



IEEE Recommended Practice for the Design of Flexible Buswork Located in Seismically Active Areas

IEEE Power Engineering Society

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Substations Committee

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IEEE Recommended Practice for the Design of Flexible Buswork Located in Seismically Active Areas

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of the
IEEE Power Engineering Society

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Abstract: The engineering and design of flexible bus connections for bus and equipment in electric power substations is described. This recommended practice gives guidance to the substation engineer who is unfamiliar with seismic considerations in the engineering and design of connections, and provides engineers with the current state of knowledge of the dynamic effects of high-voltage connections and conductors.

Keywords: bus, conductor, conductor slack, connections, earthquakes, electrical equipment, flexible bus, flexible buswork, interconnected equipment, interconnection, seismic, substations

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Introduction

This introduction is not part of IEEE Std 1527-2006, IEEE Recommended Practice for the Design of Flexible Buswork Located in Seismically Active Areas.

This introduction provides some background on the rationale used to develop this recommended practice. This information is meant to aid in the understanding and usage of this recommended practice.

Flexible buswork consisting mainly of bare aluminum or copper conductors with bolted or welded connector hardware have been used for many years as part of the electrical buswork system in substations. In general, they are utilized to simplify equipment interconnection with the main bus because they are easy to install and help ensure that the vertical and horizontal load limits of the equipment terminals are not exceeded. However, recent earthquakes in many parts of the world demonstrated that more attention must be paid to these flexible buswork designs for facilities in seismically active areas because flexible buswork can increase the probability that a facility will still be operational after an earthquake.

During an earthquake, flexible buswork conductors may transfer significant mechanical forces at the equipment terminals, due to the dynamic effects induced by their motion when adjacent interconnected equipment push and pull on these connections. Improperly designed flexible buswork may thus result in exceeding the load limits permitted at the equipment terminals. This can lead to a piece of relatively inexpensive equipment contributing to the failure of a more expensive one and perhaps, starting a cascade effect that could result in loss of substantial revenue and expensive equipment.

This recommended practice will cover how to design flexible buswork for substation buswork systems or equipment connections to account for seismic movement. It provides a more detailed discussion of the material covered in IEEE Std 693™ to guide the substation designers with this aspect of seismic design. In short, this recommended practice covers how to determine the amount of seismically-induced equipment motion that may occur, how to determine conductor flexibility, how to specify the amount of slack required, and what other factors must be considered as part of the design of flexible buswork for new and existing installations. It will also report on the current state of knowledge concerning the dynamic effects of conductors and flexible high-current buswork interconnections.

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1. Overview

The use of suitably designed and installed flexible buswork connections must be considered when seismically hardening a substation. Installation of buswork connections to the equipment is a factor that greatly affects the seismic performance of the installed equipment. If the buswork is not properly designed, equipment that would otherwise survive may fail, resulting in unnecessary financial losses. The use of seismically designed and installed flexible connections increases the probability that a facility will still be operational after an earthquake.

This recommended practice will cover the design of flexible buswork connections to account for seismic movement, as well as other factors that must be considered as part of this design, as per the general decision tree diagram shown in Figure C.1.

This recommended practice also contains five annexes. Annex A and Annex B contain the tables referenced in the main body of the recommended practice, while Annex C and Annex D contain the figures referenced. Annex E provides the latest information on dynamic effects of conductors and a Bibliography is presented in Annex F.

1.1 Scope

The scope of this document is the engineering and design of flexible bus connections for bus and equipment in electric power substations.

1.2 Purpose

This document was prepared to provide guidance to the substation designer on flexible buswork seismic design and to provide information accounting for the current state of knowledge concerning the dynamic effects of conductors and high-current connections.

2. Normative references

This recommended practice shall be used in conjunction with the following publications. If the following publications are superseded by an approved revision, the revision shall apply:

IEEE Std 605TM-1998, IEEE Guide for Design of Substation Bus Structures.^{1, 2}

IEEE Std 693TM-2005, IEEE Recommended Practice for the Seismic Design of Substations.

