6.0 Jointing of Copper Busbars

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6.1 Introduction

Busbar joints are of two types; linear joints required to assemble manageable lengths into the installation and T-joints required to make tap-off connections. Joints need to be mechanically strong, resistant to environmental effects and have a low resistance that can be maintained over the load cycle and throughout the life of the joint.

6.2 Busbar Jointing Methods

Efficient joints in copper busbar conductors can be made very simply by bolting, clamping, riveting, soldering or welding. Bolting and clamping are used extensively on-site. Shaped busbars may be prefabricated by using friction stir welding.

Bolted joints are formed by overlapping the bars and bolting through the overlap area. They are compact, reliable and versatile but have the disadvantage that holes must be drilled or punched through the conductors, causing some distortion of the current flow in the bar. Bolted joints also tend to have a less uniform contact pressure than those made by clamping but, despite these issues, bolted joints are very commonly used and have proven to be reliable. They can be assembled on-site without difficulty.

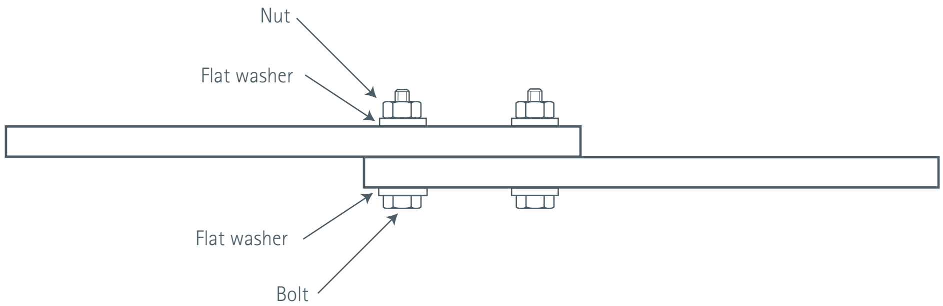


Figure 60 – A typical bolted joint

Clamped joints are formed by overlapping the bars and applying an external clamp around the overlap. Since there are no bolt holes, the current flow is not disturbed resulting in lower joint resistance. The extra mass at the joint helps to reduce temperature excursions under cyclic loads. Well-designed clamps give an even contact pressure and are easy to assemble, but take up more space than a bolted joint and are more expensive to manufacture.

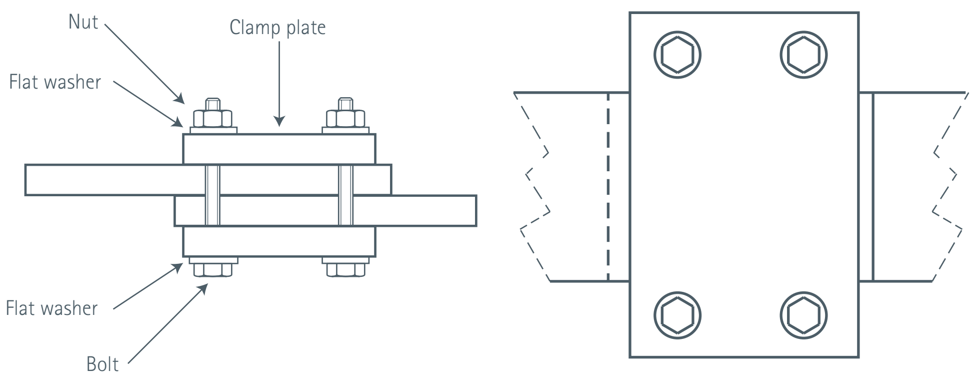


Figure 61 – A simple clamped joint

Riveted joints are similar to bolted joints. They can be efficient if well made; it is difficult to control the contact pressure. They cannot easily be dismantled or tightened in service and they are difficult to install.

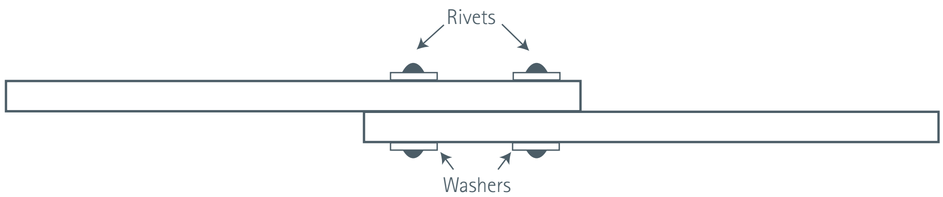


Figure 62 – A riveted joint

Soldered or brazed joints are rarely used for busbars unless they are reinforced with bolts or clamps since heating under short-circuit conditions can make them both mechanically and electrically unsound.

