

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

IEEE Power and Energy Society

Sponsored by the
Substations Committee



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Abstract: Recommended practices for the engineering and design of flexible and rigid bus connections for bus and equipment in electric power substations located in seismically active areas are provided in this document.

Keywords: bus, buswork, conductor, connections, earthquakes, electrical equipment, flexible bus, flexible buswork, IEEE 1527™, interconnected equipment, interconnection, rigid bus, rigid buswork, seismic, seismic design, slack, substations

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Introduction

This introduction is not part of IEEE Std 1527-2018, IEEE Recommended Practice for the Design of Buswork Located in Seismically Active Areas.

During an earthquake, buswork conductors may transfer significant forces at their equipment terminals, due to the dynamic effects induced by their motion when adjacent interconnected equipment items push and pull on them. The use of suitably designed and installed buswork connections, either flexible or rigid, must be considered when seismically hardening a substation. Installation of buswork is a factor that may greatly affect the seismic performance of the installed equipment. If the buswork is not properly designed, equipment that would otherwise survive may fail. The use of seismically designed buswork increases the probability that a facility will still be operational after an earthquake. This document provides recommended practices to give guidance to the substation engineer regarding seismic considerations in the engineering and design of connections, and to provide engineers and equipment manufacturers with the knowledge of the dynamic effects of connections on interconnected equipment during seismic events. It also provides methods to account for the effects of connections in the seismic qualification of substation equipment. These effects are not accounted for in detail in any other standard.

Contents

1. Overview.....	14
1.1 Scope.....	14
1.2 Purpose.....	14
1.3 Application.....	14
2. Normative references	15
3. Definitions, acronyms, and abbreviations	15
3.1 Definitions.....	15
3.2 Acronyms and abbreviations	17
4. General design process.....	17
4.1 Introduction.....	17
4.2 Main design criteria.....	18
4.3 Design process for seismic connections	19
5. Equipment movement and elongation demand.....	20
5.1 Introduction.....	20
5.2 Seismic input.....	21
5.3 Foundation considerations.....	21
5.4 Basic connection geometry.....	21
5.5 Determination of the elongation demand.....	22
6. Design of flexible conductor	28
6.1 Advantages and limitations of flexible connection	28
6.2 Available shapes, required conductor length, and qualitative behavior	29
6.3 Verification of clearances, flexibility, and stability using the nonlinear finite element method.....	33
6.4 Verification of clearances, stability, and flexibility experimentally	39
6.5 Spacers for bundled conductors.....	41
6.6 Standardized configuration design	42
7. Design of rigid bus with flexible connector	44
7.1 General description.....	44
7.2 Advantages and limitations of RB-FCs.....	46
7.3 Design principles of an RB-FC.....	47
7.4 Available methods to evaluate the interaction effect.....	47
7.5 Determination of RB-FC in-line load displacement properties.....	48
7.6 Evaluation of interaction between equipment connected by rigid bus using a simplified analysis method	50
8. Methodology to account for the interaction effects of conductors in the seismic qualification of substation equipment.....	56
8.1 Introduction.....	56
8.2 Inclusion of interaction effects in the seismic qualification of equipment	56
9. Other considerations.....	58
Annex A (informative) Bibliography.....	59
Annex B (informative) Electrical clearances.....	62
Annex C (informative) Generalized single-degree-of-freedom (SDOF) method	64
Annex D (informative) Comparison between combination methods to obtain the elongation demand.....	67

Annex E (informative) Effect of adding slack on the catenary configuration	69
Annex F (informative) Examples of finite element calculations.....	72
Annex G (informative) Common conductor input properties for finite element calculations.....	74
Annex H (informative) Examples of flexibility calculations for flexible conductors	75
Annex I (informative) Maximum horizontal forces measured during experiments.....	77
Annex J (informative) Other considerations.....	78

List of Figures

Figure 1—Flowchart for design of seismic connections.....	20
Figure 2—Basic connection geometry	21
Figure 3—Determination of basic geometry from connector extremities	22
Figure 4—Upper-bound displacement according to IEEE Std 693 performance level required spectra for 2% damping	24
Figure 5—Difference between required response spectrum and time history input spectrum	26
Figure 6—Basic flexible conductor configurations	29
Figure 7—General procedure to establish the initial configuration of the conductor.....	37
Figure 8—Measured geometry of a configuration under its self-weight (Stevenson and Beattie [B31]).....	39
Figure 9—Experimental investigation of stability using water-filled tubes (Stevenson and Beattie [B31])...	40
Figure 10—Schematic of experimental setup to investigate flexibility (Stevenson and Beattie [B31])	41
Figure 11—Recommended spacer installation for AACs.....	42
Figure 12—RB-FC (Filiatrault, Kremmidas, Elgamal, and Seible [B19])	45
Figure 13—Flexible strap connectors (Song, Der Kiureghian, and Sackman, “Seismic Response and Reliability...” [B28])	45
Figure 14—Slider connectors (Song, Der Kiureghian, and Sackman, “Seismic Response and Reliability...” [B28])	46
Figure 15—ATC-24 [B4] test protocol.....	48
Figure 16—Load displacement response of a spring connector at different ductility levels (Filiatrault, Kremmidas, Elgamal, and Seible [B19]).....	49
Figure 17—Comparison between experimental results and modeling of flexible connectors (Song, Der Kiureghian, and Sackman, “Seismic Response and Reliability...” [B28]).....	50
Figure 18—Model of two equipment items connected by a linear RB-FC	52
Figure 19—Definition of $A_{E[\Delta x]}$ and equivalent stiffness of an RB-FC	55
Figure B.1—Schematic view of electrical clearance distance requirements	62
Figure B.2—Practical example of required clearances.....	63
Figure C.1—Generalized SDOF system	64
Figure C.2—Results of survey on first modal participation factor (Dastous, Filiatrault, and Pierre [B9]).....	65
Figure E.1—Effect of adding slack for catenary shapes of different spans	70
Figure E.2—Effect of adding slack on the sag.....	71
Figure F.1—Comparison between calculated and measured shape of a catenary configuration.....	72
Figure F.2—Clearance check with the finite-element method.....	72

