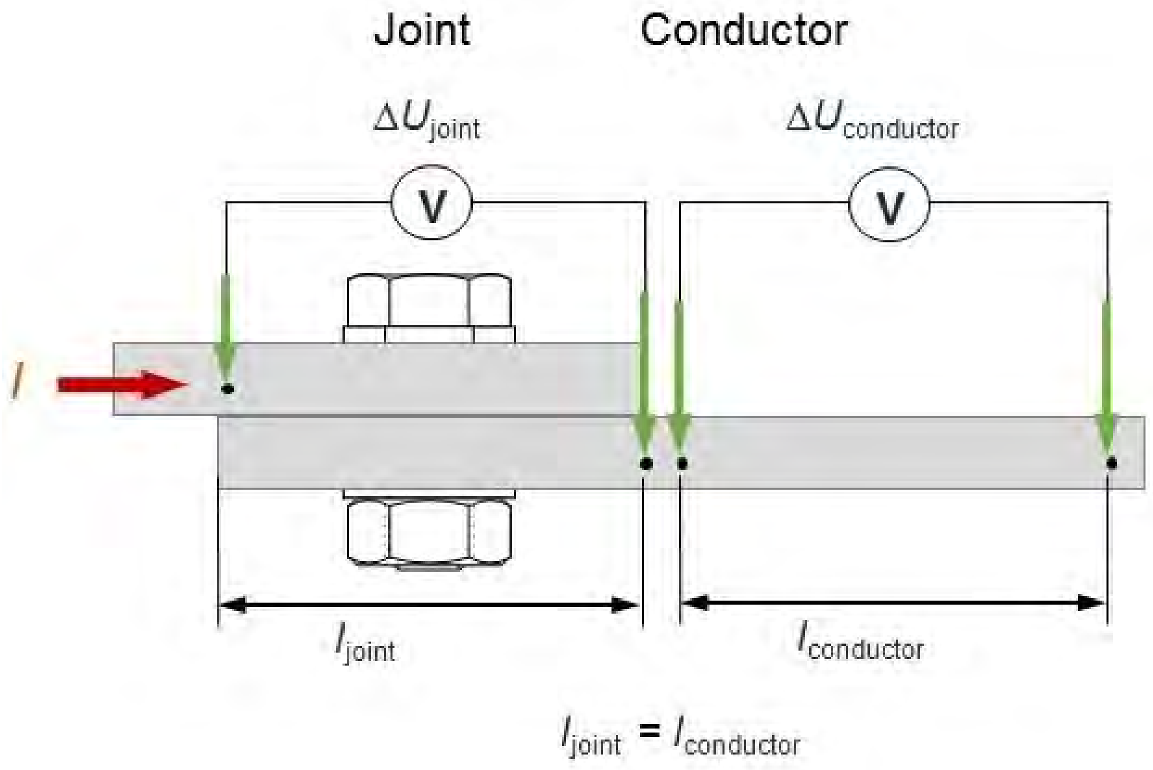
ELECTRICAL CONTACTS AND CONNECTIONS

$$k_u = \frac{\Delta U_{joint}}{\Delta U_{conductor}} = \frac{R_{joint}}{R_{conductor}} = \frac{P_{joint}}{P_{conductor}}$$



General validation:
- no additional losses $k_u = 1$

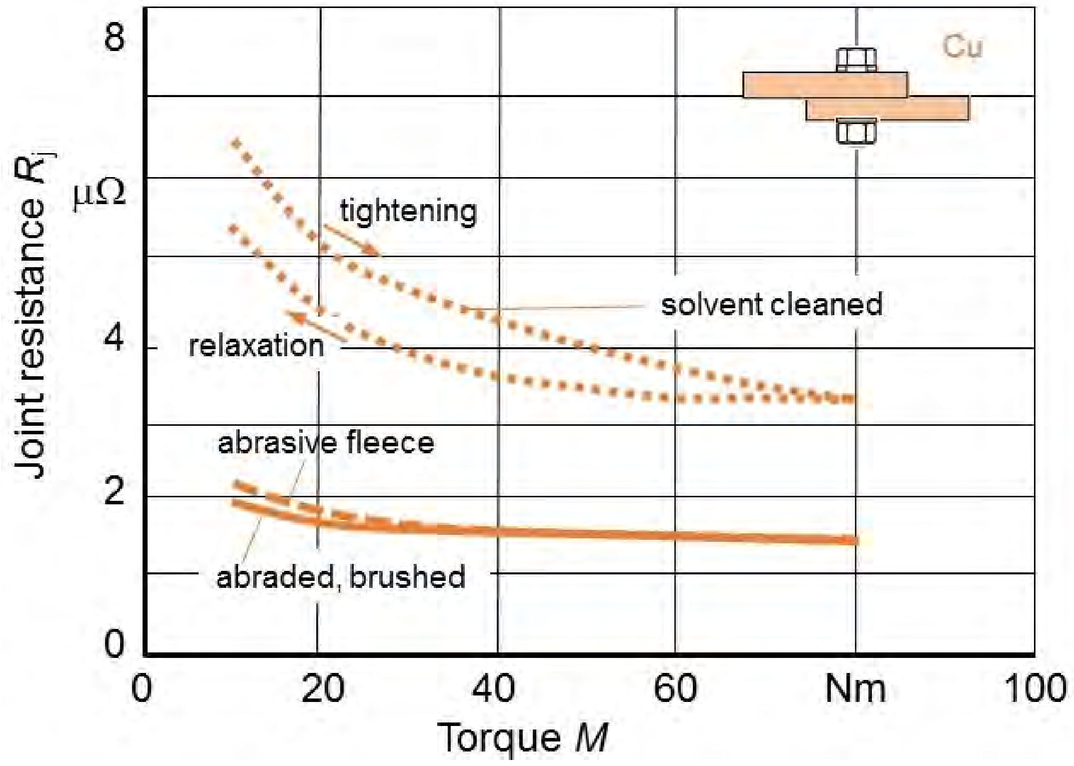
busbar connection:
- minimum $k_u = 0{,}5$ (2x cross section area)
- equal temperature $k_u = 1{,}5$ (larger surface area)

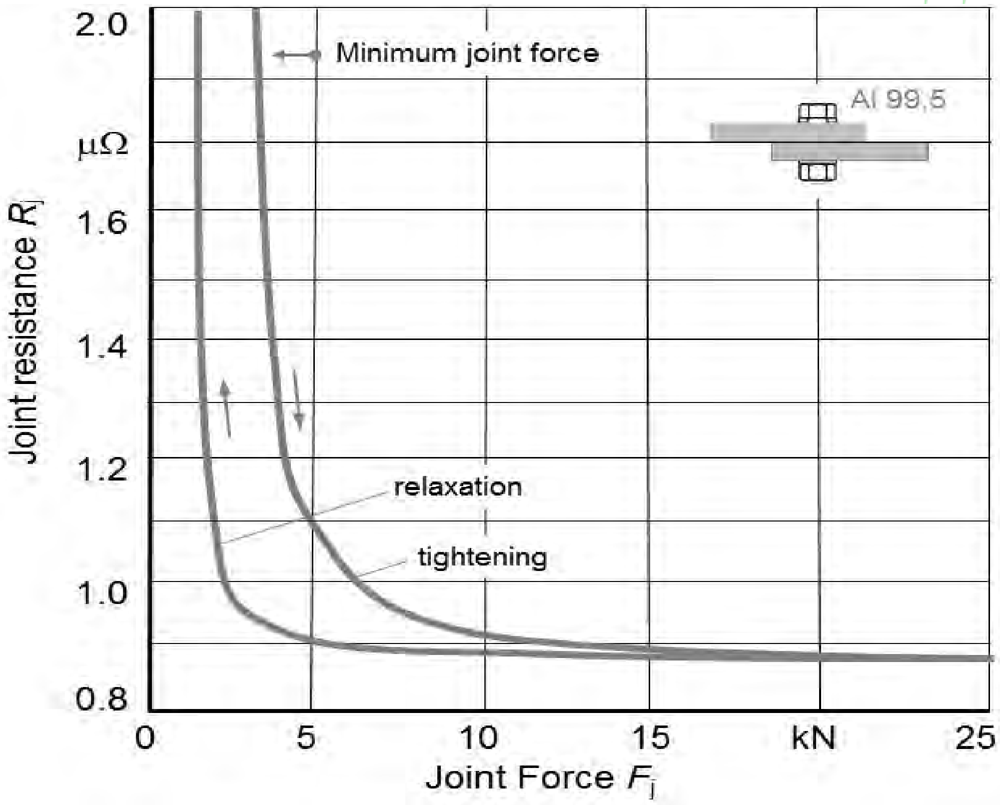
($k_{u0} = 0.8$ to 2.3)

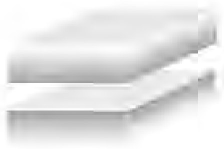
performance factor k_u is a simple and very useful criterion

ELECTRICAL CONTACTS AND CONNECTIONS

$$\frac{R_c}{\mu\Omega} = \frac{(10^{-3} C \rho)}{(0,1 \frac{F_j}{N})}$$



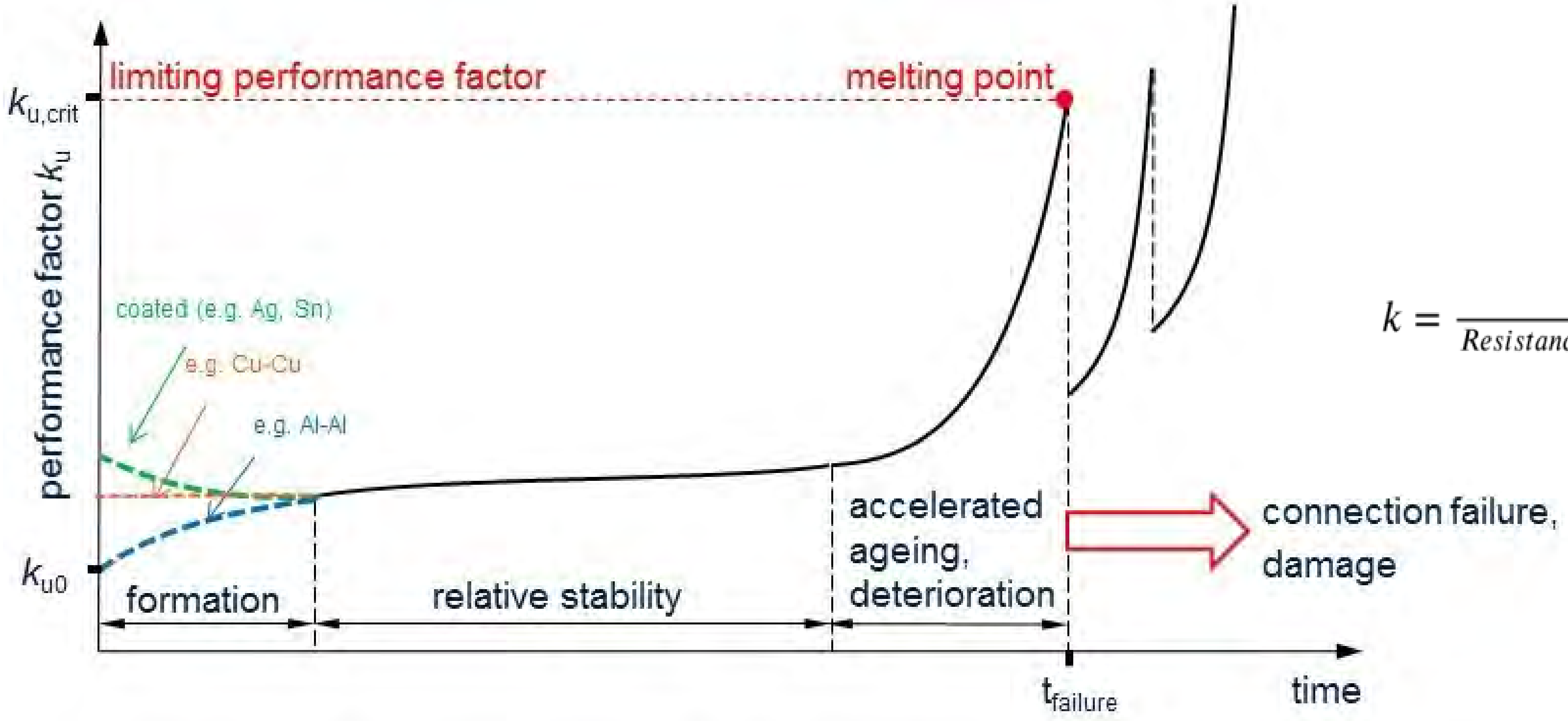



flat – flat brushed

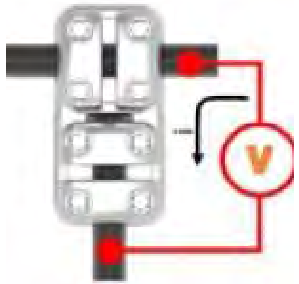

flat – flat

Lifetime Ageing of an Electrical Contact

- The performance factor k has proven to be useful for evaluating the measured joint resistance