Figure 63 – A soldered joint

Welded joints are made by butting the ends of the bars and welding. They are compact and have the advantage that the current-carrying capacity is unimpaired, as the joint is effectively a continuous copper conductor. However, it may not be safe or desirable to make welded joints *in situ*.

Welding of copper is discussed in Copper Development Association Publication 98, Cost-Effective Manufacturing: Joining of Copper and Copper Alloys.

Figure 64 – A welded joint

The following sections apply to bolted and clamped joints.

6.3 Joint Resistance

In principle, a clamped or bolted joint is made by bringing together two flat surfaces under controlled (and maintained) pressure, as shown in Figure 65.

Figure 65 – An overlapped joint

The resistance of a joint is mainly dependent on two factors:

1. The streamline effect or spreading resistance, R_S, due to the diversion of the current flow through the joint
2. The contact resistance or interface resistance of the joint, R_i.

The total joint resistance, R_j, is given by:

$$R_j = R_S + R_i$$

This applies specifically to direct current applications. Where alternating currents are flowing, the changes in resistance due to skin and proximity effects in the joint zone must also be taken into account.

6.3.1 Streamline Effect

When current flows through a joint formed by two overlapping conductors, the lines of current flow are distorted and the effective resistance of the joint is increased since current flows only through a portion of the material.

Provided that the width of both bars is the same, the streamline effect is dependent only on the ratio of the length of the overlap to the thickness of the bars and not on the width. This is shown in Figure 66.

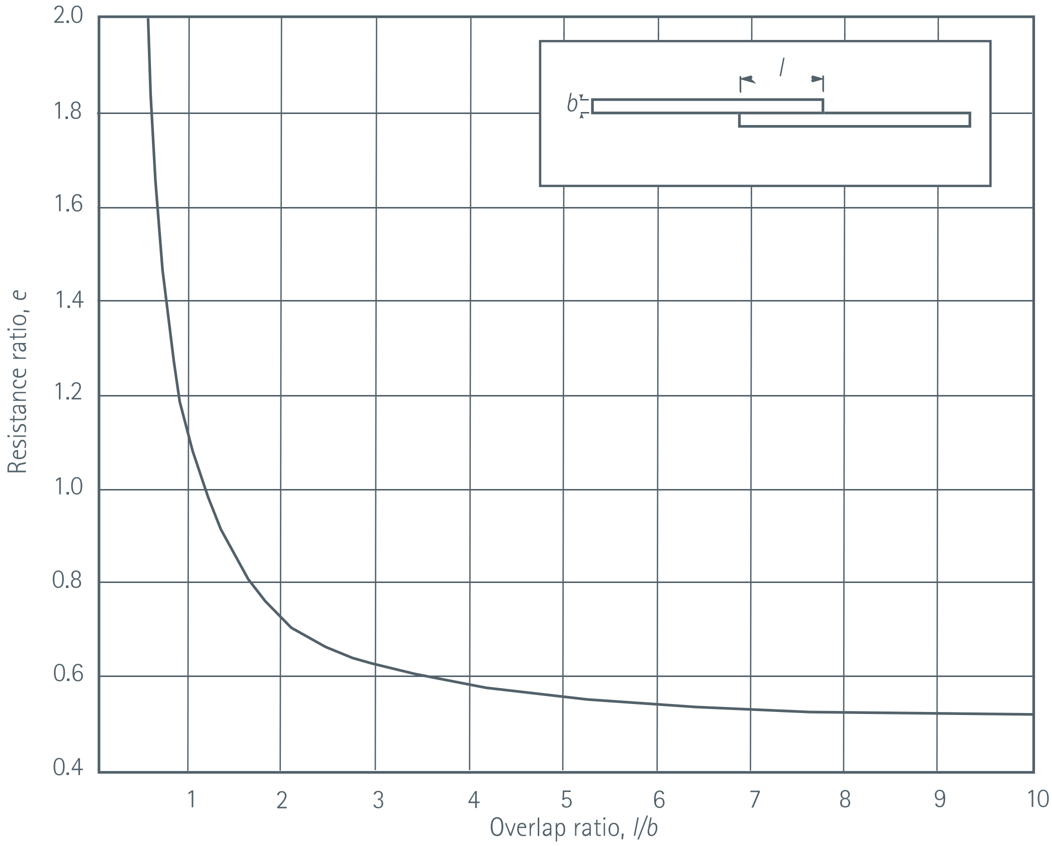


Figure 66 – Streamline effect in overlapped joints

The current density in the direction perpendicular to the bar, i.e. as current transfers from one bar to the other, is highly non-uniform and is concentrated around the edges.