IEEE Std 738TM-1993, IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors.

3. Definitions, abbreviations, and acronyms

For the purposes of this recommended practice, the following terms and definitions apply. The *Authoritative Dictionary of IEEE Standard Terms* [B3]³ should be referenced for terms not defined in this clause.

3.1 Definitions

3.1.1 basketing of conductors (also called “bird caging”): The unraveling or untwisting of outer and inner strands. Basketing can be caused by the following:

- a) Minimum bending radius is violated
- b) Ends being twisted opposite to direction of twist

3.1.2 bundled conductor: An assembly of two or more conductors used as a single conductor and employing spacers to maintain a predetermined configuration. The individual conductors of this assembly are called subconductors.

3.1.3 complete quadratic combination (CQC method): A modal combination method, especially useful for systems with closely spaced frequencies.

3.1.4 conductor configuration: The generic term for a flexible buswork connection geometry that has been designed to accommodate a certain amount of movement at its end points, without putting undue strain or stress on these end points.

3.1.5 critical damping: The least amount of viscous damping that causes a single-degree-of-freedom system to return to its original position without oscillation after initial disturbance.

3.1.6 damping: An energy dissipation mechanism that reduces the response amplification and broadens the vibratory response over frequency in the region of resonance. Damping is usually expressed as a percentage of critical damping. *See also: critical damping.*

3.1.7 drops: The field or construction term for the flexible buswork connections made between a high buswork section, either rigid or strain, and a piece of equipment or lower buswork section.

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³The numbers in brackets correspond to those of the bibliography in Annex F.

3.1.8 flexible buswork or flexible buswork connections: The terms given to the section of buswork that is usually made up of stranded bare conductors (as opposed to rigid conductors) electrically interconnecting two pieces of equipment, a piece of equipment and a section of rigid bus or two sections of rigid bus.

3.1.9 g: Acceleration due to gravity, that is 9.81 m/s^2 .

3.1.10 ground acceleration: The acceleration of the ground resulting from the motion of a given earthquake. The maximum or peak ground acceleration is the zero period acceleration (ZPA) of the ground response spectrum.

3.1.11 natural frequency: A frequency at which a body or system vibrates due to its own physical characteristics (mass and stiffness) when the body or system is distorted and then released.

3.1.12 pinch effect: The “pinch effect” is caused by the bending of the conductor during the high velocity movement caused by the short-circuit forces near where a spacer or equipment terminal clamp is attached.

3.1.13 pull-push tests: The name given to the test to determine how flexible a certain conductor configuration is when its end points are pulled apart or pushed together. The results of this test are units of force per displacement of the conductor from its connection point.

3.1.14 response spectrum: A plot of the maximum response of an array of single-degree-of-freedom (SDOF) identically damped oscillators with different frequencies, all subjected to the same base excitation. *See also:* **single-degree-of-freedom system (SDOF system).**

3.1.15 seismically decouple: The term to describe how two pieces of equipment or a piece of equipment and a rigid bus section can be interconnected electrically by a flexible buswork connection, which ideally allows independent movement, or at least, minimized interaction between the two components.

3.1.16 seismicity: Seismic activity; the occurrence of earthquakes in time and space.

3.1.17 single-degree-of-freedom system (SDOF system): The idealization of a physical system in which its mass, its elastic properties (flexibility or rigidity), its energy-loss mechanism (damping), and its external source of excitation (loading), are assumed to be concentrated in a single physical element.

3.1.18 slack (or “conductor slack”): The difference between the conductor length and the straight line distance between its attachment points; the amount of displacement that a conductor in a given configuration can be stretched to straighten it up completely.