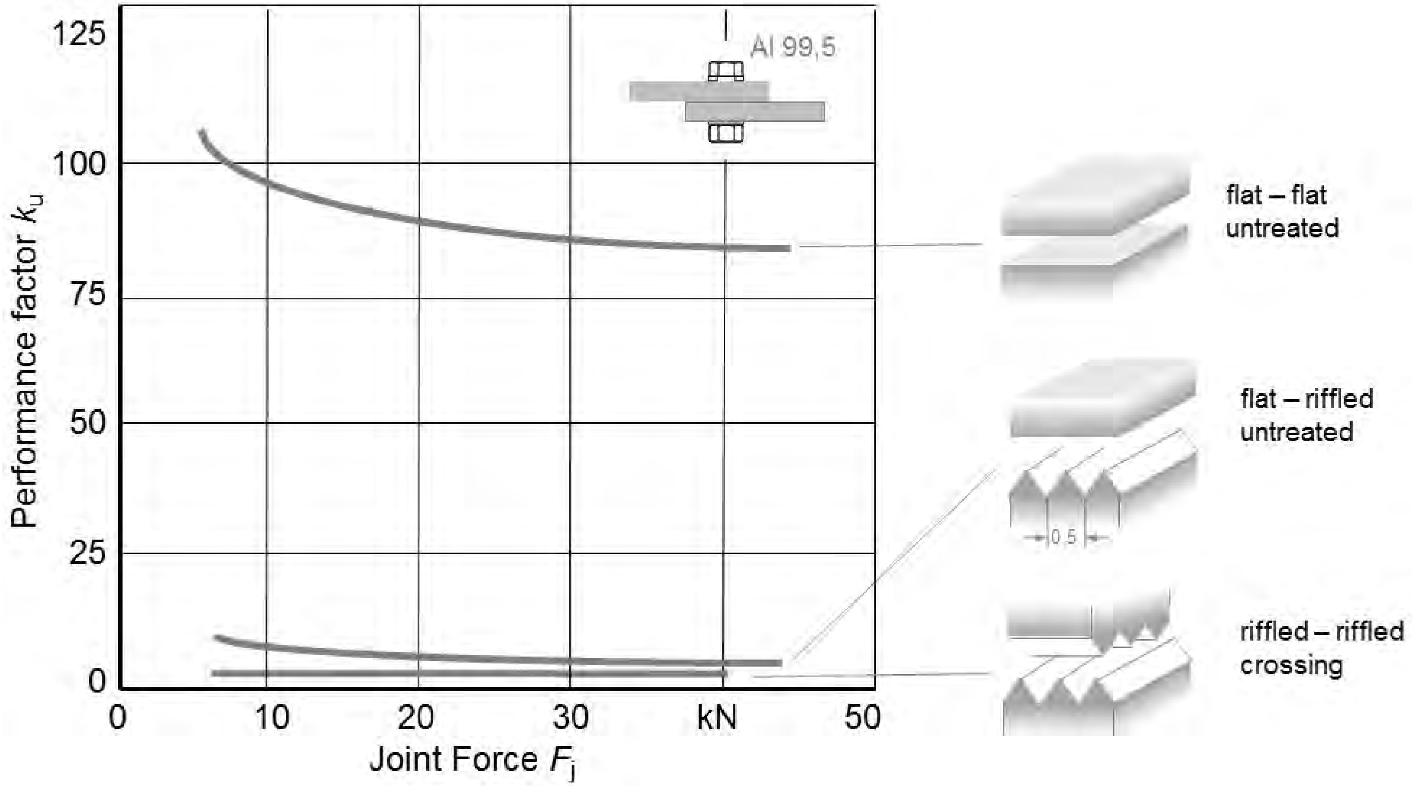


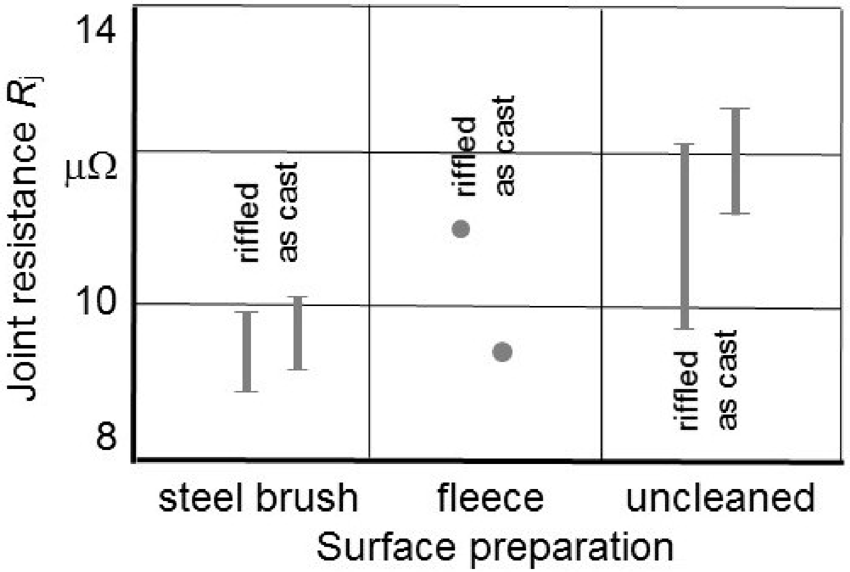
$$k = \frac{Joint\ resistance}{Resistance\ of\ the\ same\ lengt\ of\ the\ conductor}\ or\ \frac{R_j}{R_c\ X\ L_j}$$

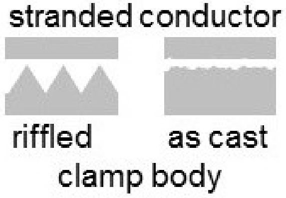


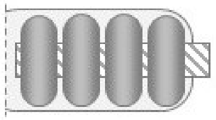
k_{u0} - initial performance factor directly after construction (t = 0)

$k_{u,crit}$ - critical (limiting) performance factor ($t = t_{failure}$)


125
100
75
50
25
0
Performance factor k_u
0
10
20
30
kN
50
Joint Force F_j
Al 99,5
flat – flat
untreated
flat – riffled
untreated
0.5
riffled – riffled
crossing


14
μΩ
10
8
Joint resistance R_j
riffled
as cast
riffled
as cast
riffled
as cast
steel brush
fleece
uncleaned
Surface preparation


stranded conductor
riffled
as cast
clamp body

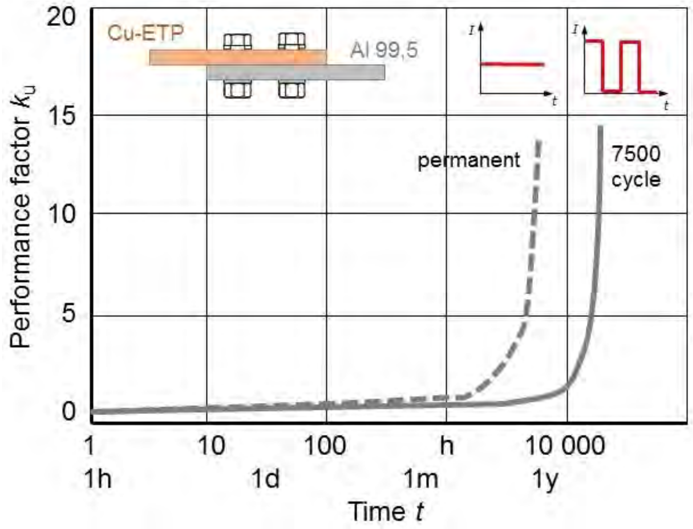


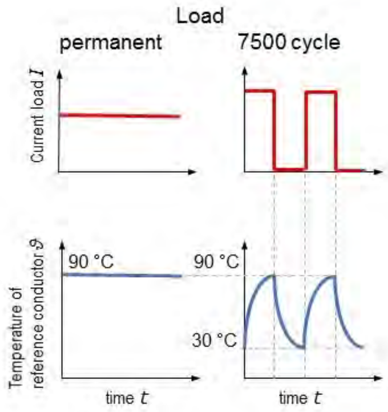
Degradation and Mitigation Measures

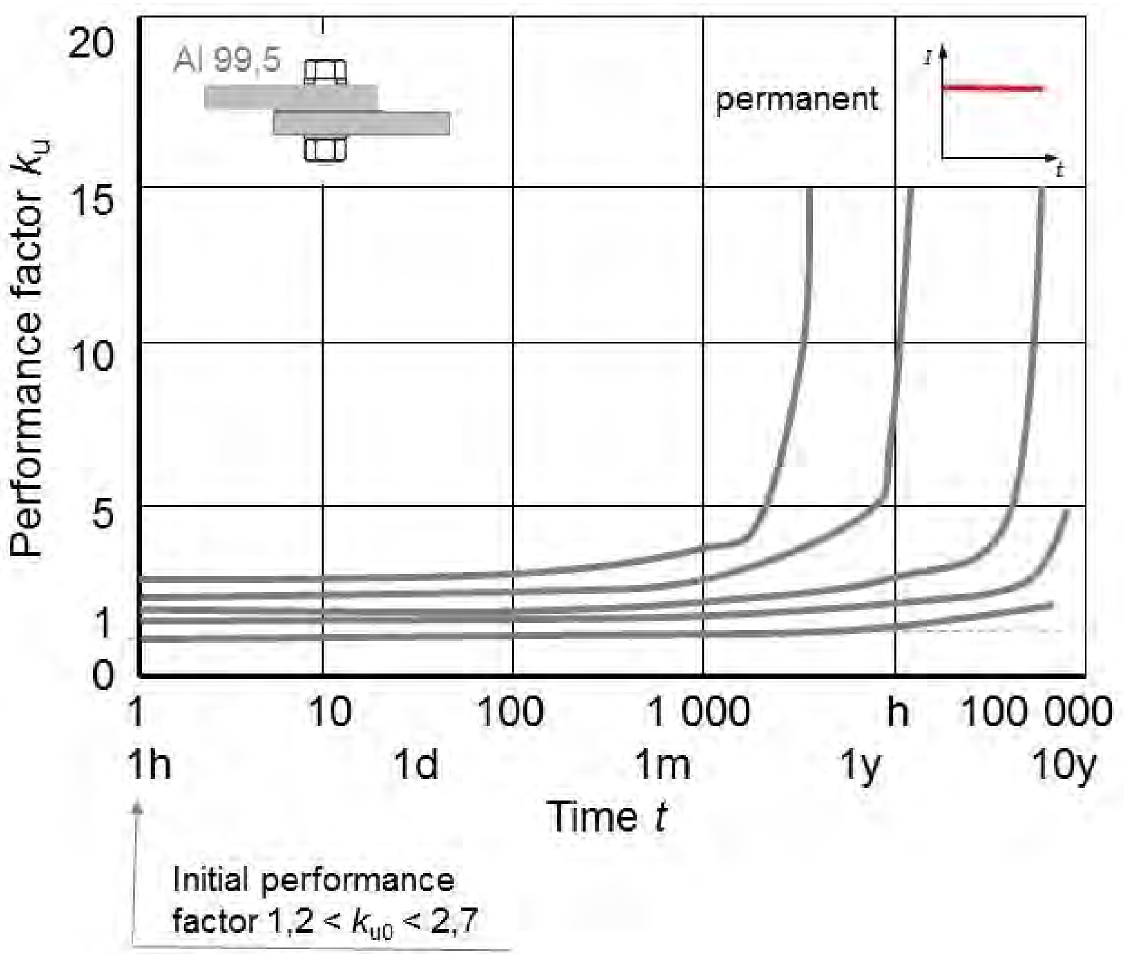
1. Chemical Corrosion
    - Oxide layers
2. Bimetallic Galvanic Corrosion
3. Joint force reduction
4. Loading cycle influence

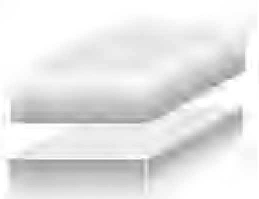
Micro contact between copper and aluminium

Degraded micro contact after corrosion



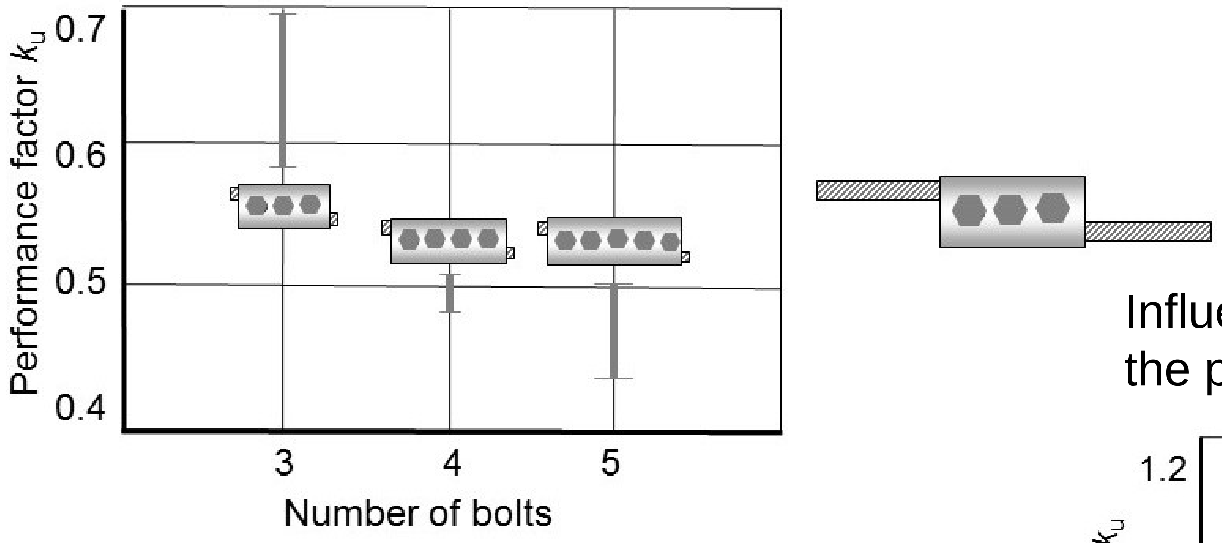




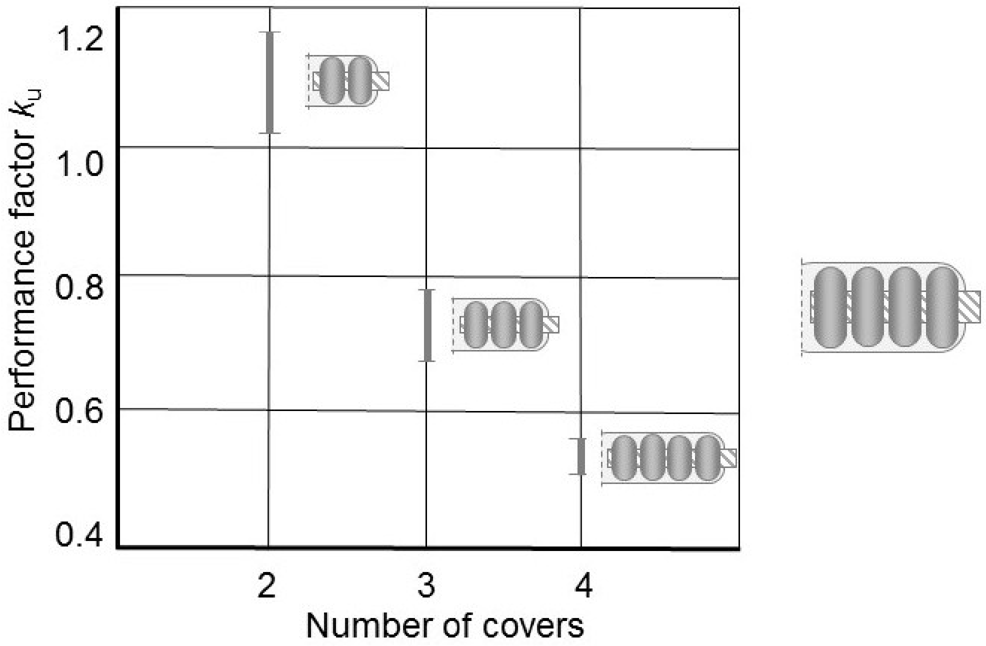


Experimental long-term tests with bolted Aluminum-connections over 8.2 years

Influence of the number of bolts in parallel-groove clamps on the performance factor after installation