The resistance ratio *e* in Figure 66 is the ratio of the resistance of a joint due to streamline effect R_S, to the resistance of an equal length of single conductor R_b, i.e.

$$e = \frac{R_s}{R_b} = \frac{ab}{\rho l} R_s$$

where:

- a is the width of bar, mm
- b is the thickness of bar, mm
- l is the length of overlap, mm
- ρ is the resistivity of the conductor, µΩ mm
- R_S is the resistance of overlap section in µΩ (to which contact resistance must be added)

hence:

$$R_s = \frac{e\rho l}{ab}$$

From the graph it can be seen that the streamline effect falls very rapidly for *l/b* ratios up to two, and then very much more slowly for values up to ten. This means that, in most cases, the streamline effect has a limited effect as the overlap is often much greater than five times the thickness in order to allow space for bolting or clamping. There is no advantage in allowing very long overlaps; it is only necessary to allow enough space to accommodate sufficient bolts to achieve the required contact pressure.

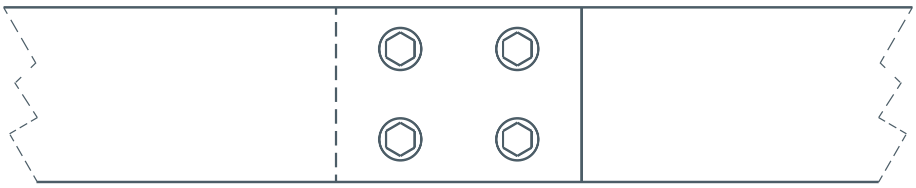
In the case of bolted joints, the bolt holes also reduce efficiency due to the streamline effect. The resistance ratio of a bolted overlap section can be estimated by:

$$R_{sb} = \frac{e\rho l}{(a - nd)b}$$

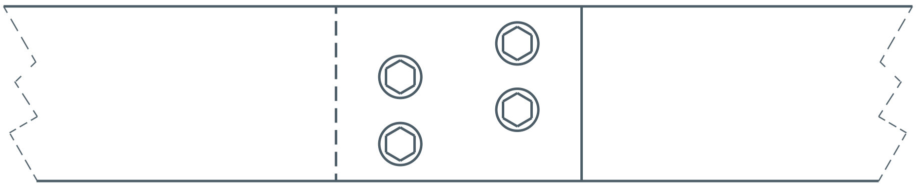
where:

d is the diameter of the holes
n is the number of holes across the width of the bars.

It follows that holes should be placed in-line along the length of the joint, as shown in Figure 67; offsetting the holes increases the resistance by increasing the disturbance of the current flow. In Figure 67a, the value of n is 2 while in Figure 67b the value of n is 4.



a) Correct bolt placement



b) Incorrect bolt placement

Figure 67 - Bolt placement in overlapped joints

It has been found that the distortion effect in the tap-off of a T-joint is about the same as that in a straight joint. Note that the current flow in the straight bar is disturbed by the presence of bolt holes.

It has been shown that the current distortion is reduced if the ends of the bars are angled at less than 45 degrees, as shown in Figure 68. The initial joint resistance is reduced by 15%. Because the current flow is more uniform, the development of localised hot spots is reduced, leading to a factor of 1.3 to 1.5 reduction in the rate of increase in resistance under current cycling.

Figure 68 – Overlap joint between bars with angled ends

6.3.2 Contact Resistance

There are two main factors that affect the actual interface resistance of the surfaces:

1. The condition of the surfaces
2. The total applied pressure.

6.3.2.1 Condition of Contact Surfaces

In practice, an electrical contact between the solids is formed only at discrete areas within the contact interface and these areas (known as 'a-spots') are the only current conducting paths. The a-spots typically occupy an area of the order of 1% of the overlap area.

Obviously, the larger the number of a-spots, the more uniform the current distribution across the joint area will be. This can be encouraged by ensuring that the surfaces of the conductors are flat and roughened (which removes the oxide layer and produces a large number of asperities) immediately before assembly. As the contact pressure is increased, the higher peaks make contact, disrupt any remaining surface oxide and form metal to metal contact.

In some areas an oxide film may remain. Copper oxide films on copper form relatively slowly and are semiconducting because copper ions diffuse into the oxide layer. When copper oxide films are compressed between two copper surfaces, diffusion can take place in both directions so conduction takes place in both directions. This is very different from aluminium, where the oxide is a very good insulator and forms within microseconds of exposure to air.

Since the area of each a-spot contact is small, the current density is high, leading to higher voltage drop and local heating. In a well-made joint this heat is quickly dissipated into the mass of the conductor and the temperature of the interface will be only slightly above that of the bulk material. However, if the contact pressure is too low and the joint has deteriorated, local over-heating may be enough to induce basic metallurgical changes including softening and melting of the material at the a-spot. At first sight this may appear to be advantageous, however, as the joint cools the material contracts and fractures and is subsequently liable to oxidise.