3.1.19 square root of the sum of squares method (SRSS method): A modal combination method used to obtain an estimation of the complete response of a system, by summing up the square of each modal response considered in the analysis (such as displacement, force, etc.) and then taking the square root of the result. This method assumes that individual maximum modal responses do not occur at the same time, which is the case when modal frequencies are spaced by more than 20% with each other. *See also:* **complete quadratic combination (CQC method).**

3.1.20 standalone equipment displacement: The motion of equipment without conductor(s) attached to it, that is without interconnection with other equipment.

3.1.21 time history: A record of earthquake ground motion (either natural or artificial), usually in terms of acceleration, as a function of time.

3.2 Abbreviations and acronyms

AAC	all aluminium conductor
BIL	basic impulse level
CQC	complete quadratic combination
MDOF	multi-degree-of-freedom
SDOF	single-degree-of-freedom
SRSS	square root of sum of squares
ZPA	zero period acceleration

4. Equipment movement

All equipment can be adversely affected in an earthquake by an adjacent moving or stationary component connected to it. Therefore, care must be given to the placement of important components so that movement of adjacent components does not cause damage that would lessen the ability of a facility to operate. Equipment that is interconnected by flexible conductors must have some provision in the installation (e.g., sufficient flexible conductor slack) that allows for any relative displacement between the equipment that will occur during an earthquake.

As a result of analysis, testing, and earthquake experience, individual items of major equipment and buswork supports have been found to move by varying degrees depending on their mass, mounting height, type and size of support structure, soil type, and seismicity. Adjacent structures that differ in their dynamic response may experience large relative displacements. All connections between equipment elements must be sufficiently long and flexible to permit relative axial and lateral movements and torsional motions. This will avoid impacting forces or the transfer of forces between the individual components when any existing slack in the buswork is used up. The amount of movement combined with the distance between the connection points results in the need for specifically configured flexible bus conductors.

The movement of a piece of equipment in the horizontal direction of the conductor (from one equipment to the other) must first be determined in order to ascertain the relative displacement between items and thereby choose the appropriate conductor configuration. The calculation and testing methods to determine equipment movement are described in this clause. A qualification level as well as an appropriate design response spectrum must first be selected before any calculation or testing method is used (see, for example, IEEE Std 693⁴).

4.1 Calculation methods to evaluate standalone equipment displacement

Due to the effect of the flexible conductors, it is difficult to calculate with accuracy what will be an equipment displacement in its connected configuration. It is then easier and preferable to obtain the equipment displacement in its standalone configuration, i.e., without conductors connected. On average, the standalone displacement is a conservative value of the connected equipment displacement (Dastous et al [B9]), thus being relevant for design purposes

⁴Information on references can be found in Clause 2.

4.1.1 Recommended method for candlestick and frame type equipment

The use of a design response spectrum along with the generalized single-degree-of-freedom (SDOF) method is recommended to obtain the equipment displacement for design purposes. This method assumes that the equipment oscillates principally in one vibration mode shape as shown in Figure C.2.

The generalized SDOF method is recommended for equipment that has simple vibration modes such as candlestick and frame type; it is not recommended for equipment that has more complex vibration modes such as dead tank circuit breakers or bushings on power transformers (see 4.1.2 for such equipment).

The maximum displacement at the attachment point for such a system using the response spectrum method is given by Equation (1):

$$x_{\max} = \frac{L}{m^*} S_d(f, \zeta) = \frac{L}{m^* \omega^2} S_a(f, \zeta) \quad (1)$$

where

- $\frac{L}{m^*}$ is the modal-participation factor
- L is the effective mass producing the external inertia loading
- m^* is the generalized mass
- $S_d(f, \zeta)$ is the spectral displacement from the design response spectrum used
- $S_a(f, \zeta)$ is the spectral acceleration from the design response spectrum used
- f is the natural frequency of the mode shape
- ζ is the damping ratio of the mode shape
- ω is the natural circular frequency given by $2\pi f$