Influence of the number of covers in substation clamps on the performance factor after installation



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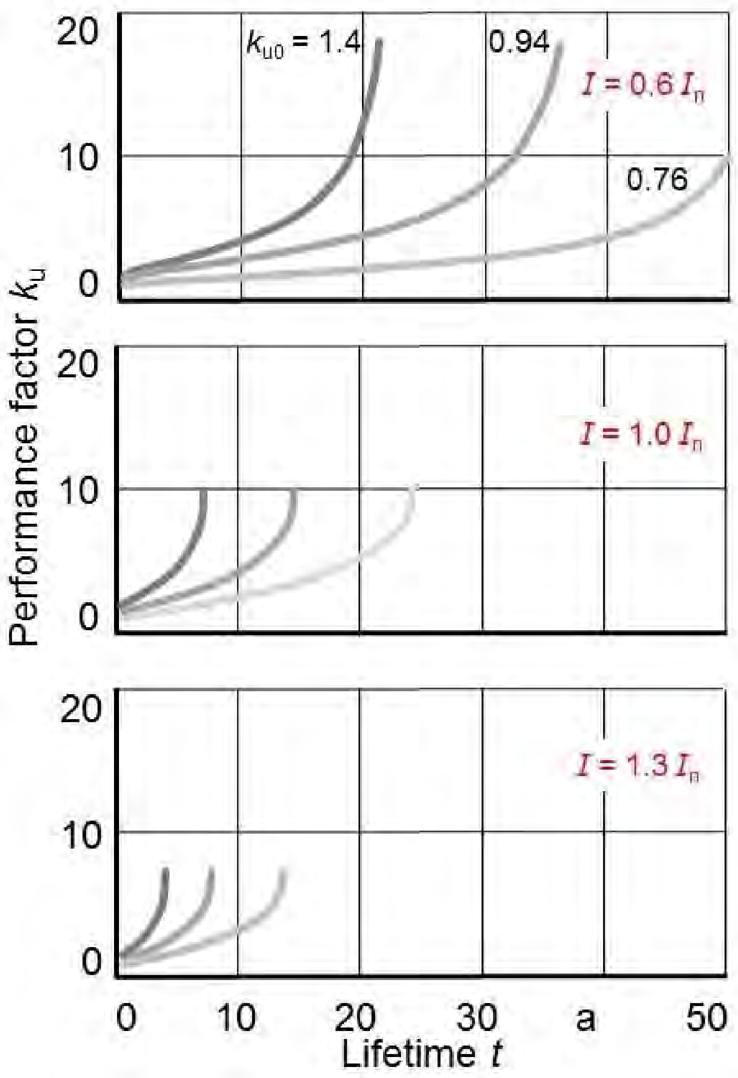
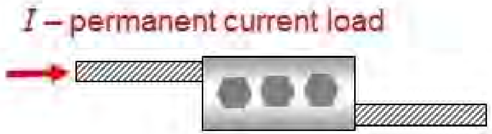


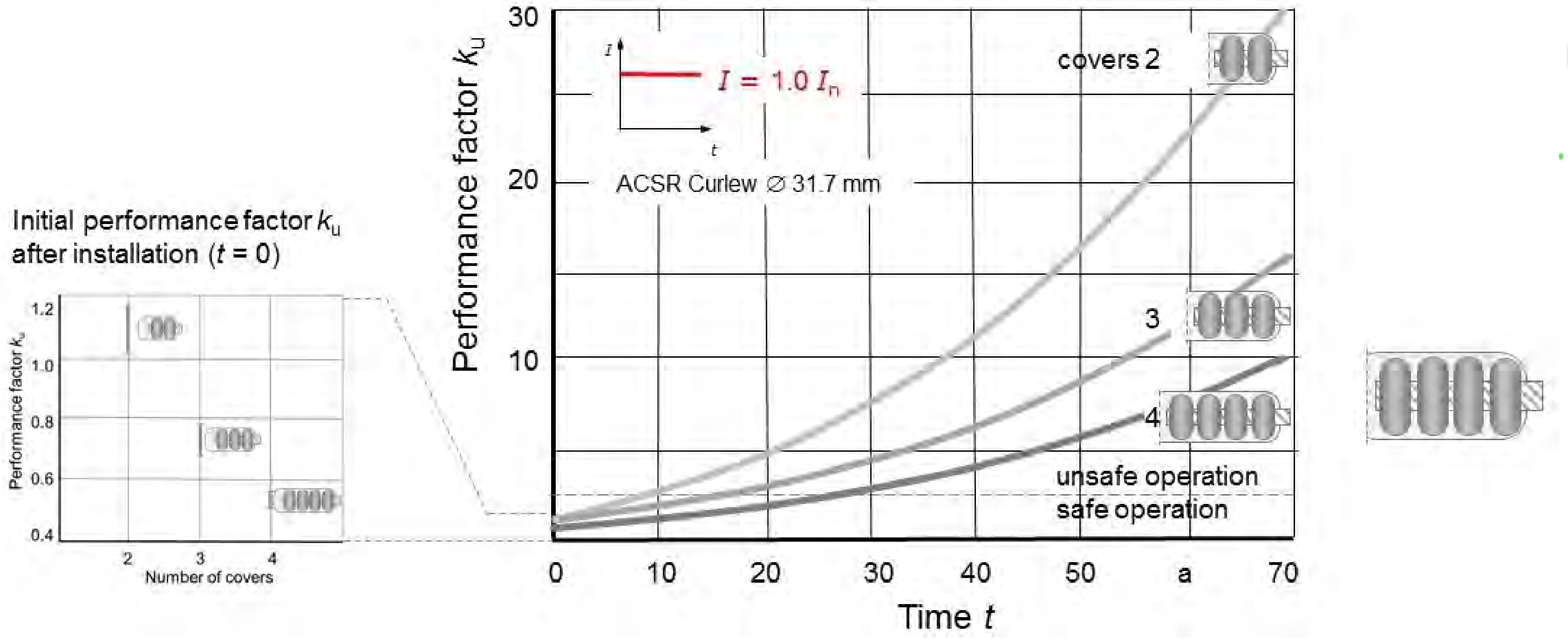


Conductor ACSR 185/30

Initial performance factor k_{u0} after installation:

min	0,76
average	0,94
max	1,40

Indoor laboratory long-term test



Calculated lifetime of substation clamps depending on number of covers

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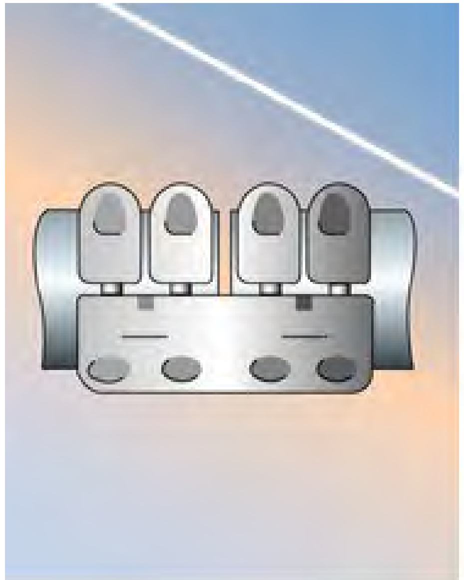
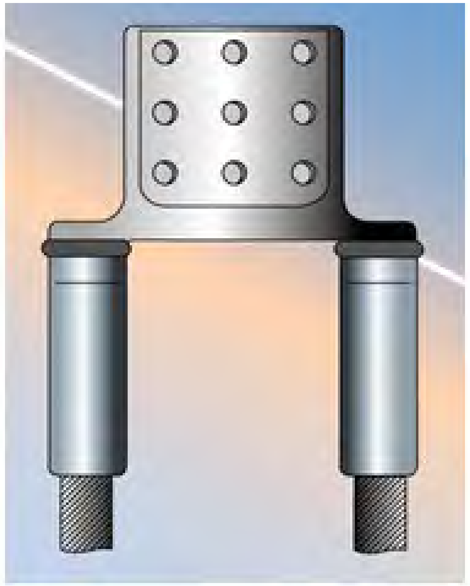
3. Classification of substation connectors

Connecting Technologies

1. Bolted



2. Compressed



3. Welded

Typical Arrangements

- **Connectors**: The connectors have both mechanical and electrical functionalities Joints (jointing two conductors)

- **Terminal connectors** (connections of conductors to electrical equipment)

- **Derivation connectors** (derivation of a tap conductor from a main conductor as Tee, Parallel groove…)

- **Clamps or supports**: Clamps typically have mechanical function without carrying permanent current e.g mechanical supports (for rigid and flexible conductors)

- **Spacers** (for conductor bundles from twin and up to 4 and sometime above)

- **Accessories**: Product family including earthing stirrups, end caps for tubular conductor, corona shields

4. Design of busbars and connections in air insulated substation

Design of busbars and connections in AIS substations

Types of connections

1. This chapter focusses on the design implications of connecting flexible or rigid, single or bundled conductors to HV equipment with connectors/clamps, either bolted, welded or compressed.
2. Of importance are equipment and component mechanical and thermal behavior under static and dynamic conditions.
3. Types of connections
   - Flexible: single or multi bundle stranded conductor connections strung between equipment or termination points,
   - Rigid: tubular conductor connections between equipment or for busbars.

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Design of busbars and connections in AIS substations

Busbar design

1. Busbars are the central nodes of substations, collecting and distributing power through incoming and outgoing feeders.
2. Circuit configurations depends on the substation criticality, flexibility, supply security and other network requirements.
3. Important factors influencing busbar design:
   - Network criteria,
   - Electrical criteria,
   - Physical layout,
   - Environmental criteria.

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Design of busbars and connections in AIS substations

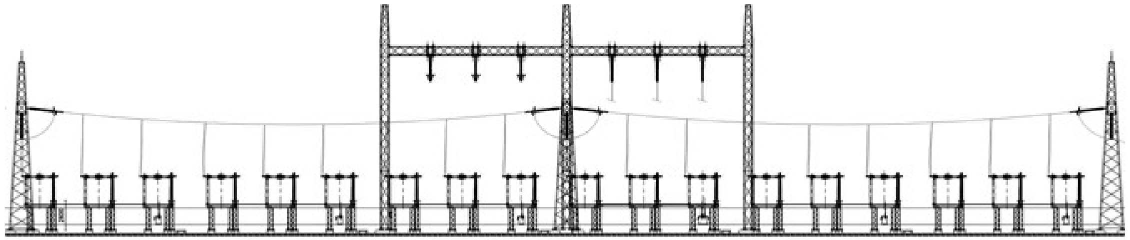
Factors impacting on busbar design

1. Network:
   - Circuit configuration, number of busbars.
2. Electrical:
   - Rated current, short-circuit current, rated voltage, corona, radio interference (RIV), conductor type (flexible/rigid) and configuration.
3. Environmental:
   - Temperature (Dt), ice, wind, earthquake, pollution, altitude above sea level, expansion.
4. Mechanical:
   - Tensile forces and stresses, individual loads (e.g. down dropper), vibrations.
5. Electromechanical:
   - Short-circuit forces between conductors, drop forces, pinch forces.
6. Spatial:
   - Minimum clearances and heights, conductor sag, conductor swing.

Design of busbars and connections in AIS substations

Long flexible connections

1. Long flexible connections can be considered as short overhead lines and treaded as such.
2. Impact of design decisions, i.e.:
   - Decreasing tension forces: bigger sag and higher gantries but also higher drop forces.
   - Increasing tension forces: reducing sag, reducing gantry height but increase loading on structures and equipment.
3. Different types of clamps are available for use:
   - Tension clamps : Wedge, bolted, compression.
   - Non-tension clamps: T-connectors, parallel groove, flexible bus supports, conductor spacers.



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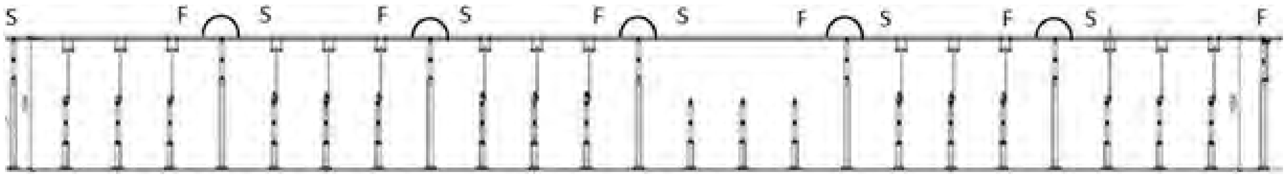
Design of busbars and connections in AIS substations

Rigid tubular connections

1. Design considerations include:
   - Type of rigid conductor.
   - Type of post insulator.
   - Type of conductor supports and connectors.
2. Types of support and coupling clamps include:
   - Pinned or flexible.
   - Sliding/expansion.
   - Fixed or rigid.
3. Other clamps
   - End caps with/without damping conductor fixing point.
   - T-connectors for connecting conductors.