Figure F.3—Comparison between calculated and measured forces of static push-pull tests (Dastous, “Nonlinear Finite Element Analysis...” [B8]).....	73
Figure H.1—Load-displacement curve with 0.25 m cyclic displacement	75
Figure H.2—Load-displacement curve with 1.25 m cyclic displacement	76
Figure J.1—Conductor sizes to minimize corona loss.....	79
Figure J.2—Conductor capacity derating factor due to proximity effects	81
Figure J.3—Recommended aluminum adapters for 3000 A, 4000 A, and 5000 A applications.....	84
Figure J.4—5000 A rated multiple conductor termination arrangement.....	85
Figure J.5—Typical copper or aluminum terminal pad adapters	88
Figure J.6—Clamps used to prevent bird caging.....	89

List of Tables

Table 1—Upper-bound displacement for IEEE Std 693 performance level required spectra at 2% damping	24
Table 2—Summary of basic flexible configurations characteristics	29
Table 3—Example of standardized rigid bus bar dimensions	43
Table 4—Standardized table for the 145 kv example	44
Table 5—Available load-displacement curves for rigid bus flexible connector	49
Table 6—MAF for seismic qualification of substation equipment	57
Table 7—ETFs for seismic qualification at the IEEE Std 693 performance level	58
Table C.1—Results of survey on first modal participation factor	65
Table G.1—Common conductor input properties for finite element calculations ^a	74
Table I.1—Maximum horizontal forces measured during experiments with flexible connections ^{a,d}	77
Table J.1—Recommended aluminum conductor current carrying capacity based on 70 °C maximum	80
Table J.2—Current carrying capacity of bare copper	80
Table J.3—Recommended terminal pad size and hole configuration	83

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

1. Overview

The use of suitably designed and installed ~~flexible~~ buswork connections, either flexible or rigid, must be considered when seismically hardening a substation. Installation of buswork ~~connections to the equipment~~ is a factor that may greatly ~~affects~~ affect 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~~ buswork 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~~ provides recommended practices for the engineering and design of flexible and rigid bus connections for bus and equipment in electric power substations located in seismically active areas. It covers the design of buswork connections in the seismic qualification of equipment covered within the scope of IEEE Std 693™.¹

1.2 Purpose

This document ~~was prepared~~ provides recommended practices to ~~provide~~ give guidance to the substation ~~designer on flexible buswork~~ engineer regarding seismic considerations in the engineering and design of buswork, and to provide ~~information accounting for the current state of~~ engineers and equipment manufacturers with the knowledge ~~concerning~~ of the dynamic effects of ~~conductors and high current~~ connections on interconnected equipment during seismic events.

1.3 Application

This document is meant for primary connections to equipment terminal(s) only and is not applicable to internal equipment connections, sensing lines, or ground connections. It reflects the practice for the design of buswork in conventional substations. Flexible alternating current transmission system (FACTS) and high voltage direct current (HVDC) substations are specialized and may have exceptional elements that are beyond the scope of the present document. Even though a known solution, telescopic buses are also beyond the scope of the present document. Those elements identified as being exceptional should have a buswork analysis developed that is consistent with the objectives of IEEE Std 1527™ and approved by the user.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

Dastous, J.-B. and A. Der Kiureghian, "Application Guide for the Design of Flexible and Rigid Bus Connections between Substation Equipment Subjected to Earthquakes," PEER Report 2010/04, Pacific Earthquake Engineering Research Center, College of Engineering, University of California at Berkeley, September 2010.

¹Information on references can be found in Clause 2.

~~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 605 ~~1998~~^{1,2,3}™, IEEE Guide for Bus Design ~~of Substation Bus Structures. in Air Insulated Substations.~~

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

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document ~~recommended practice~~, the following terms and definitions apply. The ~~Authoritative Dictionary of~~ IEEE Standards Dictionary Online ~~Terms [B3]~~³ should be consulted ~~referenced~~ for terms not defined in this clause.⁴

basketing of conductors ~~(also called “bird caging”)~~: The unraveling or untwisting of outer and inner strands on a flexible conductor. Basketing can be caused ~~by the following~~ when: 1) the minimum bending radius is violated, or 2) the ends are being twisted opposite to direction of ~~twist~~ lay. *Syn: bird caging.*

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.

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⁴IEEE Standards Dictionary Online is available at: <http://dictionary.ieee.org>.

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

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

conductor configuration: The generic term for [the conductor arrangement between items of interconnected equipment. This includes the conductor type, number of subconductors, shape, and span](#) ~~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.~~

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.

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**.

differential displacement: [The maximum relative displacement between two equipment items moving toward or away from each other during an earthquake, or for design purposes.](#)

drops (dropper): 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.

elongation demand: [The maximum stretch to which a connection would be subjected during an earthquake.](#)

equivalent terminal force (ETF) method: [Method of accounting for the effects of conductor interaction by applying a force to the terminal of an equipment. The response due to ETF is then added to the seismic response of the unconnected equipment item.](#)

flexibility slack: [The amount of additional slack required in a flexible buswork configuration to avoid its abrupt stiffening when stretched up to its elongation demand. *See also:* elongation demand, slack.](#)

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.

g: Acceleration due to gravity; that is 9.81 m/s^2 . [The unit g is not an IEEE recognized unit of measure, however, the use of the unit is so prevalent in worldwide seismic engineering standards that it has been adopted here.](#)

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.

[moment amplification factor \(MAF\) method:](#) [Method of accounting for the effects of conductor interaction by applying a factor to the seismic response of an unconnected equipment item.](#)

[multi-degree-of-freedom system \(MDOF\):](#) [The idealization of a physical system in which its displaced shape, mass, and its elastic properties are generalized by multiple \(two or more\) mass/spring systems. Energy dissipation loss systems \(a damping mechanism\) may also be incorporated into the model.](#)

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.

pinch effect: [The sudden movement of subconductors that attract each other during a short-circuit, which may result in an increase of tension at the conductors terminals. Depending on the bundle arrangement \(number of spacers, distance between conductors, span\), this generated force in the longitudinal direction of the conductor may be significant](#) ~~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.~~

push-pull 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.

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.~~

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

single-degree-of-freedom system (SDOF system): The idealization of a physical system in which its displaced shape, mass, and 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~~ are generalized by a single mass/spring system. Energy dissipation systems (a damping mechanism) may also be incorporated into the model.

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. *Syn:* conductor slack.

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).**

standalone: The configuration of an equipment item that is not connected by conductors to another equipment. The seismic qualification of equipment is usually performed in the standalone or unconnected configuration.