Since elevated temperature is the first symptom of joint failure, maintenance procedures should be established to monitor the temperature of joints with respect to that of nearby bar using thermal imaging. If, under similar load conditions, the differential temperature increases, it may be a sign of early joint degradation. As a first step, more intensive monitoring should be undertaken and, if the trend continues, remedial action taken.

It is not normally recommended that the surfaces of copper-to-copper joints are plated unless required by environmental considerations. In fact, plating may reduce the stability of the joint because, as soft materials, the plating may flow at elevated temperatures leading to reduced contact pressure.

However, to ensure a long service life, a contact aid compound is recommended to fill the voids in the contact area and prevent oxidation or corrosion. Many proprietary compounds are available or, if none are available, petroleum jelly or, for higher temperatures, silicone vacuum grease may be used.

6.3.2.2 Effect of Pressure on Contact Resistance

Joint resistance normally decreases with an increase in the size and number of bolts used. Bolt sizes usually vary from M6 to M20 with either four or six bolts being used. The appropriate torque for each bolt size depends on the bolt material and the maximum operating temperature expected.

Contact resistance falls rapidly with increasing pressure, as shown in Figure 69, but above a pressure of about 30 N/mm^2 there is little further improvement. In most cases it is not advisable to use contact pressures of less than 7 N/mm^2, with pressures above 10 N/mm^2 being preferred. The contact resistance for a joint of a particular overlap area is obtained from Figure 69 by dividing the contact resistance for 1 mm^2 by the overlap area in mm^2.

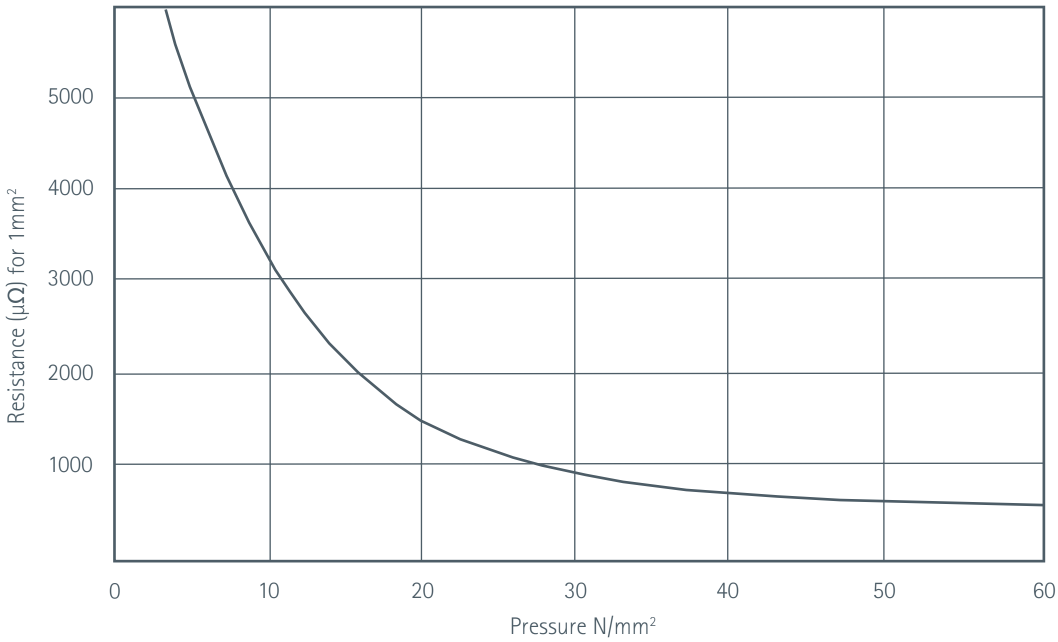


Figure 69 – The effect of pressure on the contact resistance of a joint

Contact pressure for both bolted and clamped joints is normally applied by tensioning one or more bolts. For bolted joints, the pressure is applied around the bolt holes, so using more bolts will result in a more even pressure distribution. Large, thick washers can be used to spread the load. For clamped joints, the load transferred from the bolts, which are outside the width of the conductors, depends on the rigidity of the clamps. Where the clamps are narrow, the pressure distribution provided by clamps can be quite uniform but, for wider conductors, the very rigid clamps required may be impractically large.

In everyday practice, contact pressure is impossible to measure and has to be inferred from the torque applied to the bolts from the following equation:

$$T = KFD$$

where:

T is the tightening torque (Nm)
K is a constant, often referred to as the 'nut factor' – see Table 19
F is the force (kN)
D is the nominal bolt diameter (mm) - see Table 21.

The 'nut factor' depends on a number of factors including the coefficient of friction, the surface finish and state of lubrication of the threads and other bearing surfaces. Table 19 gives typical nut factors for different states of lubrication.