Type of beam and support			α	β *)	γ
Single span beam	A and B: simple supports	A B	A: 0,5 B: 0,5	1,0	1,57
	A: fixed support B: simple support	A B	A: 0,625 B: 0,375	$\frac{8}{11} = 0{,}73$	2,45
	A and B: fixed supports	A B	A: 0,5 B: 0,5	$\frac{8}{16} = 0{,}5$	3,56
Continuous beam with equidistant simple supports	Two spans	A B A	A: 0,375 B: 1,25	$\frac{8}{11} = 0{,}73$	2,45
	Three or more spans	A B B A	A: 0,4 B: 1,1	$\frac{8}{11} = 0{,}73$	3,56

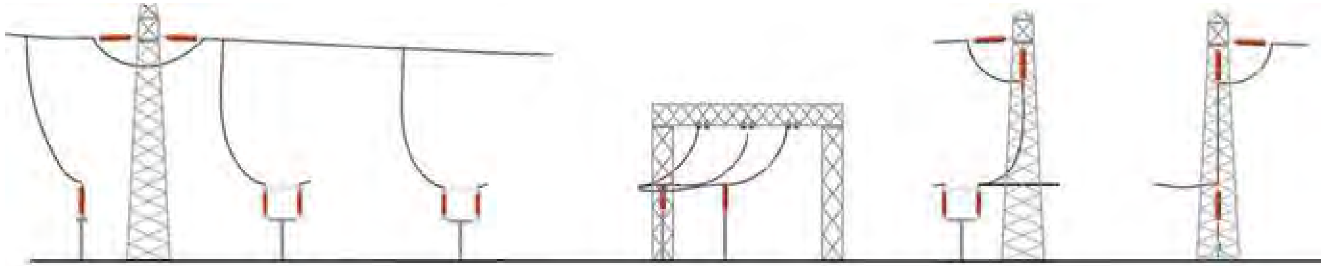
* Plasticity effects included.



Design of busbars and connections in AIS substations

Dropper & jumper design

1. Droppers are used to connect flexible or rigid busbar conductors to HV equipment at lower conductor levels.



2. Jumpers are connections between two conductors which are fixed by insulators to steel structures

Design of busbars and connections in AIS substations

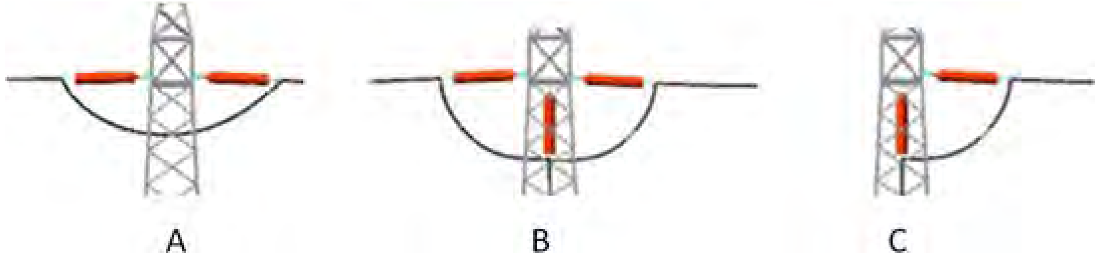
Design of apparatus connections

1. Stranded conductor connectors for apparatus connections:
   - Terminal Connectors stranded Conductor to Palm,
   - T-connectors,
   - Parallel groove connectors,
   - Bundled Terminal connectors to Vertical Stud,
   - Stranded conductor supports.
2. Tubular conductor connectors for apparatus connections:
   - Fixed Terminal tube to Palm connectors,
   - Expansion T- Connectors,
   - T-connectors.

Design of busbars and connections in AIS substations

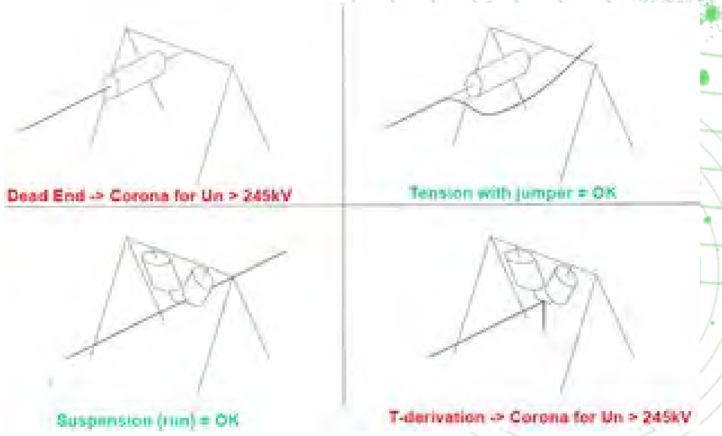
String and post insulators

1. Longer connections required include busbars and bay crossings.
2. To insulate and fix these long flexible conductors to the steel support structures, tension string or post insulators are required.
3. Insulator material include porcelain, glass or composite.
4. String insulator designs depend on the specific requirements:
   - Single tension/suspension string,
   - Multiple (2, 3, 4) tension/suspension strings with parallel insulators,
   - Multiple (2, 3, 4) tension/suspension strings with V-shaped insulators.

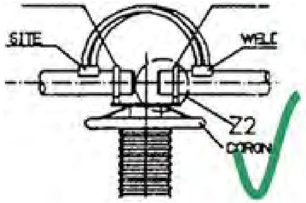


Design of busbars and connections in AIS substations

Corona mitigation



1. The presence of coronal is impacted by:
   - Voltage level and safety factor,
   - Voltage level and surface imperfections,
   - Phase conductor size and/or bundle arrangement,
   - Connector - apparatus arrangement,
   - Connector and insulator string design.
2. Overhead line corona-free composite insulators might require corona rings when used in substations, because of the lower clearances and different layouts in substations.



5. Technical specification and Quality

How to specify Connector Requirements?

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Properties of Connectors & What to look for

1. Ampacity
   - Reduce the temperature of the connection
2. Short Circuit current capabilities
   - Reduce impact of short time overload by proper design
3. Voltage
   - Reduce the Corona/RIV
4. Mechanical Load
   - Reduce the stresses on connectors/terminals

5. Installation can only be influenced by site personal but has a huge impact on the lifetime of connectors

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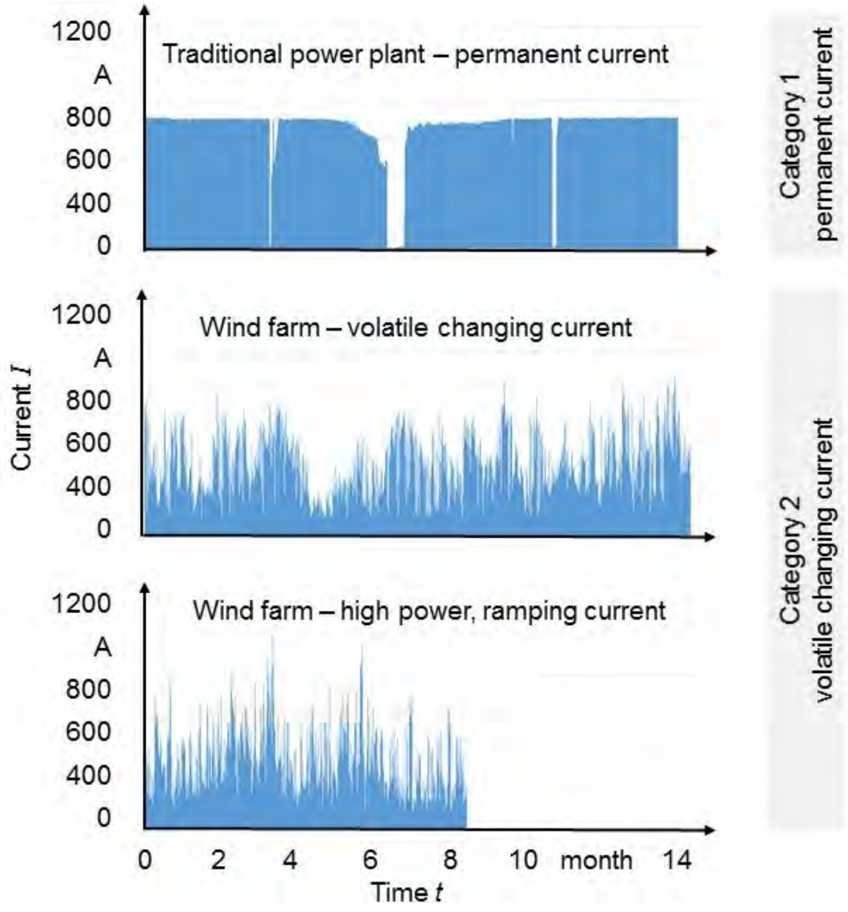
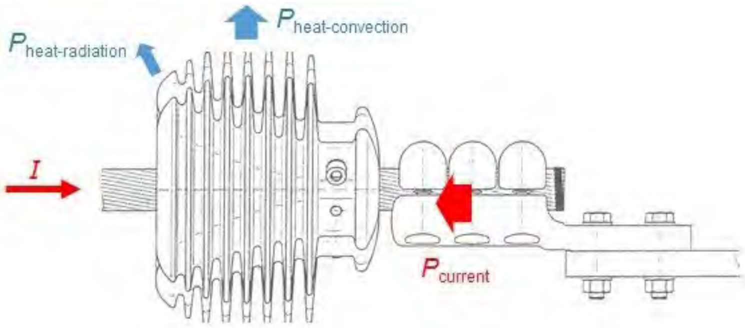
Other Specification Parameters

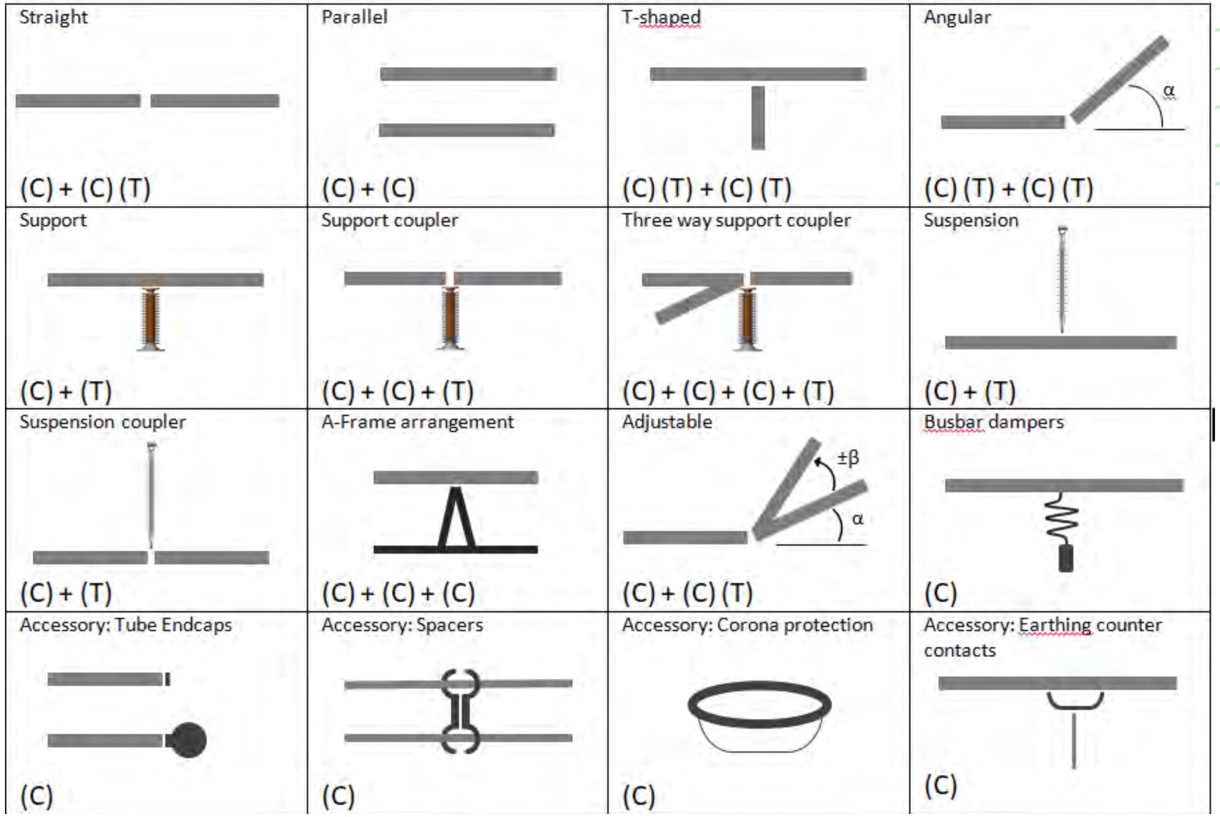
1. Installation Area:
   - Indoor/Outdoor
   - Altitude
   - Seismic
2. Mechanical Loads
   - Static
   - Dynamic
3. Electrical Load-profile
4. Connecting Materials





Geometry

1. Mechanical and electrical connection of contact partners
2. Typical conductors (C) are:
   - stranded conductors
   - rigid conductors like tubes or bars
   - bundles of conductors
3. Typical terminals (T) are:
   - flat or palm terminals
   - stem (stud) type terminals
   - insulator flanges and couplings
   - suspension and attachment points

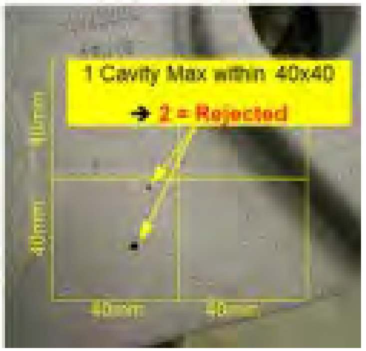


Quality

1. Connector Material:
   - **Contact surfaces**
   - **Conductor grooves**
   - **Casting body**
   - **Covers**
2. Bolt Material
   - **Aluminium**
   - **Coppar**