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

terminal: An electrical connection interface provided with substation electrical equipment to which the user attaches their system rated electrical conductor(s).

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

3.2 Acronyms and abbreviations

AAC	all ~~aluminium~~ <u>aluminum</u> conductor
<u>ACSR</u>	<u>aluminum conductor steel reinforced</u>
BIL	basic impulse level
CQC	complete quadratic combination
<u>ETF</u>	<u>equivalent terminal force</u>
<u>FACTS</u>	<u>flexible alternating current transmission system</u>
<u>HVDC</u>	<u>high voltage direct current</u>
<u>MAF</u>	<u>moment amplification factor</u>
MDOF	multi-degree-of-freedom
<u>RB-FC</u>	<u>rigid bus-flexible connector system</u>
<u>RIV</u>	<u>radio interference voltage</u>

SDOF	single-degree-of-freedom
SRSS	square root of sum of squares
ZPA	zero period acceleration

4. General design process

4.1 Introduction

During an earthquake, electrically interconnected equipment may move relative to one another, stretching and compressing the connection in-between equipment items. This differential (relative) displacement may result in additional forces transmitted from the conductors to the equipment terminal(s). Hence, equipment that would otherwise survive in a standalone configuration may fail. Also, the connection itself creates some degree of interaction between equipment that may adversely modify their connected behavior, as opposed to their standalone behavior. The use of properly designed and installed connections increases the probability that a facility will remain operational before, during, and after an earthquake.

4.2 Main design criteria

This subclause presents an overview of the main mechanical criteria that a seismically designed connection must meet in order to be adequate.

4.2.1 Primary purpose of equipment terminals

The primary purpose of a terminal on substation equipment is to provide an electrical connection interface. In fulfilling this primary function some inherent strength is required to withstand both nominal and exceptional conditions (which includes seismic conditions). Users are reminded that equipment terminals are not meant to be structural supports and that spans and conductor weights should be scrutinized to ensure that loads transmitted to the terminal are minimized.

4.2.2 Permitting differential displacement between equipment

An adequate connection must allow the interconnected equipment to displace without sudden impact due to loss of all available slack. To do so, the maximum differential displacement that can occur during an earthquake between interconnected equipment must be evaluated. This displacement is termed the elongation demand and is detailed in Clause 5.

It has been established for flexible conductors that the amount of required slack must be at least equal to the elongation demand. Due to the stiffness and the inertia of flexible conductors, the elongation demand is the minimum amount of required slack. Depending on the conductor shape and/or flexibility, an additional length, termed here as flexibility slack, is often needed so that the transmitted forces will be within acceptable levels.

Rigid buses with a flexible connector should also allow for the differential displacement to take place without sudden impact. However, the dynamic properties of the coupled system, i.e., the equipment items and the connection, have a strong influence on the differential displacement and may reduce it, as compared to the differential displacement between the standalone equipment items.

4.2.3 Meeting electrical clearances

As with any air-insulated buswork, it is important that a flexible buswork connection maintains the minimum electrical clearances, as specified in such documents as the National Electrical Safety Code® (NESC®) (Accredited Standards Committee C2-2012) [B1] and as discussed in the following subclauses, to help ensure the proper operation and integrity of the facility and safety.⁵

Rigid buses should also meet such clearances at all times. Even though they deform much less than flexible buses, their flexible connectors add flexibility to the assembly and therefore should be checked for the required clearances.

⁵The numbers in brackets correspond to those of the bibliography in Annex A.

However, during a seismic event it has been deemed unrealistic to demand that clearances be met at all times, because the motion of equipment items and conductors may then be large. Therefore, minimum electrical clearances need not apply to seismic load conditions. However, it is recognized that the motion of conductors during a seismic event might be an issue in regard to short-circuit possibilities. It is recommended that appropriate solutions be identified and implemented, if needed. In the same way, it is recognized that interconnected equipment with seismic protective devices, such as base isolation, might lead to large motions of conductors during a seismic event. Furthermore, maintenance of clearances under loads other than seismic may be an issue for flexible buses (that may permit large displacements) and therefore, need to be addressed as needed.

4.2.3.1 Safety clearances

Equipment normally has horizontal electrical safety clearances in addition to the vertical electrical safety clearances. The minimum vertical safety clearance is detailed in Annex B. The horizontal electrical safety clearances are evaluated using a similar methodology. Every equipment configuration must be evaluated for its own unique electrical safety clearances.

4.2.3.2 Phase-to-ground clearances

All buswork should be designed such that phase-to-ground clearances are maintained under loads other than seismic. The phase-to-ground clearance is detailed in Annex B. Every equipment configuration must be evaluated for its own unique phase-to-ground clearance.

4.2.3.3 Phase-to-phase clearances

All buswork should be designed such that phase-to-phase clearances are maintained under loads other than seismic.

4.2.4 Forces from interaction effects at equipment terminals

Even for a flexible connection with sufficient slack or for a rigid bus with a flexible connector, significant forces may be transferred to the terminals due to interaction effects between moving equipment items during an earthquake. Therefore, the equipment, as well as the terminal hardware, should be designed to withstand such forces combined with gravitational loads, in addition to the nominal operation loads that may apply. The loads from interaction effects to be considered are presented in Clause 8 of this recommended practice. Their application to equipment qualification is detailed in IEEE Std 693.

In addition, the following loads may also generate forces at the equipment terminals:

- Wind
- Ice
- Electrical fault condition (short circuit)