Table 19 – Nut Factors for Different States of Lubrication

Bolt Lubrication	Nut Factor
Dry	0.20 – 0.22
Contact aid compound	0.19 – 0.21
Boundary lubricant (Mo_2S)	0.15 – 0.16

It is important to control the rate of applying the torque as well as the final value; bolts should be gradually tightened in rotation.

The correct tightening torque must be carefully determined to provide sufficient initial contact pressure at ambient temperature while not exceeding the proof or yield stress of the bolt material over the working temperature range of the joint. Differential expansion between the bolt and bar materials results in an increase or decrease in bolt tension (and therefore contact pressure) as temperature changes. Galvanised steel bolts are often used with copper busbars but copper alloy bolts, e.g. aluminium bronze (CW307G), are preferred because their coefficients of expansion closely match that of copper, resulting in a more stable contact pressure. Copper alloy bolts also have the advantage that the possibility of dissimilar metal corrosion is avoided and are also to be preferred where high magnetic fields are expected. Because these alloys do not have an easily discernible yield stress, however, care has to be taken not to exceed the correct tightening torque and the bolt stress over the working temperature range should not exceed 95% of proof strength.

Because of the strength of copper, deformation of the conductor under the pressure of the joint is not normally a consideration.

Table 20 shows the proof strength and coefficient of thermal expansion of some typical bolt materials compared to copper. It is clear from this table that the choice of bolt material will determine the thermal stability of the joint.

Table 20 – Proof Strength and Coefficient of Thermal Expansion for Copper and Typical Bolt Materials

Material	Proof Strength MPa	Coefficient of Expansion Per Degree C
Copper (reference)	Fully annealed - 50 Full temper - 340	16.5×10^{-6}
High tensile steel	700	11.1×10^{-6}
Stainless steel 316	414	15.9×10^{-6}
Aluminium bronze CW307G	400	16.2×10^{-6}
Stainless steel 304	207	17.2×10^{-6}
Silicon bronze C651000	365	17.8×10^{-6}

The increase in force (F_{supp}) due to an increase in temperature (ΔT)is given by:

$$F_{supp} = \frac{(\alpha_a - \alpha_b) A_b E_b}{1 + \frac{t}{a}\left(1 + \frac{A_b}{A_w}\right) + \frac{A_b E_b}{A_a E_a}} \Delta T$$

where:

α_a is the coefficient of expansion of the busbar conductor
α_b is the coefficient of expansion of the bolt
A_b is the bolt cross-sectional area
E_b is the elastic modulus of the bolt
E_a is the elastic modulus of the busbar
t is the thickness of the washer
a is the thickness of the busbar
A_w is the apparent area under the washer
A_a is the apparent area of the joint overlap.

The change in bolt stress is proportional to (α_a-α_b) so, for a joint made with high tensile steel bolt, the tension will increase considerably ($\Delta\alpha$ = 5.5 x 10^{-6}) while, if the joint were made with CW307G bolts, the tension will reduce only slightly ($\Delta\alpha$ = -0.3 x 10^{-6}).

In any case, the joint must be designed so that the maximum tension in the bolts, at any temperature within the working range, must be less than 95% of yield stress to avoid the risk of plastic deformation which would ultimately lead to loosening of the joint and failure.

The stress in the bolt is calculated using the Tensile Stress Area (see Table 21), not the nominal area.

Table 21 – Typical Thread Characteristics

Size Designation	Nominal (Major) Diameter D_n	Nominal Shank Area A_n	Pitch (mm per thread) p	Pitch Diameter d_p	Minor Diameter Area A_s	Tensile Stress Area A_{ts}
M6	6.00	28.274	1.000	5.3505	17.894	20.123
M8	8.00	50.265	1.250	7.1881	32.841	36.609
M10	10.00	78.540	1.500	9.0257	52.292	57.990
M12	12.00	113.10	1.750	10.863	76.247	84.267
M14	14.00	153.94	2.000	12.701	104.71	115.44
M16	16.00	201.06	2.000	14.701	144.12	156.67
M20	20.00	314.16	2.500	18.376	225.19	244.79
M22	22.00	380.13	2.500	20.376	281.53	303.40
M24	24.00	452.39	3.000	22.051	324.27	352.50
M27	27.00	572.56	3.000	25.051	427.09	459.41
M30	30.00	706.86	3.500	27.727	518.99	560.59
M33	33.00	855.30	3.500	30.727	647.19	693.55
M36	36.00	1017.9	4.000	33.402	759.28	816.72

If the design requirement is such that high tensile steel bolts must be used, the incremental force, F_{supp}, may be so high as to exceed 95% of the proof stress of the bolts. In these cases, disc-spring, or Belleville, washers must be used, as shown in Figure 70. The height and the spring rate of the washer are selected to reduce the value of F_{supp} according to the following equation:

$$F_{supp} = \frac{(\alpha_a - \alpha_b)A_b E_b}{1 + \frac{h}{a} + \frac{t}{a}\left(1 + \frac{A_b}{A_w}\right) + \frac{A_b E_b}{A_a E_a} + \frac{A_b E_b}{aK}} \Delta T$$

where:

h is the overall height of the disc-spring washer
K is the spring rate of the disc-spring washer.