The value of the effective mass L is given by Equation (2):

$$L = \psi(y_0) \int_0^h m(y) \psi(y) dy \quad (2)$$

where

- $\psi(y)$ is the value of the mode shape at point y along the equipment height (see Figure C.2)
- h is the equipment total length (including support if included in analysis)
- y is the position along the equipment length from zero at the base
- y_0 is the position at the attachment point
- $m(y)$ is the mass distribution by unit length

The generalized mass m^* is given by Equation (3):

$$m^* = \int_0^h m(y) [\psi(y)]^2 dy \quad (3)$$

The modal-participation factor L/m^* characterizes the difference between a lumped and a generalized SDOF system, as L/m^* is generally different from unity as for the lumped system. This factor can be calculated if the mass and stiffness distribution of the system (leading to a correct evaluation of the mode shape) are known with sufficient accuracy.

For equipment for which only the natural frequency and damping of the first mode are known or estimated, such a method can be used as long as the value of the first modal-participation factor L/m^* is representative. Theoretical and calculated values of this factor are given in Dastous et al [B9].

If information about this factor is not available, Equation (4) gives a bound value covering 95% of equipment observed so far (candlestick and frame type only):

$$x_{\max|95\%} = 1.62 \times S_d(f, \zeta) = 1.62 \times \frac{S_d(f, \zeta)}{\omega^2} \quad (4)$$

where

$x_{\max|95\%}$ is the displacement bound value covering 95% of candlestick and frame type equipment.

Using IEEE Std 693 required response spectrum for the high level, Table A.1 presents estimated values of displacement using Equation (4) for different first mode natural frequencies. The standalone displacements presented in Table A.1 are bound values for informational purposes. It is recommended that displacement values determined in qualification be used in design.

Note that in Table A.1, displacement might be very important at low frequencies. In cases where this poses problems in design, such as for electrical clearances requirement (it is recommended that clearances be maintained during seismic movement even though that might prove difficult for large displacements), it is recommended to use site-specific spectra to evaluate more precisely the displacement (see 4.3). For example, North American eastern earthquakes tend to have much less energy at low frequencies, which results in significant decrease of the displacements presented in Table A.1 for frequencies below 2 Hz.

4.1.2 Alternative method for other equipment than candlestick and frame type

An alternative method that is valid for any type of equipment is to model the equipment as a multi-degree-of-freedom (MDOF) system using the finite element method. In case of a linear model (displacements and deformations assumed small and material properties assumed constant), the displacement at any nodal point j of the system comprising n -nodal points can be obtained using the principle of modal superposition given by Equation (5).

$$(X) = [\Phi] \times (Z(t)) \quad (5)$$

where

- (X) is the vector of the displacement at the n -nodal points
- $[\Phi]$ is the modal matrix composed of each mode shape j
- $Z(t)$ is the vector of the generalized displacements

Once the mode shapes have been computed by any standard technique, the solution of Equation (5) using the response spectrum method can be computed by solving for the generalized displacements, whose governing equations are identical to Equation (1) for any mode. It is assumed here that each mode is assigned a viscous damping ratio. Since it is statistically improbable that each mode will reach its maximum value at the same time during an earthquake, a statistical combination of the maximum modal responses must be used to estimate the maximum displacement. One appropriate statistical combination that can be used is the SRSS method, which would translate here as in Equation (6).

$$x_{\max} = \sqrt{\left(\frac{L_1}{m_1^*} S_{d1}\right)^2 + \left(\frac{L_2}{m_2^*} S_{d2}\right)^2 + \dots + \left(\frac{L_n}{m_n^*} S_{dn}\right)^2} \quad (6)$$

where L_j and m_j^* are given for each mode j by Equation (2) and Equation (3) while S_{dj} is the spectral displacement for each mode j of frequency f_j and damping ratio ζ_j .