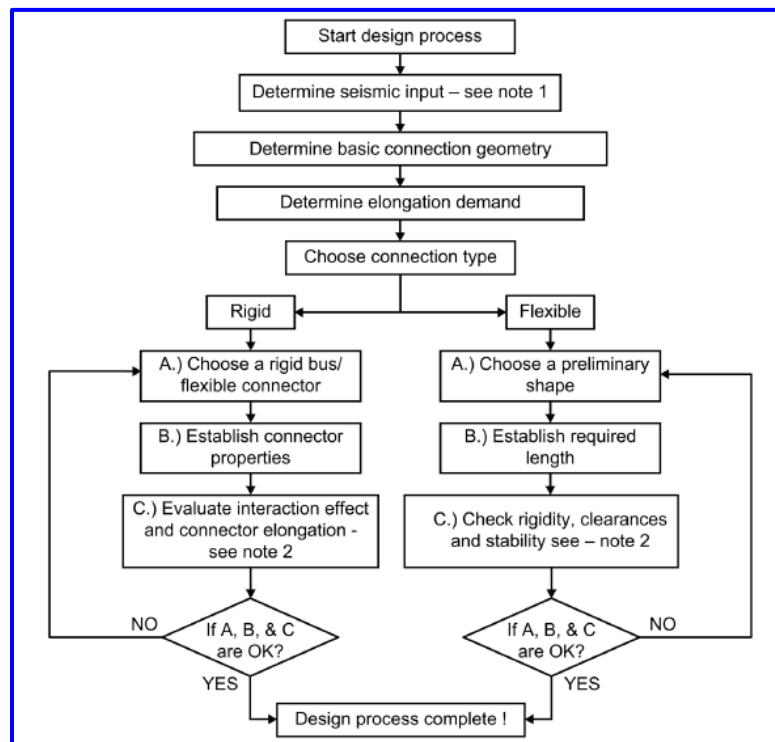
The evaluation of these non-seismic loads is detailed in IEEE Std 605™. These loads are not to be considered concurrent with the terminal loads from interaction effects; the probability of such loads occurring simultaneously during a seismic event being considered negligible in this recommended practice.

4.2.5 Stability and resistance to permanent deformation under operational loads

Flexible or rigid connections must be designed such that their shapes regain their original form after the application of any operational loads that may occur from ice, wind, short circuit, and seismic events; i.e., they should not sustain any permanent deformation. For example, a connection must be designed so that it does not collapse under the application of ice weight. However, it must be recognized that this requirement may be difficult to meet for extreme events having a low probability of occurrence, and it is left to the user to decide up to which level of loading this requirement may apply.

4.3 Design process for seismic connections

Assuming that all electrical parameters (e.g., number and dimensions of conductors, clearance requirements, etc.) have been determined beforehand, the flowchart in Figure 1⁶ shows the mechanical design of connections valid for rigid and flexible connections.



(New)

NOTE 1—The elongation demand based on the standalone equipment displacements (see Clause 5) may be determined either using the IEEE Std 693 spectrum or a site-specific spectrum. The use of a site-specific spectrum may provide a smaller and more realistic elongation demand than the IEEE Std 693 spectrum, as the latter may be much more conservative, especially in the low frequency range.

NOTE 2—Terminal loads and their effects should also be within the maximum values specified in 8.2.

Figure 1—Flowchart for design of seismic connections

⁶Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

5. Equipment movement and elongation demand

5.1 Introduction

Clause 5 describes how to establish the elongation demand from the 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 their associated 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~~ Interconnected structures that differ in their dynamic response may experience large relative displacements. All equipment connections ~~between equipment elements must~~ should be sufficiently ~~long and~~ flexible to permit relative axial ~~and~~ lateral ~~movements~~, and torsional motions. This will avoid ~~impacting~~ impact forces or the transfer of excessive 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~~ and the required electrical clearances result in the need for ~~specifically configured flexible bus conductors~~ specific conductor configurations.

5.2 Seismic input

The movement of ~~a piece~~ an item 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~~ differential displacement between items and thereby choose the appropriate conductor configuration. ~~The calculation and testing methods~~ To determine ~~equipment~~ this movement ~~are described in this clause~~, a seismic qualification level ~~as well as an appropriate design response spectrum must~~ should first be selected ~~before any calculation or testing method is used (see, for example, using the local geotechnical and established risk management factors. Where applicable, users are strongly recommended to select a seismic qualification level established in~~ IEEE Std 693⁴.

5.3 Foundation considerations

For interconnected equipment not on the same foundation (which is most often the case), the expected differential motions between equipment due to foundation motion or soft soils may be considered if deemed important, such as to account for a probable surface fault rupture or soil liquefaction. In such cases, the service of a geotechnical engineer is recommended to estimate the amount of relative displacement that should be conservatively added to the relative displacement as calculated per this standard, to obtain the total elongation demand. It should be noted that the resulting elongation demand may be large and infeasible to counteract in practice without special foundation designs or ground improvement.

5.4 Basic connection geometry

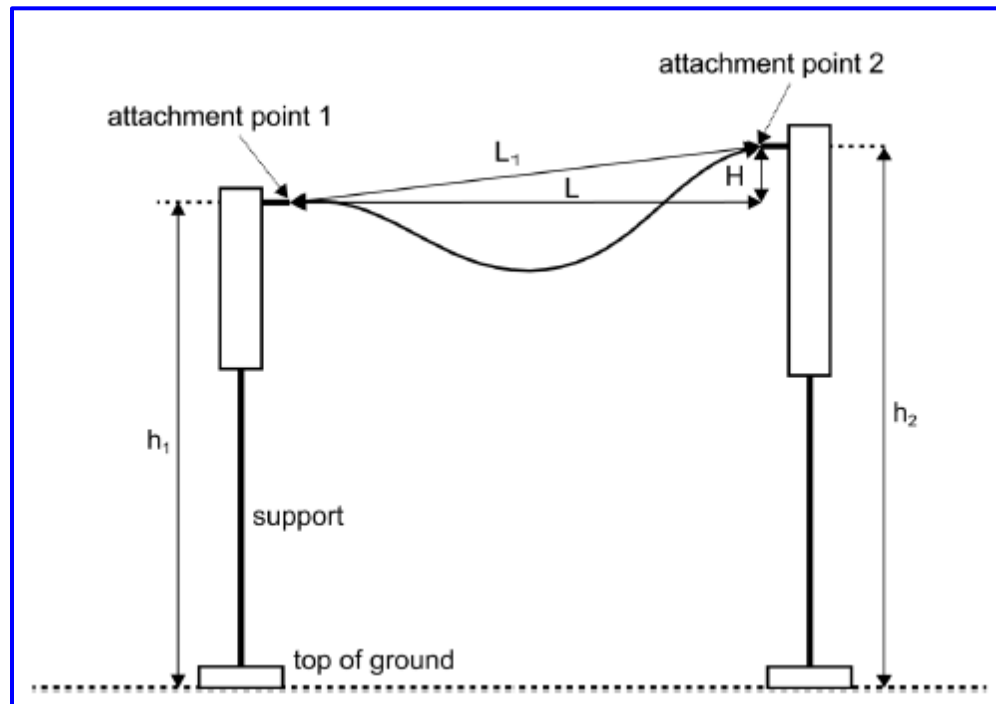
The basic geometry of a connection is shown in Figure 2 and defined by the following:

- The orientation of the equipment terminals
- The horizontal distance between its attachment points: L
- The vertical separation between its attachment points: $H (= h_2 - h_1)$

⁴~~Information on references can be found in Clause 2.~~

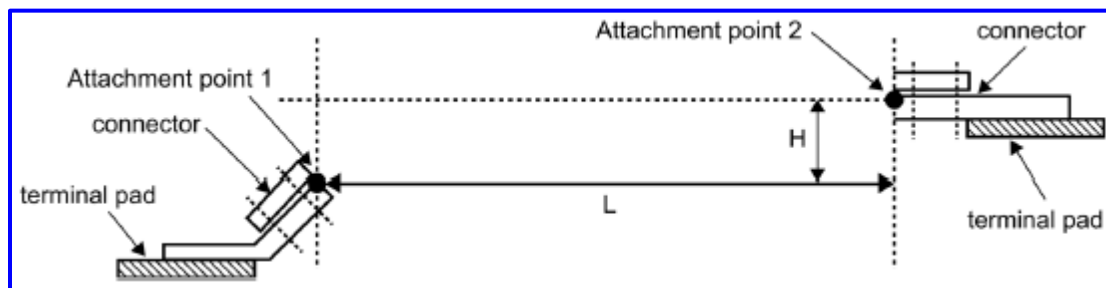
— The straight-line distance between attachment points (chord length): L_1

Figure 3 illustrates the concept of an attachment point for a flexible conductor. The attachment point is defined as the point at which the conductor is free to rotate relative to the attachment lug.



(New)

Figure 2— Basic connection geometry



(New)

Figure 3— Determination of basic geometry from connector extremities

5.5 Determination of the elongation demand

5.5.1 ~~Calculation methods to evaluate~~ Standalone versus connected equipment displacement

Due to the mass and stiffness of the conductor, and the resulting interaction with the connected equipment, the displacements of equipment items in their connected configuration cannot be evaluated in a simple fashion. Sophisticated methods, such as the nonlinear finite element method or other analytical/numerical methods are required to obtain results. Therefore, it is easier and preferable for design purposes to use the equipment displacements in their standalone configurations, i.e., without conductors connected. Moreover, the standalone displacements are more readily available from equipment seismic qualification tests or analytical qualification, which are usually conducted on the standalone equipment.

The standalone differential displacement is usually a conservative estimate of the differential displacement between connected equipment in cases of flexible connections (Dastous, Filiatrault, and Pierre [B9]) and, therefore an estimation of the elongation demand can be obtained from it. For equipment interconnected by a rigid bus/flexible connector system, it has been shown that depending on the connector properties, the response of the higher-frequency equipment in a pair can be amplified, while the response of the lower-frequency item is usually de-amplified. However, the net result is that the differential displacement between the interconnected items is most often smaller than the standalone differential displacement (Song, Der Kiureghian, and Sackman, "Seismic interaction in electrical substation equipment..." [B27]) Therefore, using the standalone differential displacements of equipment items is normally a conservative estimate of the elongation demand for rigid bus/ flexible connector systems.

~~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~~

5.5.2 Required displacement components

Because the nature of earthquake excitation is three dimensional, the standalone displacement input to establish the elongation demand should theoretically comprise two horizontal orthogonal components and a vertical one. However, as demonstrated in Dastous and Der Kiureghian, "Application Guide for the Design of Flexible and Rigid Bus Connections between Substation Equipment Subjected to Earthquakes," the elongation demand is generally well approximated using only the longitudinal horizontal differential displacement, which is the maximum relative displacement in the horizontal direction between two equipment items. The elongation demand, denoted by e_o , is therefore given as follows in Equation (1):

$$e_o = D_L \quad (1)$$

(New)

where

D_L is the maximum differential displacement between two equipment items in the longitudinal horizontal direction

The determination of this value from the standalone displacement of each item is described in the following clauses.

5.5.3 Determination of standalone displacement

Whenever the maximum displacement is available from a seismic qualification report, it is recommended to use it directly as long as the qualification has been done analytically/numerically (usually with the finite element method).

The displacement of the standalone equipment may be determined by any of the following methods:

- Generalized single-degree-of-freedom method (simplified calculation)
- Dynamic analysis
- Evaluation displacement through testing (test derived displacement)

[Each of these methods are detailed in the following subclauses.](#)

[5.5.3.1 Generalized single-degree-of-freedom method](#)

~~4.1.1 Recommended method for candlestick and frame type equipment~~

[When the information on the displacement is missing from the qualification report](#), the use of a design response spectrum along with the generalized single-degree-of-freedom (SDOF) method ~~is recommended~~ [may be applicable](#) to obtain the equipment displacement for design purposes. [This method and the derivation of some equations following are detailed in Annex C.](#) ~~This method assumes that the equipment oscillates principally in one vibration mode shape as shown in Figure C-2.~~ The maximum displacement $x_{\max}$ at the attachment point for such a system using the response spectrum method is given as follows in Equation (2 ~~4~~):

~~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).~~

$$x_{\max} = \alpha_1 \times S_d(f, \zeta) = \alpha_1 \times \frac{S_a(f, \zeta)}{(2 \times \pi \times f)^2} \quad (2)$$

[\(New\)](#)

[where](#)

[\$\alpha_1\$ is the modal-participation factor associated with the frequency \$f\$ and damping \$\zeta\$ of the mode shape \$\psi\(y\)\$](#)

[\$S_d\(f, \zeta\)\$ is the spectral displacement at frequency \$f\$ and damping \$\zeta\$](#)