In practice, the joint would be assembled normally with the required torque for the required contact pressure. In service, as the joint temperature rises, the spring is compressed, limiting the increase in bolt tension to a safe value.

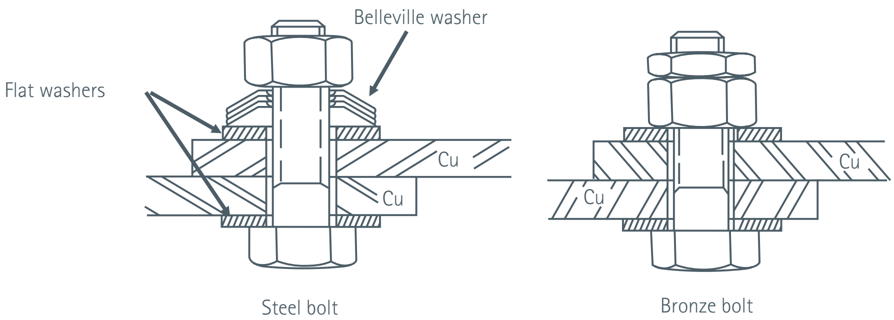


Figure 70 – Possible bolting techniques for copper busbars

Changing the design of a bolted joint, for example by introducing a longitudinal slot (see Figure 71), can reduce the contact resistance by 30 to 40%. The reduction in resistance is attributed to an improvement in the uniformity of contact pressure in each 'leg' of the joint leading to increased contact area.

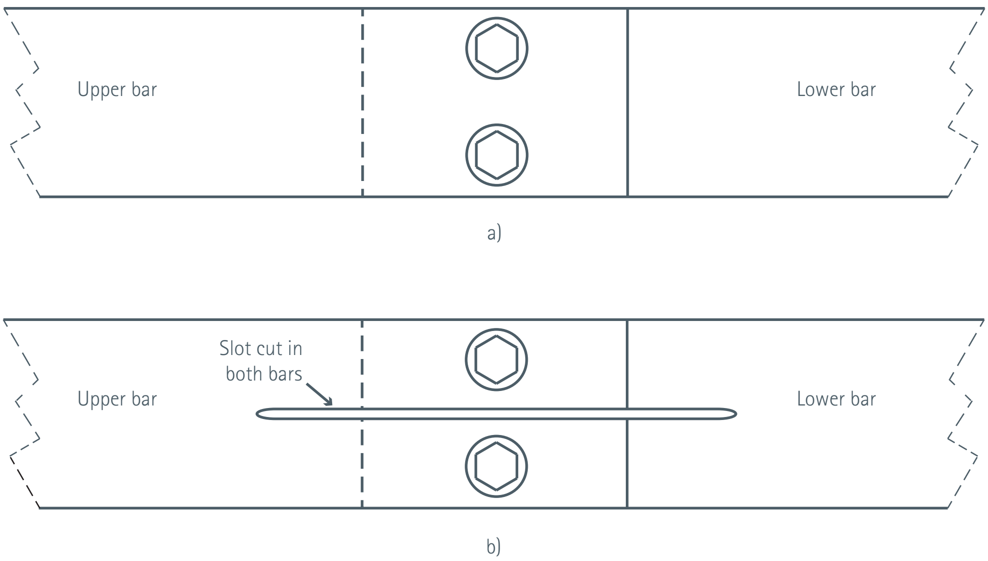


Figure 71 – Joint with a longitudinal slot

6.4 Bolting Arrangements

Although the required bolting arrangements should always be calculated for the circumstances of the installation, many sources give recommendations. Those given in Table 22 have been used for many years and are given here as a rough guide.

The recommended torque settings may be used for high-tensile steel (8.8) or aluminium bronze (CW307G, formerly C104) fasteners with unlubricated threads of normal surface finish.