REJECTED

REJECTED



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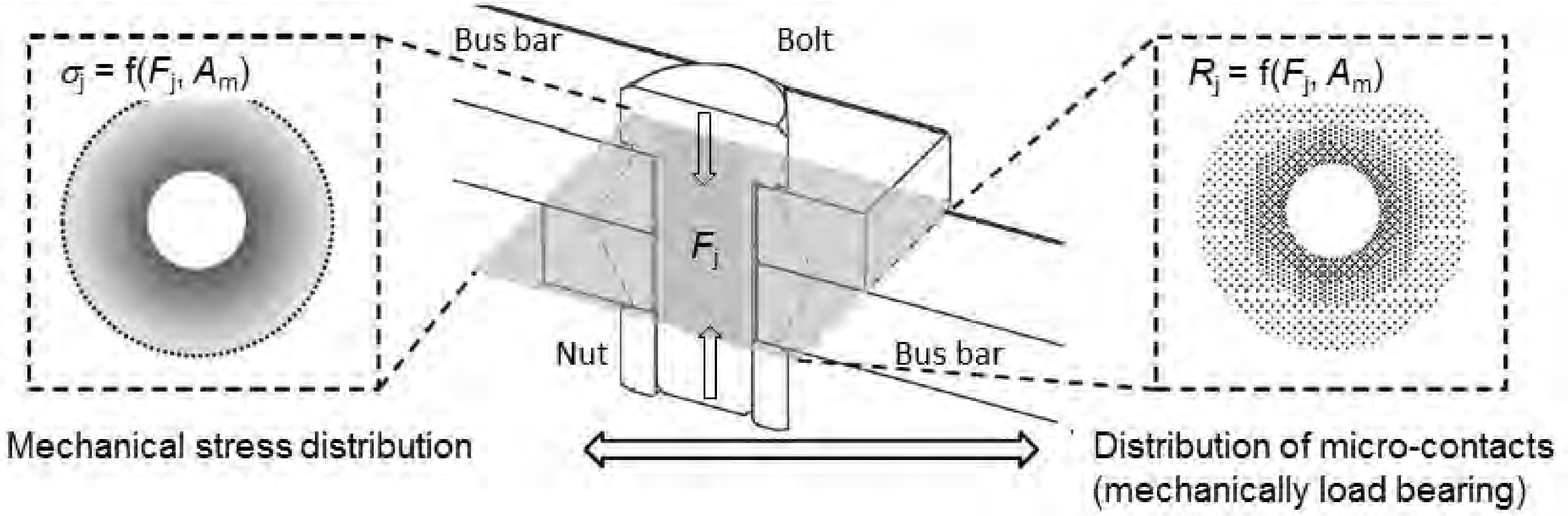
Relationship between mechanical stress, the connection resistance depending on the connection force and the mechanically load- bearing contact surfaces of a bolted connection



1. J -mechanical stress
2. Fj -Joint force
3. Am-Mechanically load bearing micro-contacts
4. Rj -Joint resistance

6. Installation Procedures

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Introduction

Installation as a critical component to connection's performance and longevity

Installation of clamps and connectors in a substation is key to the reliability and longevity of the connections. Installation improperly done can drive short to medium term to serious electrical or/and mechanical damages of the infrastructure and equipment's.

Overview of the procedure

Preparation of the contact surfaces of both connector(s) and conductor(s)

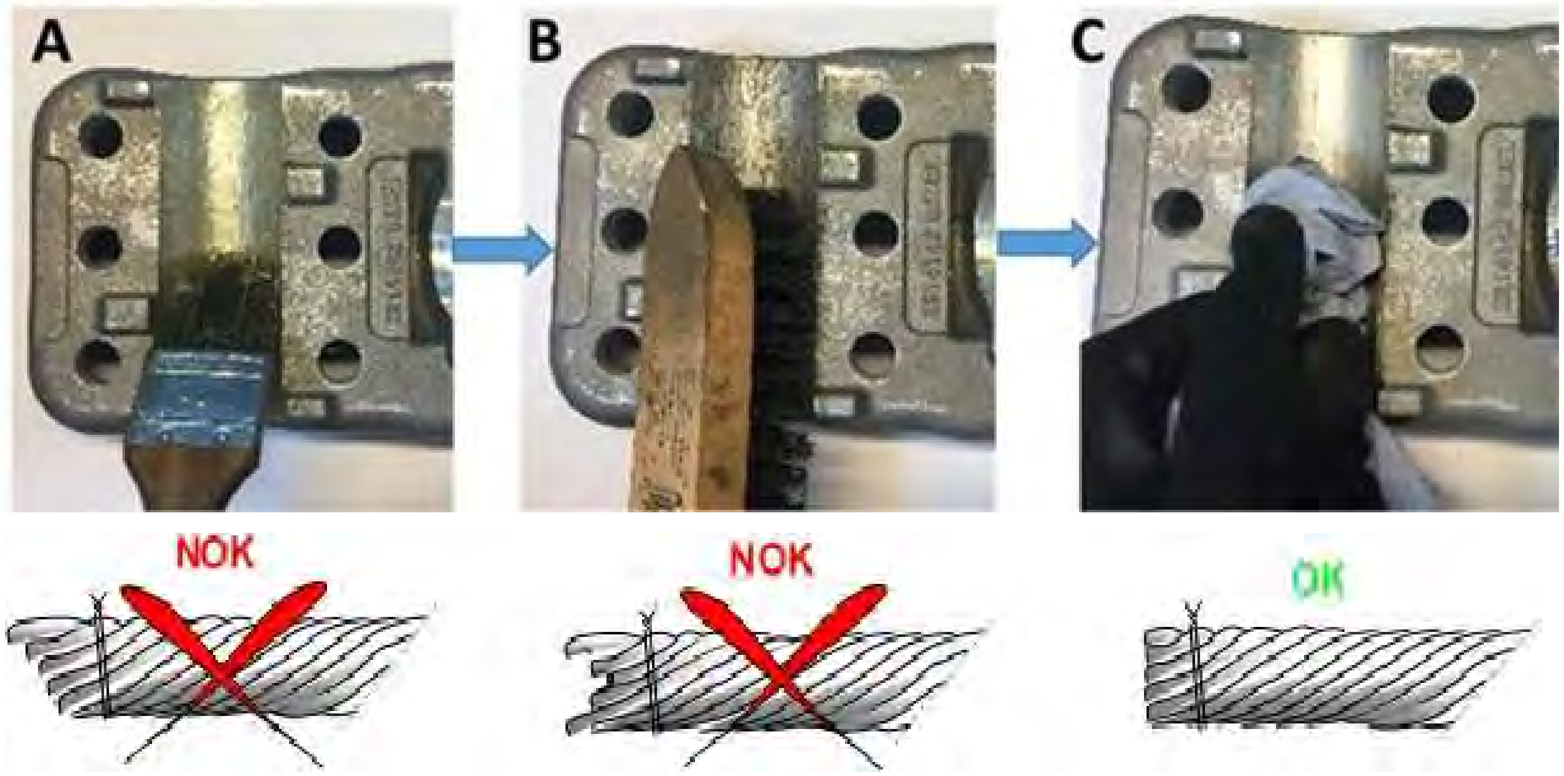
1. A proper preparation of the contact surfaces is mandatory and especially on aluminium connections as aluminium and its alloys have the physical property to become instantaneously oxidized when in contact with the air.

Steps of contact surfaces preparation (for both connector and conductor)

1. Deoxidation by brushing the contact surfaces under neutral grease →
2. Wipe the surfaces with a clean cloth to remove the dirty grease after brushing →
3. Apply a thin layer of contact aid compound (usually delivered by the manufacturer)

Installation

- Key to the reliability and longevity of the connection's installation
- Improperly done can drive short to medium term to serious electrical damages

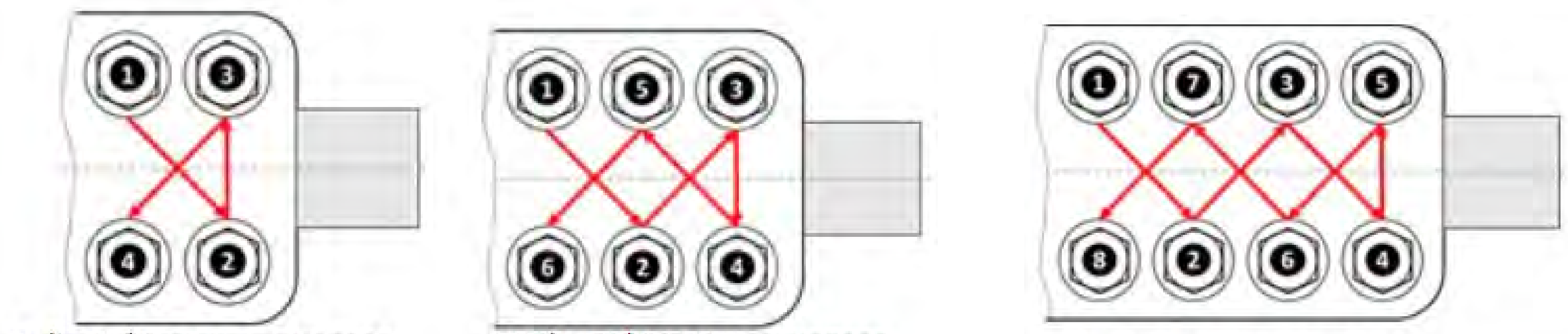


Overview of the procedure

Proper tightening of bolts must be applied to any bolted connectors

1. It is important to distribute uniformly the pressure on the conductor by crossing application of the torque across all the bolts, Application value of the torque must be given by the connectors’ manufacturer,

Tightening sequences of bolted connectors



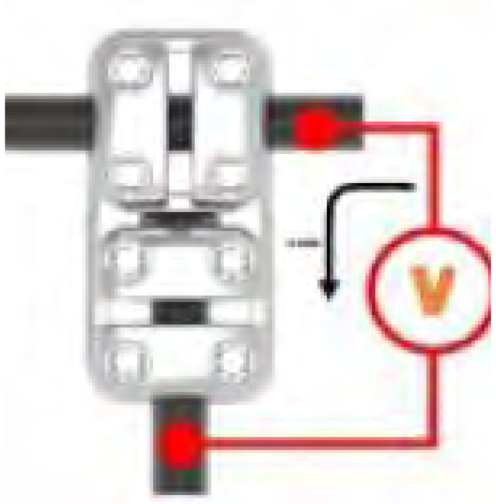
Bolts tightening sequences | 6 Bolts tightening sequences | 8 Bolts tightening sequences

Overview of the procedure

Verification of the electrical resistance

1. The performance factor k has proven to be useful for evaluating the measured joint resistance

Measurement of voltage drop under DC



Equation of the Performance Factor k:tor k

$$k = \frac{Joint\ resistance}{Resistance\ of\ the\ same\ lengt\ of\ the\ conductor}\ or\ \frac{R_j}{R_c\ X\ L_j}$$

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7. Maintenance and Monitoring

Maintenance & Monitoring

- Asset Management
- Risk Management
- Product & Installation Reliability
- Maintenance
  - Event-oriented
  - Preventive
- Condition Monitoring
  - Visual Inspection
  - Simple Thermography
  - Residual Lifetime Analysis

ambient temperature ϑ_0 = 13,5°C
solar radiation P_{SH} = 90 W/m²
wind speed v = 0,5m/s
relative current I_{load}/I_{rated} = 0,24

Data input

Phase	L1	L2	L3
Temperature rise $\Delta\vartheta_{connector}$ in K	2,8	3,2	22,9
Performance factor k_u	5,9	6,8	49,5
Residual life time in years	45,6	33,9	0,3

Hot spot detection

$\Rightarrow$ Recommendation: maintenance in phase L3 is urgently required in the next few weeks

Maintenance recommendation

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Asset Management and Market Trends

- Asset Management for connectors typically includes one of the following approaches:
  1. Traditional Asset Management approach:
     - Using legacy specifications and designs based on utility experience
     - Reliance on high-level technical experience, calculations, empirical testing and operational performance
  2. Use of component Monitoring, Calculation, Simulation:
     - Treat the connector as a separate asset
     - Establish and maintain a “Digital twin" of connectors
     - Select the best design for all the expected loads, conditions, ageing behaviour
     - Requires the collection of experience with modern simulation tools
- Reliance on traditional asset management approaches results in increased risk of premature failures, considering changing loads & load profiles

Using the Digital Twin in Power Industries

- Building a specialized digital twin for the energy industry is an absolute necessity and the technologies are there!
- Monitoring, artificial intelligence, simulations and end-to-end digital workflows can make much more sensible use of the scarce resource of the skilled worker
- Digital Twins in Power systems are based in RAMI4.0
- Digital inventory for planning and engineering of brownfield project
- Collection and visualization of the incoming live data
- Simulation of physical processes and events
- Based on existing Standards (CIM (IEC 61970-301), IFC, ECLASS)

8. Testing

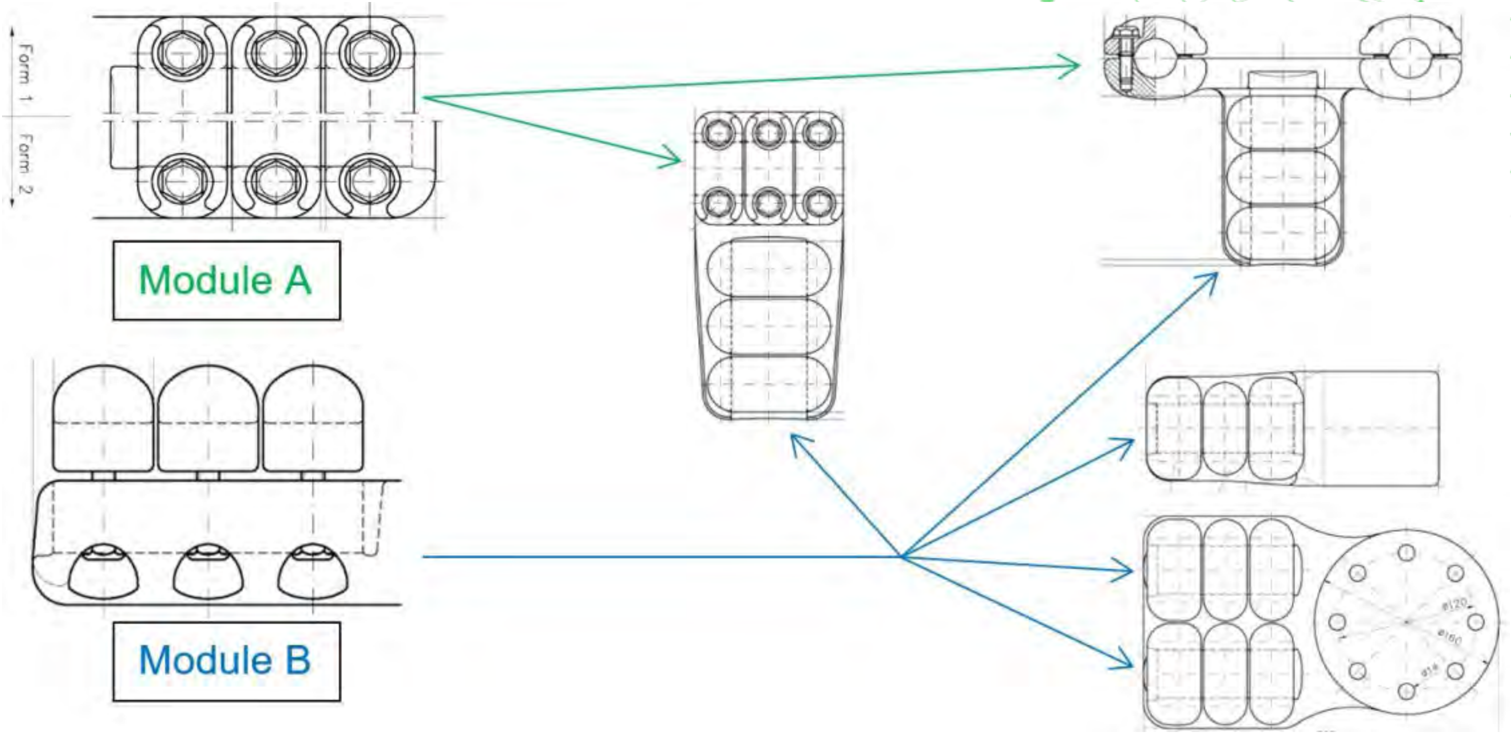
How reliable are the test of substations connectors?