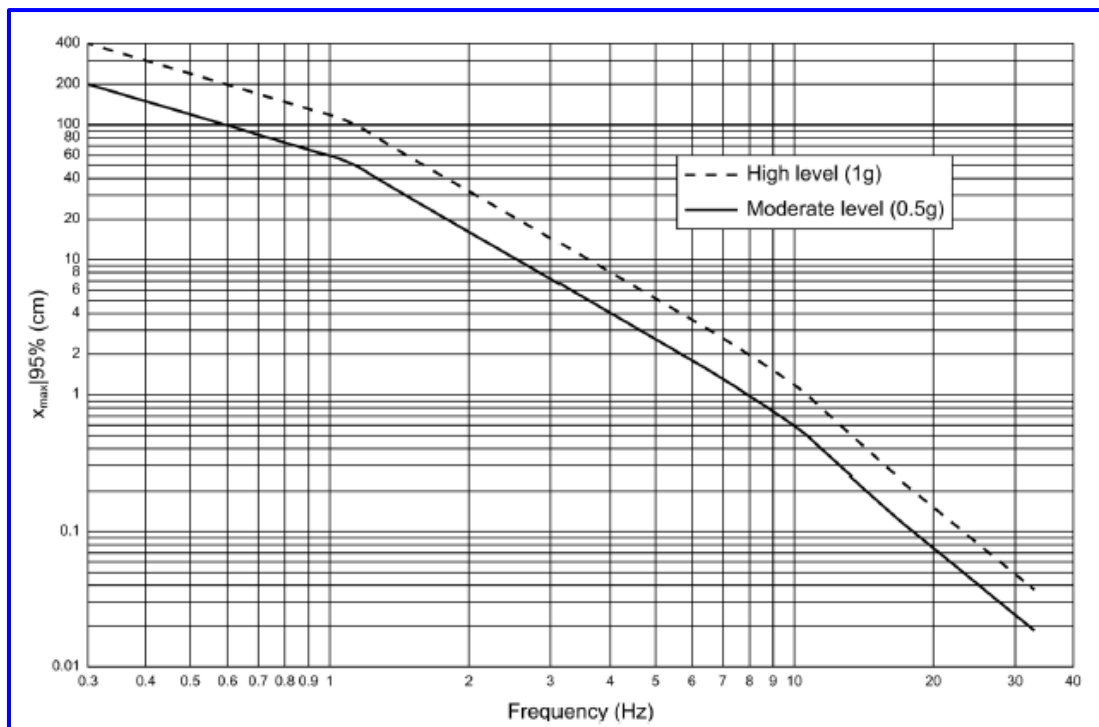
[\$S_a\(f, \zeta\)\$ is the spectral acceleration at frequency \$f\$ and damping \$\zeta\$](#)

[Equation \(3\) provides an upper-bound value on the maximum displacement for 95% of a surveyed range of various equipment types \(see Annex C\) as follows:](#)

$$x_{\max}|_{95\%} = 1.62 \times S_d(f, \zeta) = 1.62 \times \frac{S_a(f, \zeta)}{(2\pi f)^2} \quad (3)$$

(New)

It is noted that the above 95% upper-bound estimate assumes no uncertainty in the determination of spectral displacement (S_d). It is recommended that in the absence of data other than the fundamental frequency of the equipment and its damping, this equation be used to obtain a conservative estimate of the equipment maximum displacement for connection design. Based on this equation, Figure 4 provides upper-bound values for the equipment displacement as a function of the equipment fundamental frequency for 2% damping, according to the spectral displacements from the IEEE Std 693 required response spectra for the moderate- and high-performance levels. Table 1 provides values from this graph at selected frequencies.



(New)

Figure 4—Upper-bound displacement according to IEEE Std 693 performance level required spectra for 2% damping

**Table 1—Upper-bound displacement for IEEE Std 693 performance level
required spectra at 2% damping**

f (Hz)	$x_{\max} _{95\%}$ IEEE 693 moderate performance level (0.5 g) (cm)	$x_{\max} _{95\%}$ IEEE 693 high-performance level (1 g) (cm)
0.5	120	240
1	60	120
2	16	32
3	8	15
5	2.6	5.2
10	0.6	1.2
16.7	0.13	0.25
33	0.019	0.037

(New)

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

(Deleted)

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):

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

(Deleted)

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):

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

(Deleted)

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):

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

(Deleted)

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.~~

5.5.3.1.1 Equipment types not applicable to generalized single-degree-of-freedom method

At least three types of equipment generally cannot be adequately represented by the generalized SDOF method: equipment with bushings, equipment supported on complex framed or lattice/truss structures, and equipment mounted on seismic protective devices. Equipment items subjected to soil-structure interaction are also not covered by this method and should be studied accordingly.

5.5.3.1.1.1 Equipment with bushings

The generalized SDOF method is not applicable to equipment with bushings, such as dead tank circuit breakers, power transformers, or oil filled reactors, either because the bushing is not moving at the frequency of the main body of the equipment or that the bushing attachment is such that the inherent generalizations of the method are not appropriate.

An estimate can be made by performing the following:

- a) Evaluating the fundamental frequency and modal participation factor of the bushing alone on a rigid base and obtaining an intermediate displacement using the generalized SDOF method.
- b) Multiplying this intermediate value of displacement by a factor of 2 to get the final displacement.

The factor of 2 has been established empirically to account for the amplification of bushings atop tanks and may be revised in the future as it does not take into account the possible effect of rotation at the base of the bushing due to the interaction with the transformer cover (refer to IEEE Std 693).

5.5.3.1.1.2 Equipment that are supported on complex framed or lattice/truss structures

The generalized SDOF method is not applicable to equipment supported on complex framed or lattice/truss structures due to the complex mode shapes of the structure. An example of such equipment are three-phased disconnect switches mounted on a single support.

5.5.3.1.1.3 Equipment mounted on seismic protective devices

The generalized SDOF method is not applicable to equipment mounted on seismic protective devices, as their motion is largely conditioned by the dynamics of such devices, whose behavior may be complex and varying with the expected amplitude of motion. They should therefore be the subject of a separate study where the seismic behavior of seismic protective devices is taken into account, including, if needed, the effect of the equipment interconnections.

5.5.3.2 Dynamic analysis

An alternative and more precise (relative to the generalized SDOF method) method for determining equipment displacement (and its support) is via a dynamic analysis [a multi-degree-of-freedom method (MDOF)]. Recommendations for applicability, modeling, and sufficiency criteria for substation equipment are given in IEEE Std 693.

The user is cautioned that if dynamic analysis is used to obtain deflections of a type of equipment that would not be qualified by dynamic analysis within IEEE Std 693, then increased levels of scrutiny may be required with regards to modeling parameters and techniques.