Table 22 – Typical Busbar Bolting Arrangements (Single Face Overlap)

Bar Width mm	Joint Overlap mm	Joint Area mm²	Number of Bolts	Metric Bolt (Coarse Thread)	Bolt Torque Nm	Hole Size mm	Washer Diameter mm	Washer Thickness mm
16	32	512	2	M6	7.2	7	14	1.8
20	40	800	2	M6	7.2	7	14	1.8
25	60	1500	2	M8	17	10	21	2.0
30	60	1800	2	M8	17	10	21	2.0
40	70	2800	2	M10	28	11.5	24	2.2
50	70	3500	2	M12	45	14	28	2.7
60	60	3600	4	M10	28	11.5	24	2.2
80	80	6400	4	M12	45	14	28	2.7
100	100	10000	5	M12	45	15	28	2.7
120	120	14400	5	M12	45	15	28	2.7
160	160	25600	6	M16	91	20	28	2.7
200	200	40000	8	M16	91	20	28	2.7

6.4.1 Joint Efficiency

The efficiency of a joint may be measured in terms of the ratio of the resistance of the portion of the conductor comprising the joint to that of an equal length of straight conductor. It is possible to make joints with an efficiency of greater than 100% - i.e. the resistance of the joint is lower than that of an equivalent section of bar.

In terms of a complete busbar system, the proportion affected by joints is relatively small so that any inefficiency of the joints has only a small impact on the overall performance. However, joint inefficiency is important in two respects:

1. A joint with an efficiency of less than 100%, having a higher resistance, will run at a higher working temperature and experience greater temperature excursions than the normal bar. This could have an effect on the longevity of the joint and require more frequent maintenance.
2. In switchgear cabinets there will be many joints close together; less efficient joints will lead to excess heating and higher voltage drops.

The resistance of a joint, as already mentioned, is made up of two parts, one due to the distortion of lines of current flow and the other to contact resistance. The resistance due to the streamline effect at an overlapped joint is given by:

$$R_{sb} = \frac{e\rho l}{(a - nd)b}$$

where:

- e is the resistance ratio obtained from Figure 66
- a is the width of bar, mm
- b is the thickness of bar, mm
- l is the length of overlap, mm
- ρ is the resistivity of the conductor, μΩ mm (17.24 for 100% IACS copper)
- d is the diameter of the bolt holes, mm
- n is the number of holes across the width of the bars. For clamped joints, the value of n is zero.

The contact resistance, R_i, of the joint is:

$$R_i = \frac{Y}{al}$$

where Y is the contact resistance of a unit area, obtained from Figure 69.

The total joint resistance, R_j, is:

$$R_j = \frac{e\rho l}{(a - nd)b} + \frac{Y}{al}$$

Since the resistance, R_b, of an equal length of straight conductor is given by:

$$R_b = \frac{\rho l}{ab}$$

the efficiency of the joint is:

$$\frac{R_j}{R_b} = \varepsilon = \frac{ea}{a - nd} + \frac{Yb}{l^2 \rho}$$

From this equation it is apparent that the most important factor is the reduction in cross-section due to the bolt holes, i.e. the term *nd*.

Taking the parameters for a 50 mm wide busbar from Table 22, the contact force, *F*, is given by (noting that there are two 12 mm bolts):

$$F = \frac{2T}{KD}$$

$$F = \frac{2 * 45}{0.2 * 12}$$

$$F = \frac{90}{2.4}$$

$$F = 37.5\ kN$$

The area of the joint is 3500 mm², so the pressure is:

$$P = \frac{F}{3500}$$

$$P = 10.7\ N/mm^2$$

From Figure 69, a Y value of 3000 μΩ is obtained.

For 10mm thick bar, the overlap to thickness ratio is 7 so that, from Figure 66, e = 0.55.

Substituting,

$$\varepsilon = \frac{0.55 \times 50}{50 - 14} + \frac{3000 \times 10}{70^2 \times 17.24}$$

$$\varepsilon = \frac{27.5}{36} + \frac{30000}{84476}$$

$$\varepsilon = 0.764 + 0.355 = 1.12$$

This joint has a resistance of 1.12 times that of a 70 mm length of 50 mm x 10 mm copper bar, i.e. equivalent to 78.4 mm of bar. The joint temperature will be slightly higher than that of the surrounding bar.

If the joint were redesigned with an overlap of 90 mm, using three in-line bolts at the same torque, the joint efficiency becomes:

$$F = 56.25\ kN$$

The area of the joint is 4500 mm², so the pressure is:

$$P = \frac{F}{4500}$$

$$P = 12.5\ N/mm^2$$

From Figure 69, a Y value of 2600 μΩ is obtained.

For 10 mm thick bar, the overlap to thickness ratio is 9 so that, from Figure 66, e = 0.55.

Substituting,

$$\varepsilon = \frac{0.52 \times 50}{50 - 14} + \frac{2600 \times 10}{90^2 \times 17.24}$$

$$\varepsilon = \frac{26}{36} + \frac{26000}{139644}$$

$$\varepsilon = 0.722 + 0.186 = 0.91$$

In this case, the joint has a resistance of 0.91 times that of a 90 mm length of 50 mm x 10 mm copper bar, i.e. equivalent to 82 mm of the bar. This joint will run at a slightly lower temperature than the surrounding bar.