Test type Overview

Test Type	Designation	Explanation	Comments
Type	T		Independent from manufacturing batch
Sample	S	(special arrangement for FAT)	Mechanical and electrical tests performed on actual manufacturing batch. Should be agreed between the customer and the supplier
Routine	R	(FAT if in the customer presence)	Typically, not destructive

Type Testing Methodology- Modular Design

- Substation projects typically require new products to be developed
- New developed products up to 80%
- Costs & delivery time constraints
- How do we type test considering the above?

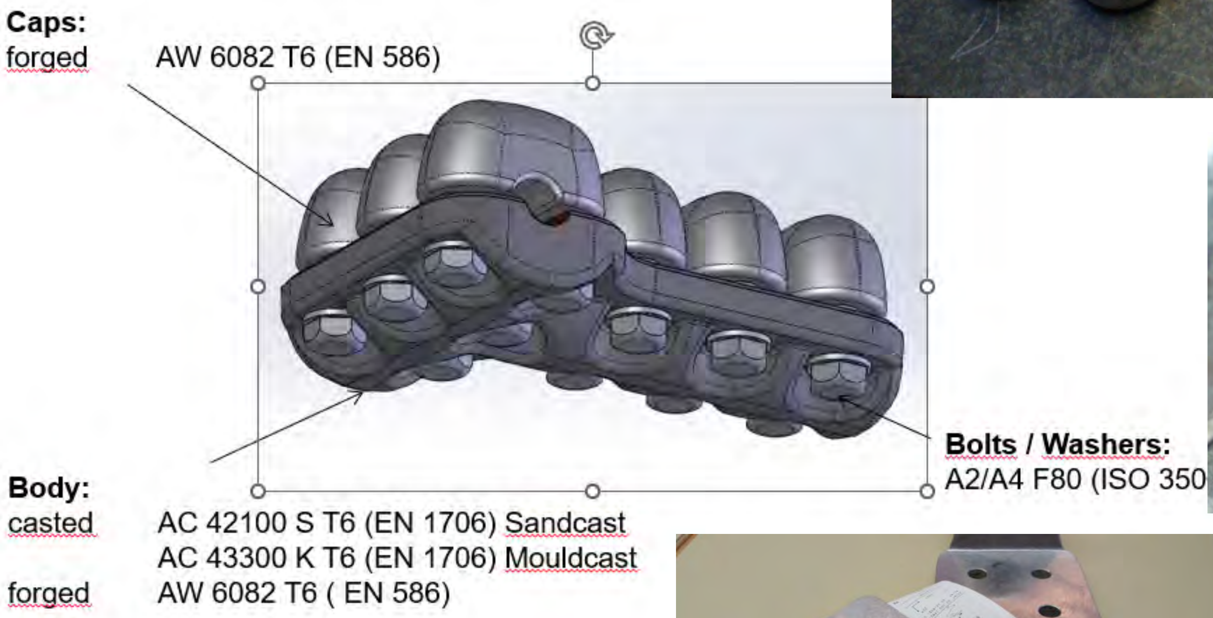


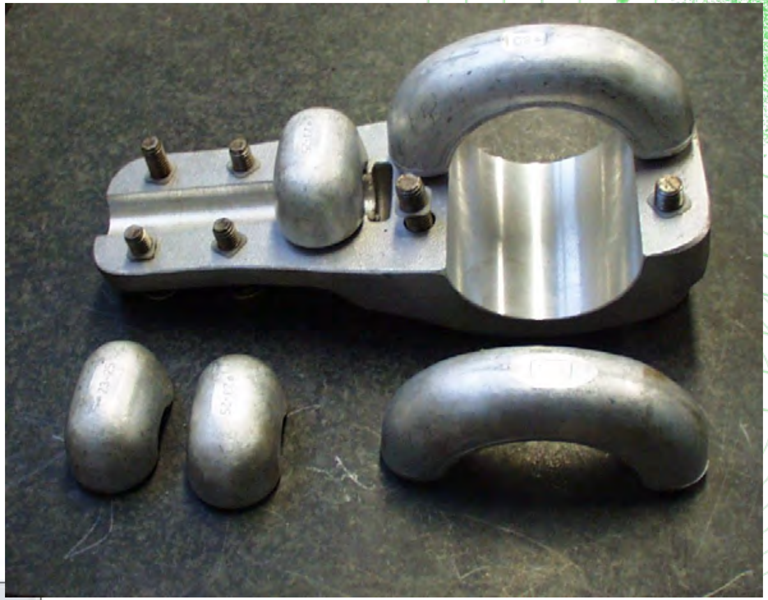
→ The Solution: Use of a **Modular Design Approach**

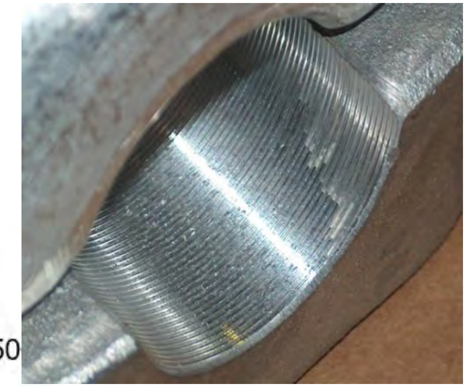
Test type Overview

Type Test

1. Not related through the manufacturing batch
2. Desing related
   - **Surfaces**
   - **Shapes**
   - **Functions**







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Test type Overview

Sample Test

1. related through the manufacturing batch
2. Check the mechanical and electrical proporties
   - **Pullout / Slipping test**
   - **Cantilever test**
   - **Bending test**
   - **Bolt torque test**
   - **Heat rise test**
   - **Resistance test**
   - **Mechanical function test**

It's necessary to coordinate this tests between customer and supplier

Test type Overview

Routine Test

1. Related through the manufacturing batch
2. Checking all properties – typically are not destructive
   - **Visual check**
   - **Marking check**
   - **Dimension check**
   - **Material certificate review**
   - **Coating thickness (hot dip galvanises, silver plated,….)**
   - **Quantity check**
   - **Assembly check**

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What are the critical test related due the Standards

IEC / Nema / ANSI

1. The diverse acceptance criteria, influenced by national utility standards, underscore the need for tailored approaches to ensure compliance and effectiveness across varying regulatory landscapes.
2. Heat cycle test – no good correlation between given test in IEC 61284 / ANSI C119-4 and life-time expectancy.
3. Heat rise test – related to substation busbar connections – the relation tube to connector value has different approaches
4. RIV Test different approaches in IEC 61284 / 62271 then desired/needed

9. Service, Operational Experience and Common Installation Mistakes

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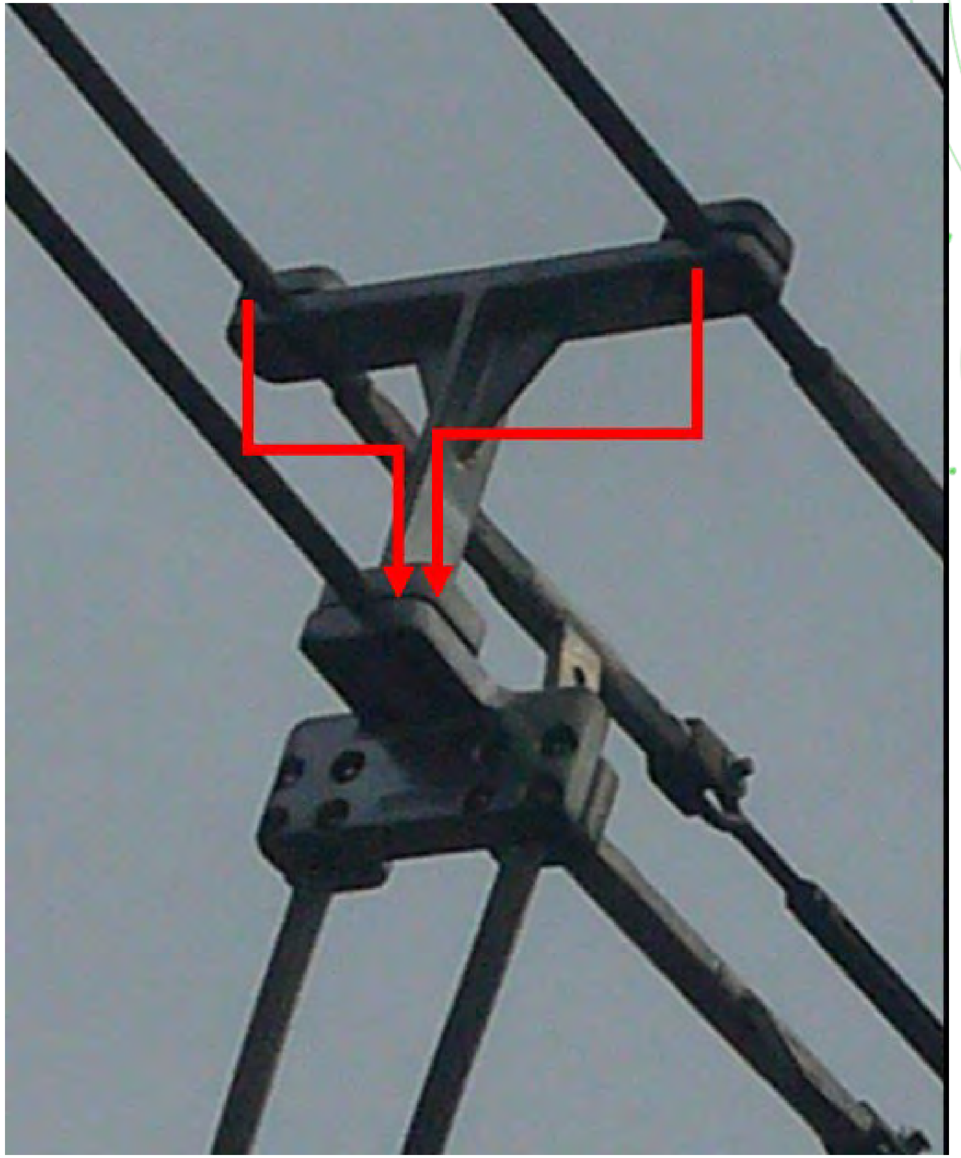
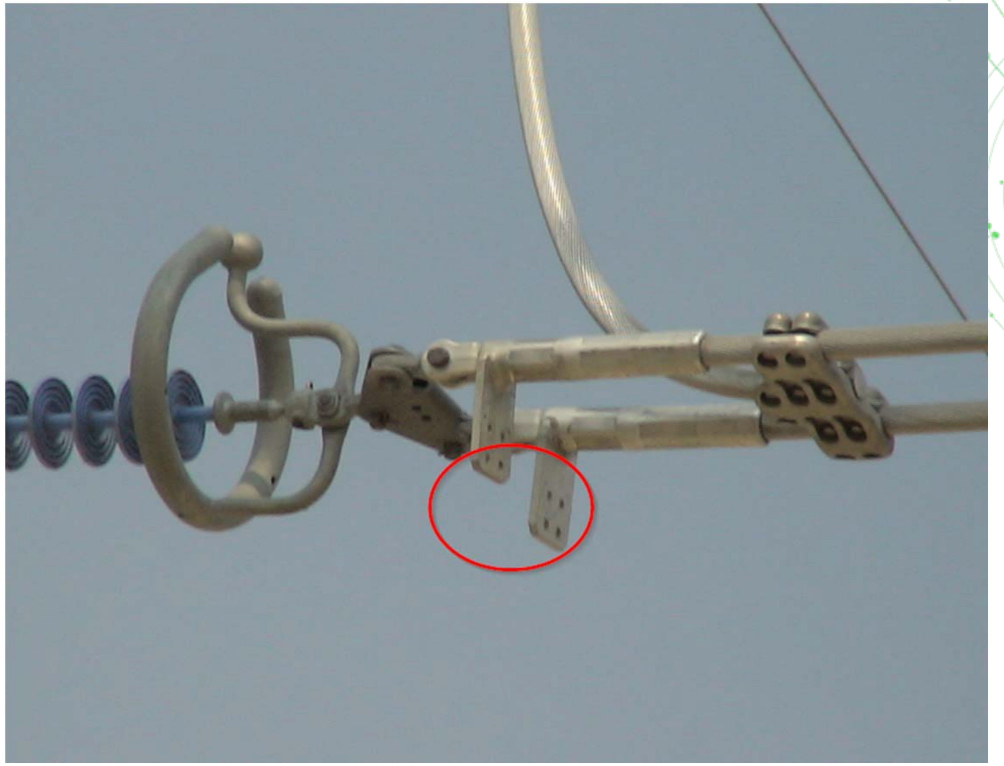
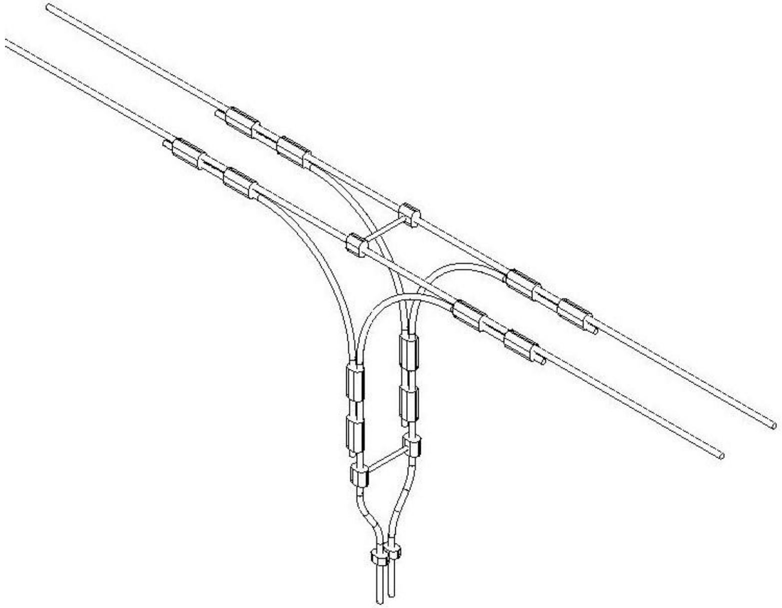
Common Mistakes