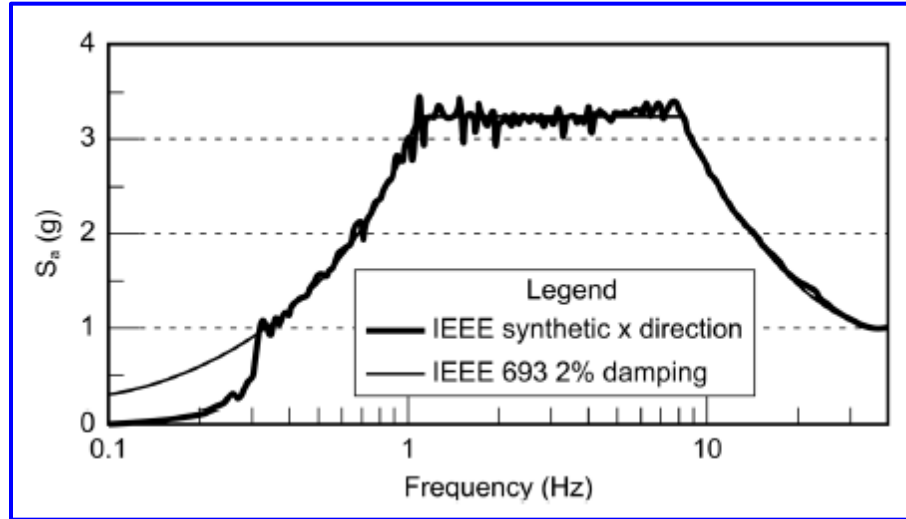
5.5.3.3 Displacement through testing

Shake table testing can be used to determine the equipment displacement when the equipment falls within the physical size and load limits of the table. Recommendations for applicability and testing for substation equipment is given in IEEE Std 693.

The standalone displacement can be obtained if measured directly using an appropriate displacement sensor. Recovery of the displacement from double integration of the measured acceleration at the top of the equipment (through an accelerometer) is also a possibility, but caution should be used when evaluating the data in case of the obtained displacement being seriously biased.

5.5.3.3.1 Test response spectrum corrections

The displacements directly measured in testing may not always correspond to the requirements of the required response spectra due to the nature of the test response spectra (e.g., the test response accelerations of the table may not match or envelope the required response spectrum accelerations at all frequencies). This is due to the limitations of shake table controls and/or the time history signal itself, whereby the spectrum cannot precisely match the required response spectrum at all frequencies. Figure 5 is an example that illustrates the difference in peak accelerations between the required response spectrum and the test response spectrum.



(New)

Figure 5— Difference between required response spectrum and time history input spectrum

At the fundamental frequency, the test response acceleration may either indicate over testing or under testing. In general, over testing is ignored as the goal of the test response spectra is to envelope the required response spectra. However, it is cautioned that significant over testing may skew displacement data unrealistically. If the test response spectrum is lower than the required response spectrum at or close to the fundamental frequency of the equipment, it is advisable to correct the measured displacement to match the required response spectrum as follows:

From the test response spectrum, obtain the spectral displacement at the fundamental frequency of the equipment, S_d TRS:

- a) Obtain an approximation of the modal participation using Equation (4) as follows:

$$\alpha_1 \cong \frac{x_{\max, \text{measured}}}{S_{d, \text{TRS}}} \quad (4)$$

(New)

- b) Obtain the corrected displacement corresponding to the required response spectrum using Equation (5) as follows:

$$x_{\max} = \alpha_1 \times S_d \quad (5)$$

(New)

where

S_d is the spectral displacement from the required response spectrum at the fundamental frequency of the equipment

This approach is valid inasmuch as the actual damping of the first vibration mode is close to the damping assumed in the evaluation of the test response spectrum. Otherwise, the modal participation factor obtained could be biased. Furthermore, there is an inherent assumption that the equipment behaves as an idealized SDOF system.

5.5.4 Combination of individual displacements to obtain elongation demand

In order to evaluate the elongation demand, the standalone displacements of a pair of interconnected equipment items must be combined in order to obtain the maximum differential displacement D_L between them. In what follows $x_{\max 1}$ and $x_{\max 2}$ denote the standalone displacements in the horizontal longitudinal direction for equipment items 1 and 2.

The following two methods are available to obtain the differential displacement:

- a) The SRSS combination is shown below in Equation (6):

$$D_L = \sqrt{x_{\max 1}^2 + x_{\max 2}^2} \quad (6)$$

(New)

- b) An adaptation of the CQC combination rule (Der Kiureghian, Sackman, and Hong, "Interaction in interconnected electrical substation equipment..." [B15]) is shown in Equation (7):

where

ρ_{12} is the correlation coefficient between $x_{\max_1}$ and $x_{\max_2}$

$$\rho_{12} = 8\zeta^2 (1+r)r^{3/2} / \left[(1-r^2)^2 + 4\zeta^2 r(1+r)^2 \right] \quad (8)$$

(New)

where

r is the ratio of the fundamental frequencies of the standalone equipment items: f_1/f_2

Note that the numbering of the equipment items is immaterial. The same numerical result is obtained for ρ_{12} when r is replaced by $1/r$ (i.e., for f_2/f_1 instead) and ζ is the critical damping ratio, which is assumed to be the same for the two equipment items.

It is to be noted that when the frequencies of interconnected equipment of light damping are separated by more than 20% relative to each other, the CQC and SRSS methods yield basically identical results, because the correlation coefficient ρ_{12} is then nearly zero.

Because the CQC and SRSS methods are statistical methods, they provide only an average value of the maximum differential displacement over an ensemble of ground motions and may, therefore, underestimate the true differential displacement for a given ground motion. To counteract this possibility, a factor of 1.25 was empirically obtained in (Dastous, "Guidelines for seismic design..." [B7]) to cover 95% of the true differential displacement using the SRSS method. Therefore, the differential displacement using the SRSS method with displacements obtained from an analysis using the design earthquake ground motions should be computed as follows in Equation (9):

$$e_o = 1.25 \times \sqrt{x_{\max_1}^2 + x_{\max_2}^2} \quad (9)$$

(New)

Such a factor has not been determined yet for the CQC method, but it is recommended using the same when this method is applied as follows in Equation (10):

$$e_o = 1.25 \times \sqrt{x_{\max_1}^2 - 2 \times \rho_{12} \times x_{\max_1} \times x_{\max_2} + x_{\max_2}^2} \quad (10)$$

(New)