The SRSS method will give a good approximation if all modal frequencies are well spaced. In case of closely spaced frequencies (within 20% usually), the modal responses can be temporarily correlated and it would therefore be advisable to use a statistical combination that takes this into account. One recommended combination is the complete quadratic combination method (CQC) (Der Kiureghian [B15], Wilson et al [B23]). With both methods (SRSS or CQC), it is to be noted that the number of modes required to obtain a sound estimate of the displacement is actually much lower than the total number of degrees of freedom considered. For most equipment that is candlestick or frame type, the first vibration mode is usually sufficient (Dastous et al [B9]) and Equation (6) then results in Equation (1).

4.2 Testing methods to evaluate standalone equipment displacement

Shake table testing can be used to determine equipment movement when the equipment falls within the physical size and load limits of the table. For shake table testing, a choice can be made between random vibration testing and time history testing. However, time history testing is usually preferred with the equipment being instrumented with accelerometers at the conductor attachment points. Time history data obtained from an earthquake record from the site (if available) or for a geologically similar site may be scaled up or down for input to the testing to match the qualification level selected, but usually more than one is used. A geoscientist should be consulted on how this is conducted.

The movement of a large piece of equipment such as a series capacitor platform can be obtained by simulating the seismic loading with a sinusoidal shaker. The platform is excited typically by a variable frequency, variable load sinusoidal shaker capable of generating up to 445 kN forces, over the 2 Hz to 20 Hz range, in any horizontal direction. The structure is instrumented with accelerometers and strain gauges to provide data to allow analysis of the response of the structure. The lever arm length of the rotating masses at the shaker can be adjusted to give a range of forces at a certain frequency. The shaker can therefore be used for spectral testing (specified acceleration “g” loads at various frequencies). This method yields the most comprehensive results of all methods available. A disadvantage is that sufficient space must be available on the platform for setting up the shaker. If a piece of equipment has to be removed temporarily to provide the space, compensation must be made for the equipment. The maximum combined modal displacement from the spectral testing results should be used for determining the equipment movement.

4.3 Site-specific conditions

To determine equipment movement, site-specific conditions must also be taken into consideration and this includes soil types and seismicity. A seismic qualification level should first be selected (see IEEE Std 693) using the site-specific soils and seismicity information. The equipment movement can then be determined by calculation or testing methods on the basis of the qualification level. Experience has shown that it is good practice to use the same qualification level to determine movement for all equipment in all substations within a reasonably large geographical area for simplicity in logistics.

Also, for interconnected equipment not on the same foundation, the expected differential motions between equipment due to foundation motion must be considered. This may be estimated separately and added to the movement determined above; this would provide a conservative estimate of the total differential motion.

Furthermore, it is recommended that, where practical and economical, interconnected equipment be placed on a monolithic foundation. This will help minimize the differential movement of the supported equipment. Rocking of the foundation has been identified as a potential problem (see IEEE Std 693). Foundations must be designed for the appropriate seismic qualification level to avoid compression, shear and bending moment failures, and overturning with soil failure.

4.4 Minimum conductor slack and necessary conductor length between equipment interconnected through flexible buswork

As stated, the conductor in a flexible buswork arrangement should possess as a minimum enough slack to accommodate the horizontal relative displacement that can occur between the moving equipment. This relative displacement, D_{rel} , can be evaluated⁵ using the expected maximum standalone equipment displacement (4.1 and 4.2) and the SRSS method as shown in Equation (7).

$$D_{\text{rel}} = 1.25 \times \sqrt{x_{\text{max},1}^2 + x_{\text{max},2}^2} \quad (7)$$

where

- D_{rel} is the maximum horizontal relative displacement between equipment 1 and 2
- $x_{\text{max},1}$ is the maximum standalone displacement of equipment 1 in the conductor direction
- $x_{\text{max},2}$ is the maximum standalone displacement of equipment 2 in the conductor direction

The 1.25 factor in Equation (7) takes into account the statistical dispersion of the SRSS method. If Equation (7) would be used with a factor of 1.0 instead, it would provide only an average value of the relative displacement (see Dastous and Pierre [B11] for more details). Equation (7) gives the minimum amount of slack required in any configuration such as those recommended in Clause 11.