Common Mistakes

Common Mistakes





10. high voltage connectors SURVEY

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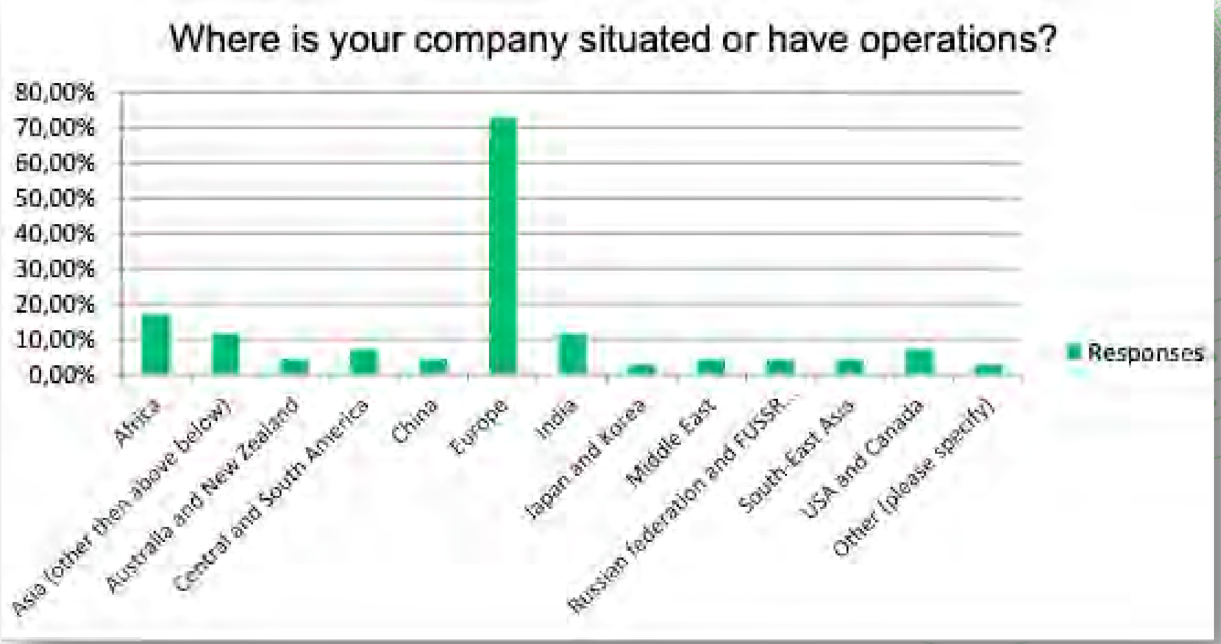
Substation Connectors Survey



- Participants:
  - electric power utilities (26)
  - connector manufacturers (15)
  - contractors (15)
- Key conclusions:
  1. Only 30% consider connectors as a separate ‘Asset‘
  2. 32% have experienced quality control systems
  3. 60% have specifications for connectors
  4. 30% monitor the installed connector
     - 60% who monitor identified hot spots
  5. 12,5% use software for monitoring and/or simulation of connectors

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11. Conclusion

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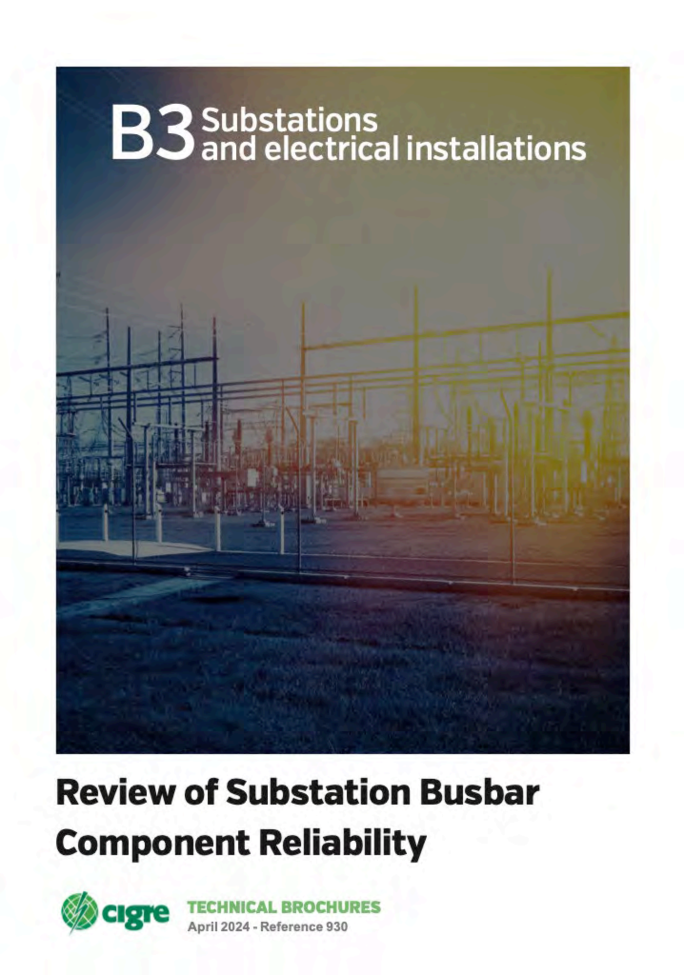
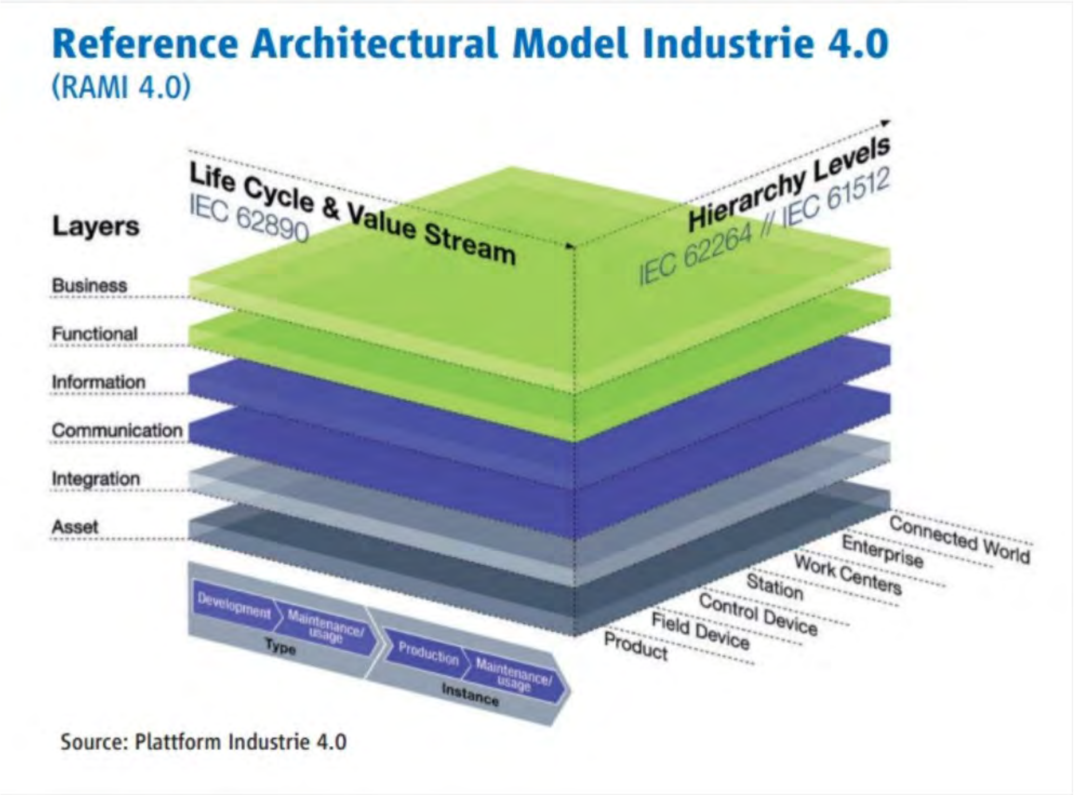
Summary

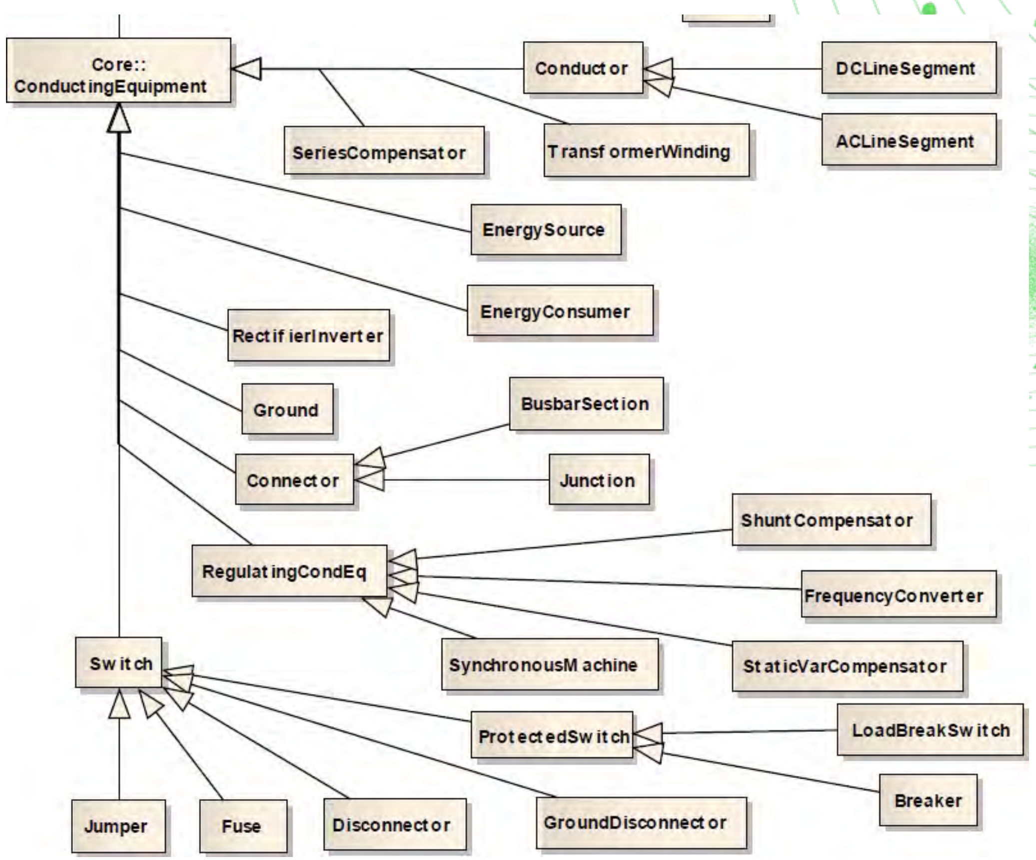
- Change in energy generation and consumption leading to different loads on the grid and therefore connectors
- Potential revenue loss in millions caused by a connector costing hundreds of €
- Monitoring of connectors & asset management
- No specific IEC standard for the design, manufacture or testing of the wide range of substation connectors
- Digital Twin!