6.5 Clamped Joints

The design criteria for bolted joints apply in principle also to clamped joints. However, some aspects require particular attention:

- The clamping plates must be designed to be rigid enough to transfer the pressure without flexing. Often, ribbed castings are used for this purpose.
- The bolts which provide the joint pressure are at the periphery of the joint and will run at a temperature somewhat below that of the bar. In some 'wrap around' lamp designs, the bolts will also be physically shorter than the thickness of the stacked bars. The bolts will therefore expand less, and joint pressure may rise excessively.

6.6 Degradation Mechanisms

The deterioration of a connector proceeds slowly at a rate determined by the nature of different processes operating in the contact zone and in the environment. This initial stage persists for a long time without causing any noticeable changes because it is an intrinsic property of clusters of a-spots that their overall constriction resistance is not sensitive to small changes in their size. However, when the contact resistance increases sufficiently to raise the local temperature, a self-accelerating deterioration resulting from the interaction of thermal, chemical, mechanical and electrical processes will be triggered, and the contact resistance will rise abruptly. Hence, no deterioration will be noticeable until the final stages of the connector life.

6.6.1 Oxidation

Oxidation of the metal–metal contacts within the contact interface is widely accepted as the most serious degradation mechanism occurring in mechanical connectors. Copper is not very active chemically and oxidises very slowly in air at ordinary temperatures. As mentioned earlier (see '6.3.2.1 Condition of Contact Surfaces'), cleaning and roughening the joint surfaces prior to assembly and the use of a contact aid will prevent oxidation.

6.6.2 Corrosion

Corrosion is a chemical or electrochemical reaction between a metallic component and the surrounding environment. It begins at an exposed metal surface with the formation of a corrosion product layer and continues as long as reactants can diffuse through the layer and sustain the reaction. The composition and characteristics of the corrosion product layer can significantly influence the corrosion rate.

Busbars are potentially affected by atmospheric, localised, crevice, pitting and galvanic corrosion. The most important factor in all these corrosion mechanisms is the presence of water. In the presence of a sulphur-bearing atmosphere, tarnishing of the copper surface occurs because of sulphide formation from hydrogen sulphide in the atmosphere. The growth of tarnished film is strongly dependent on the humidity, which can reduce it if a low sulphide concentration prevails or increase it if sulphide concentration is high.

6.6.3 Fretting

Fretting is the accelerated surface damage occurring at the interface of contacting materials subjected to small oscillatory movements. Experimental evidence shows that amplitudes of <100 nm are sufficient to produce fretting.

There is still no complete unanimity on the mechanisms of fretting, specifically with regard to the relative importance of the processes involved. Nevertheless, based on the existing knowledge of the phenomenon, it can be safely assumed that the following processes are present:

1. Disruption of oxide film on the surface by the mechanical action exposes clean and strained metal which will react with the environment and rapidly oxidise
2. The removal of material from the surfaces by adhesion wear, delamination or by shearing the microwelds formed between the asperities of the contacting surfaces when the contact was made
3. Oxidation of the wear debris and formation of hard abrasive particles that will continue to damage the surfaces by plowing
4. Formation of a thick insulating layer of oxides and wear debris (a third body) between the contacting surfaces.

The oscillatory movement of the contacting members can be produced by mechanical vibrations, differential thermal expansion, load relaxation, and by junction heating as the load is cycled. Because fretting is concerned with slip amplitudes not greater than 125 µm movement, it is ineffective in clearing away the wear debris and accumulated oxides, and a highly localised, thick insulating layer is formed in the contact zone, leading to a dramatic increase in contact resistance and, subsequently, to virtual open circuits.

6.6.4 Creep and Stress Relaxation

Creep, or cold flow, occurs when metal is subjected to a constant external force over a period of time. The rate of creep depends on stress and temperature and is higher for aluminum than for copper. Stress relaxation also depends on time, temperature, and stress but, unlike creep, is not accompanied by dimensional changes. It occurs at high stress levels and is evidenced by a reduction in the contact pressure due to changes in metallurgical structure. The change from elastic to plastic strain has the effect of significantly reducing the residual contact pressure in the joints, resulting in increased contact resistance, possibly to the point of failure.

6.6.5 Thermal Expansion

The effect of temperature variation on contact pressure has already been discussed. Longitudinal expansion is also important since it can lead to slip in the joint followed by loosening. It is important that long bars are provided with a flexible element so that movement can take place elsewhere.

6.7 Conclusion

The quality of busbar joints is crucial to the long term reliability of a busbar system. It is important to take care over the choice of joint design, the tightening torques, bolt types and the effect of temperature to ensure reliability. In-service maintenance should ideally include thermal imaging of joints so that any problems can be found before failure occurs.