The necessary conductor length between interconnected components can be estimated using Equation (8).

$$L_0 = L_1 + D_{\text{rel}} + L_2 \quad (8)$$

where

- L_0 is the necessary conductor length between interconnected components
- L_1 is the straight line distance between attachment points
- L_2 is an additional provision for the conductor configuration under consideration, as to not transfer unnecessary additional loads to the equipment when fully stretched

To understand the necessity of using the additional length L_2 , it is necessary to recognize the following two points:

- a) The conductors may be pre-bent to the configuration used, such that the conductor does not add load to the equipment except the dead weight of the conductor.
- b) All configurations have rigid moment connections between the conductor and equipment at both ends of conductors, which might add unnecessary moments to the equipment terminal due to the bending stiffness of the conductor itself, which cannot be neglected. The user must test (or calculate) and take into consideration the conductor shape, number of bundled conductors, the distance between the ends of conductors, and the conductor stiffness in determining how much additional conductor length L_2 is required.

It is to be emphasized, as an additional design rule **that all pairs of interconnected equipment with flexible buswork should be able to accommodate their relative displacements**. Otherwise, impacts might be transferred between pairs of equipment, from pairs where not enough slack would have been provided, due to the effect of multi-connected equipment.

⁵ Note that in IEEE Std 693 the relative displacement is given by the sum of the maximum displacements of individual equipment, multiplied by a 1.5 factor: $D_{\text{rel}} = 1.5 \times (x_{\text{max},1} + x_{\text{max},2})$. Flexible connections designed with this previous method are still valid as the IEEE 693 method is at all times a conservative estimate of Equation (7). The SRSS method used here with the 1.25 factor instead is simply a more refined estimate that might be especially useful for equipment with large displacements at low frequencies, for which substantial saving in slack can be obtained using Equation (7), thus in some cases permitting to respect more easily electrical clearances requirements. This note also applies to the methods presented in IEEE Std 693.

For equipment with closely spaced frequencies (less than 20% difference) and where the expected relative displacement is large enough to pose problems in the design, the SRSS method used in Equation (7) may be replaced with an adaptation of the CQC method (Der Kiureghian et al [B14]). However, this method requires a precise knowledge of the fundamental frequencies and the associated damping to be of relevant use. In all cases, the CQC method is conservatively covered by the SRSS method; this is why the latter is preferred due to its simplicity of use.

An example of the use of Equation (7) and Equation (8) follows:

For the installation of an adjacent circuit breaker and disconnect switch where L_1 equals 3000 mm and L_2 has been selected as 800 mm, the maximum standalone displacement of the circuit breaker is 55 mm and the corresponding maximum for the disconnect switch is 75 mm. The relative displacement is given, using Equation (7), by:

$$D_{\text{rel}} = 1.25 \sqrt{55^2 + 75^2} = 116 \text{ mm}$$

so that the necessary conductor length is given, using Equation (8), by:

$$L_0 = 3000 \text{ mm} + 116 \text{ mm} + 800 \text{ mm} = 3916 \text{ mm} = 3.92 \text{ m}$$

5. Other connection possibilities

Due to the reduced height of the buswork, the greater inherent stiffness and relatively smaller mass of the components, most equipment at the 12 kV, 25 kV, and 69 kV voltage levels is able to withstand greater seismic forces and will be subject to far less differential movement. While rigid buswork design is generally acceptable, areas of concern are connections to major equipment bushings. Transformer, circuit breaker and voltage regulator bushings, in addition to being vulnerable, will require considerable lead times to replace should damage occur and therefore, must be subject to a high level of protection if service is to be readily restored subsequent to a seismic event.

The flexible buswork from rigid buswork to equipment bushings is ideally accomplished by using stranded bare conductor, braided conductor, or expansion terminal connectors. The latter two will limit flexibility sufficiently to avoid compromising the phase-to-phase clearances under short-circuit loading and the voltage gradient across the insulators, particularly for 12 kV and 25 kV equipment.