Annexes

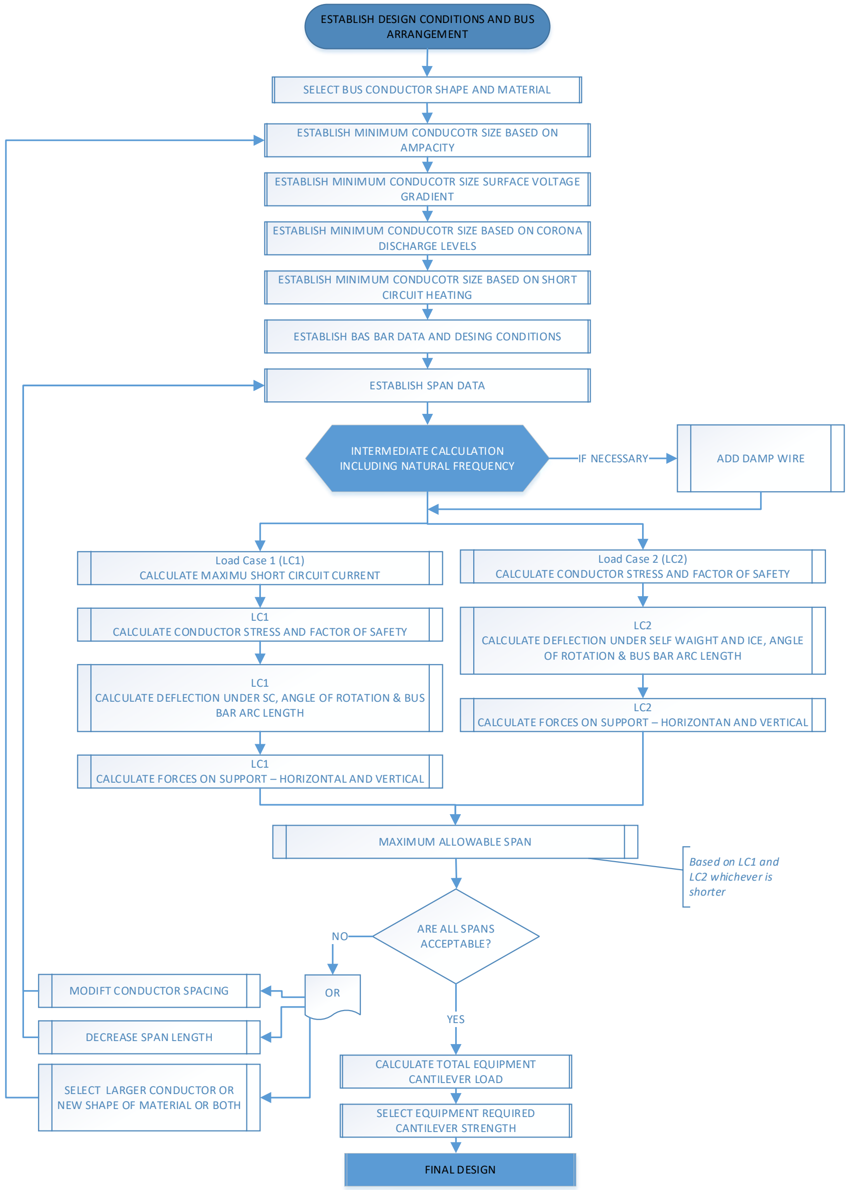
C: Digital twin (model) of a physical object

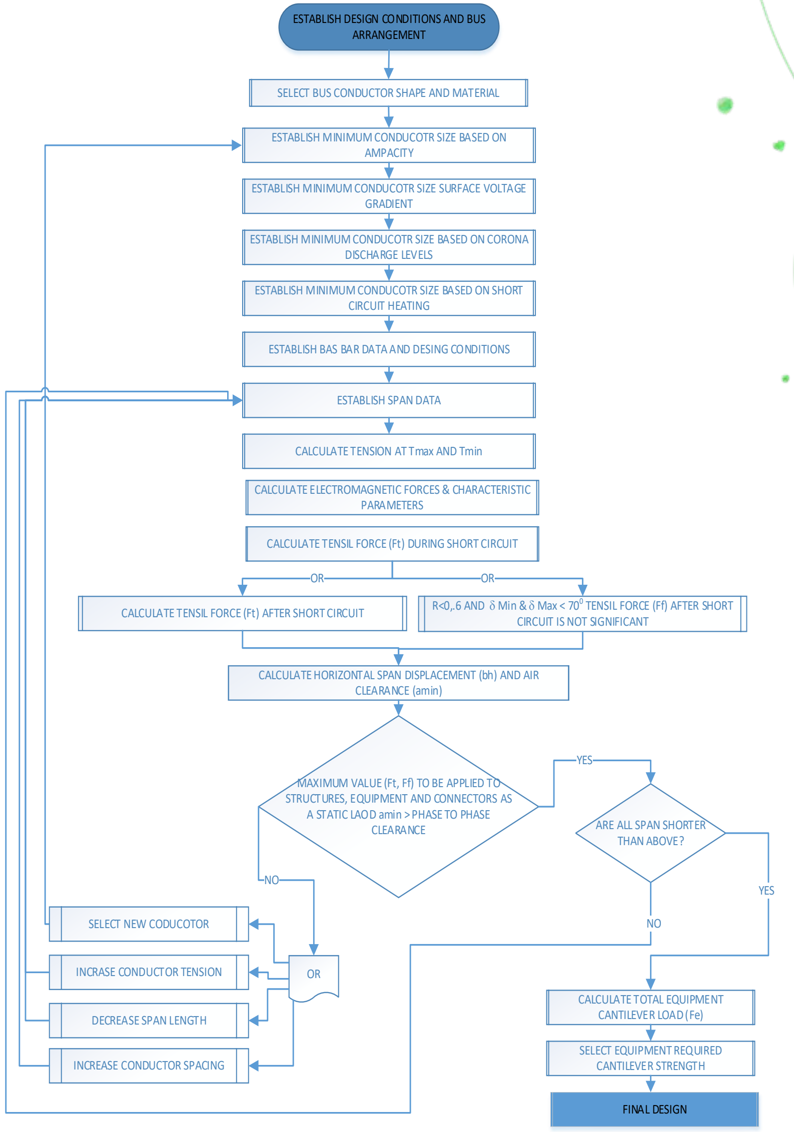




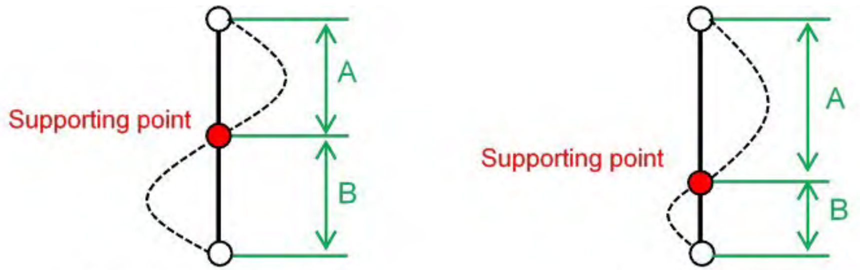
Class tree for connectors according to IEC 61970-301:2011

D: Design processes for rigid and flexible conductors





E: Case studies: Seismic design of aluminium tube bus bar in Japan

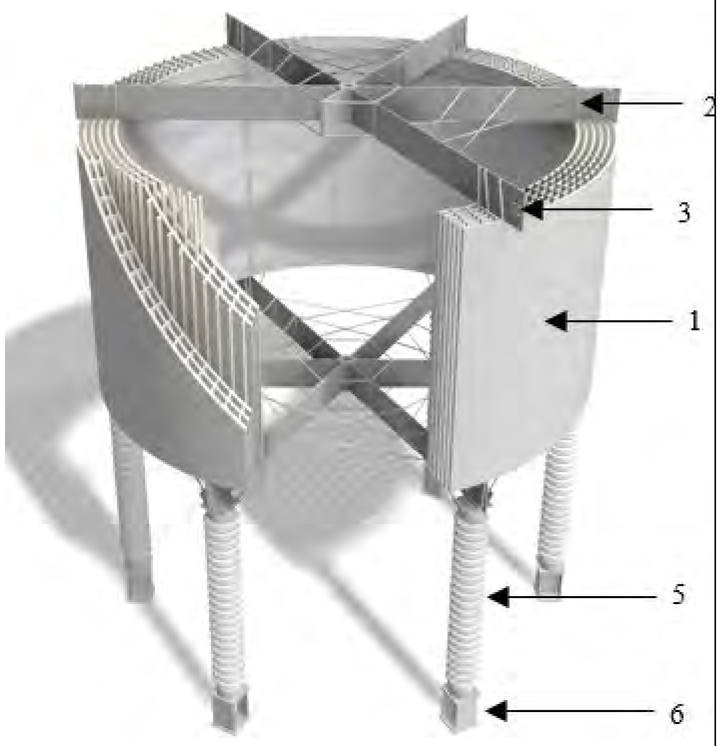


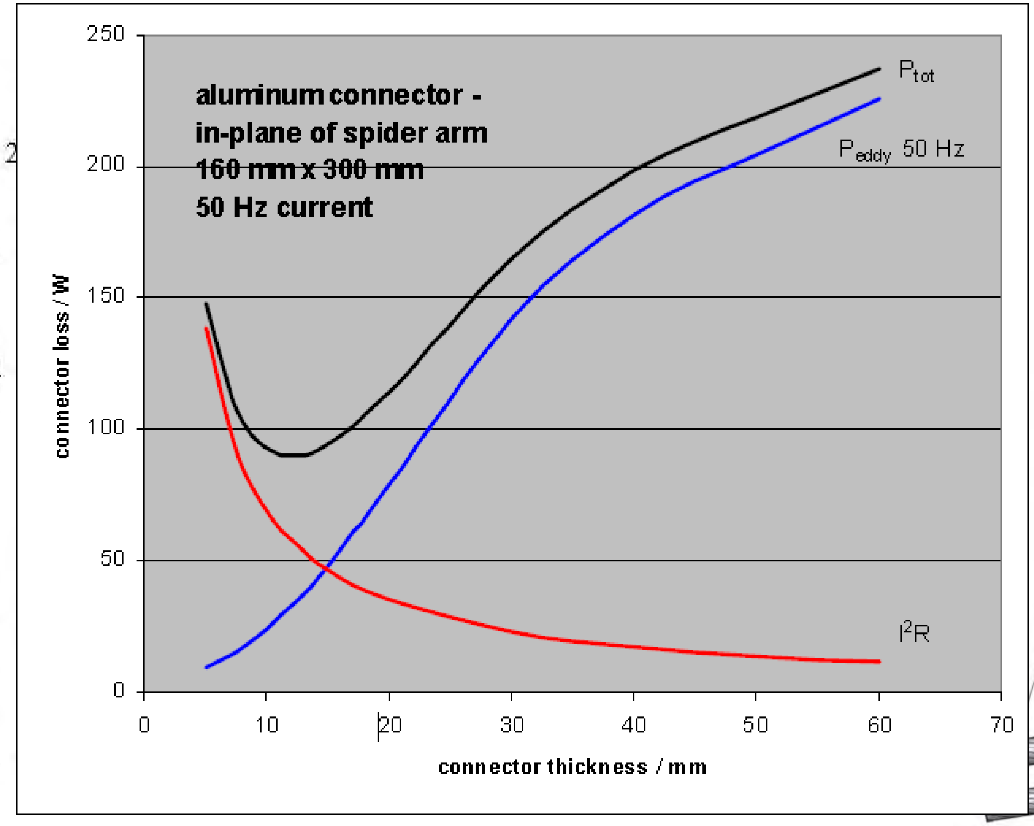
[Even support]
If "A" equal "B", resonance might occur and high load may generate at the support insulator.

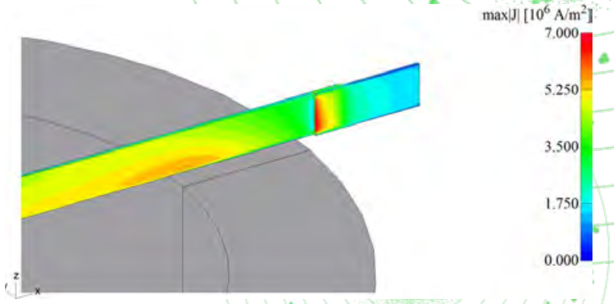
[Uneven support]
If "A" not equal "B", resonance can be avoided.

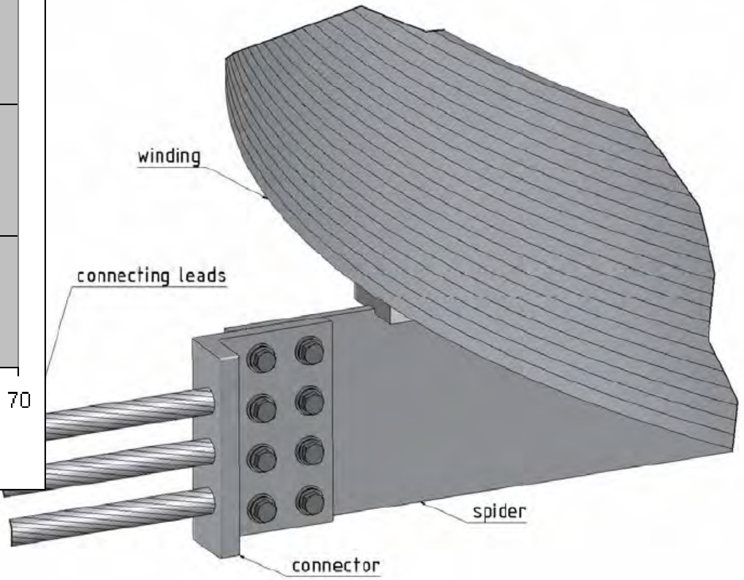
Aluminium bracket with a slide support mechanism

F: Special Considerations when connecting Air- Core Reactors









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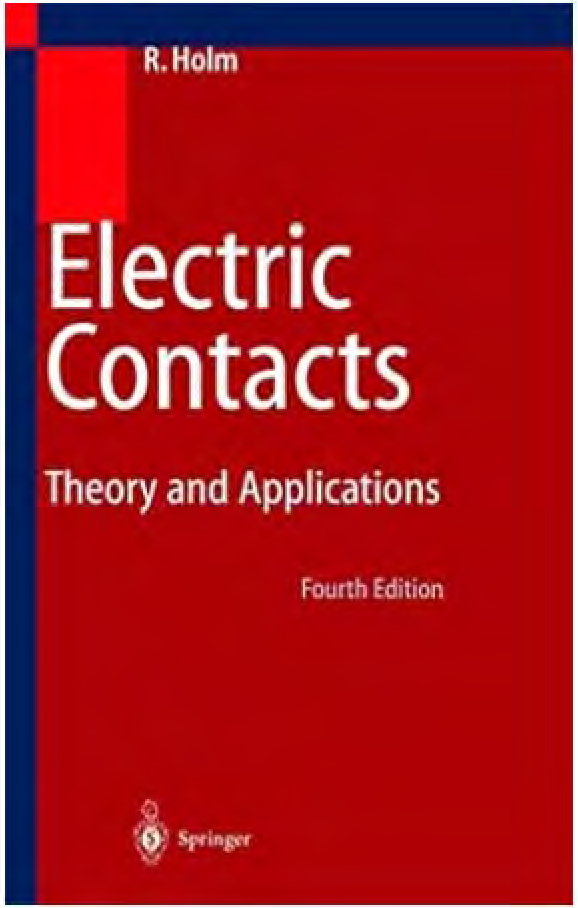
Ragnar Holm:

Electric Contacts: Theory and Application

https://www.amazon.com/Electric-Contacts-Application-Ragnar-Holm/dp/3540038752



Frågor?

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