6. High-current connections

For the purpose of this document, high-current flexible buswork connections are defined as those being capable of carrying 3000 A or more, and should utilize the conductor configurations discussed in Clause 11. They can have either bolted or welded connection joints and normally utilize two or more bare stranded conductors or plates connected in parallel. These conductors or plates can be either copper or aluminum, although aluminum is more widely used. As with the lower current flexible buswork connection, the basic design factors must be considered and satisfied. However, unlike the lower current flexible buswork connection designs, stricter attention must be paid to the connection method, the current density capacity, the contact surface area, the surface preparation, and the contact pressure or “clamping” to ensure that the high-current flexible buswork connection functions properly in-service.

For connections with current-carrying capacities of up to and including 5000 A, bolted joints can be used as part of the flexible buswork connection provided that they are properly designed and installed. For

connections with current-carrying capacities of greater than 5000 A, welded connection hardware should be considered.

For bolted aluminum connections, experience has shown that good joint performance occurs if the current density limit assumed for the contact surfaces is approximately 0.15 A/mm^2 , but making this assumption is restrictive and requires large connection surfaces assuming total area overlap. Therefore, for practical purposes, a current density of between 0.23 A/mm^2 to 0.27 A/mm^2 can be assumed based on total area overlap if proper surface preparation is done prior to installation.

NEMA CC 1-2002 [B20] describes the size and hole configuration for the manufacturing of a variety of bolted terminal pads for connectors and equipment based on this higher-current density. The terminal pad size that this practice recommends for the 3000 A to 5000 A current range is given in Table A.2.

Furthermore, when two surfaces are brought together under mechanical pressure, contact is made where the highest peaks or “asperities” meet, at which point, due to the applied pressure, plastic deformation of the metal surfaces occurs; however, if the mated surfaces are relatively smooth, then the number of low peaks involved in this plastic deformation is small. The current flowing across the interface of these two surfaces is restricted to a small area of contact, which causes heating. Thus, if the two surfaces are rougher, i.e., there is a greater variation in peak heights, fewer high peak contact points will be made, but more peaks will be deformed and enmeshed so that better metal-to-metal connection will be achieved. To obtain this greater variation in peaks, the contact surface must be abraded. This can be achieved using the appropriate sandpaper or brush (depending on the conductor material), while ensuring all debris is removed with a soft brush, an approved oxide inhibitor is applied, and the connector bolted immediately. Tools such as drills, files and sandpaper used on aluminum connectors shall not previously have been used on copper conductors because traces of copper salts on an aluminum contact surface should be avoided.

This metal-to-metal contact created as a result of the applied mechanical load in a bolted connection after proper surface preparation is only maintained if the bolt connection design does not allow the mechanical load to decrease below critical values. With this in mind, a practical design range for low- to intermediate-strength alloy conductors is 5500 kPa to 8300 kPa, but for high-strength alloy conductors a clamping pressure of 8300 kPa should be used. Therefore, using Equation (9) and the pad sizes from Table A.2, the required bolt load can be determined to be approximately 21 kN for high-strength alloy conductors.

$$F_b = \frac{p_j \times A_p}{n_b} \quad (9)$$

where

- F_b is the required bolt load (N)
- p_j is the joint pressure (Pa)
- A_p is the pad area (m^2)
- n_b is the number of bolts

In general, it is desirable to use bolts that have a known elastic-proof load, and for high-current connections, non-magnetic bolts should be used to avoid overheating due to hysteresis losses in locations where extremely high magnetic fields are present. The bolts should have similar thermal expansion coefficient as the material the pads are made of, and they should have sufficient tensile strength for the clamping pressure required. See Clause 7 for more details.

If the tensile strength of the materials used is not known or is less than 145 MPa, conical spring washers could be used to ensure the required clamping pressure is maintained. Usually, only one such washer is all that is required, plus a flat washer larger in diameter than the spring washer to stop it from digging into the