The CQC method is more precise and will be particularly useful when expected displacements are large and fundamental frequencies of interconnected equipment are closer than 20%, so that a reduced and more realistic value of the demand will then be obtained. It is noted that when the two equipment items have theoretically identical frequencies and damping ratios, the CQC formulation correctly predicts zero differential displacement, as opposed to the SRSS combination method. However, in practice similar equipment items will rarely be of identical frequencies and damping ratios, and will therefore experience some degree of interaction. Therefore, for identical connected items, it is recommended to establish a minimum relative displacement value as shown in Equation (11):

$$D_L = \text{maximum value of } (1.25 \times x_{\max_1}, 1.25 \times x_{\max_2}) \quad (11)$$

(New)

For demand displacement estimation, at least two alternative approaches are available as described below. The utility should decide what level of risk it wishes to accept. The approaches are as follows:

- a) Utility uses site-specific spectra for the installation site having the desired exceedance probability to estimate the displacement demand. These spectra may be developed from national hazard maps or site-specific seismic studies. It is recommended that the site-specific spectrum be set at not less than 10% probability of exceedance in 50 years.
- b) Utility uses displacement from seismic qualification report of equipment at either the design level or performance level. In theory, this approach results in a balanced conductor/equipment design that more fully utilizes the equipment seismic withstand capability. The displacement demand using performance level seismic input should be expected to be high.

6. Design of flexible conductor

6.1 Advantages and limitations of flexible connection

Flexible connections are often used to interconnect substation equipment due to the following advantages:

- When properly designed, they provide sufficient flexibility between equipment, especially in the case of large expected differential displacements, thus minimizing transfer of forces.
- They naturally provide sufficient provision for thermal expansion movements arising from heating of the conductors.
- More than one conductor can be used in a bundle to allow the passage of high current density.
- They are relatively easy to install.

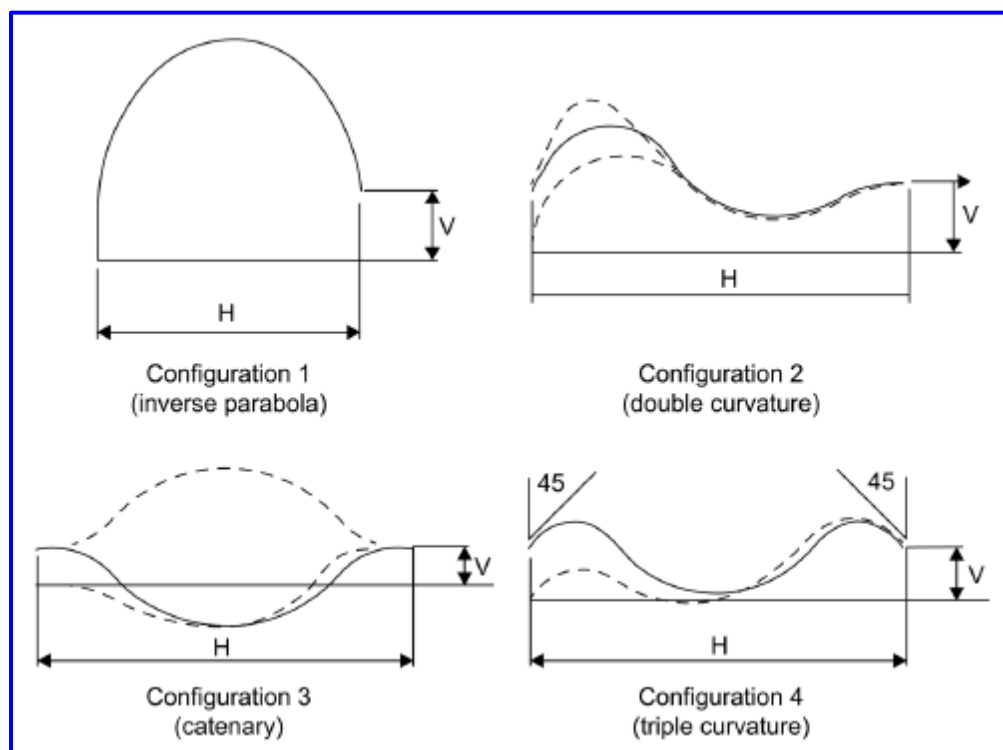
Flexible connections have the following limitations:

- For short spans (less than 1 m to 2 m, depending on the conductor size), they can be relatively rigid due to their inherent axial and bending stiffness.
- Due to their flexibility, they sag and thus may lead to clearance violations.
- Due to the two previous limitations, and depending on shape and rigidity, they can be used only for span lengths between some minimum and maximum lengths.
- They may be subjected to large lateral movements under short circuit and wind conditions, thus allowing the possibility of compromising phase-to-phase clearances during such events.

6.2 Available shapes, required conductor length, and qualitative behavior

6.2.1 Studied shapes

As a result of analysis and actual physical tests with AAC conductors aimed at establishing the flexibility characteristics, four basic configurations and slight variations of each (such as attachment at other angles) were found to be most suitable. These basic configurations are shown in Figure 6. These configurations provide the necessary conductor stretch and permit compression without applying excessive force to the bus and equipment terminations when their length is appropriately determined.



(New)

Figure 6— Basic flexible conductor configurations

All presented configurations maintain their assumed shapes within a specified span interval, outside of which the shapes may become unstable (Dastous and Paquin [B10]). The recommended use, advantages, and limitations of each configuration are summarized in Table 2.

Table 2—Summary of basic flexible configurations characteristics

Configuration	Recommended use for	Advantages	Limitations
1: Inverse parabola	—Large required slack —Clearance problems or inadequate slack with other shapes (Length should be defined such that it corresponds to a half circle when both ends are at the same height).	—Most flexible of all configurations when designed as a half circle, for the same elongation demand —Automatically meets clearances^a —Permits elongation without abrupt change of stiffness over a large range	—Limited in maximum span as may collapse under weight or climatic loading —Recommended to use in a bundle of two with spacers to provide lateral stability to wind —Requires 90° connector hardware

(New)

Table 2—Summary of basic flexible configurations characteristics

(continued)

Configuration	Recommended use for	Advantages	Limitations
2: Double curvature	—Clearance problems with catenary —One end must be attached horizontally	—May need to be pre-shaped for smaller spans —May satisfy clearances not possible with catenary	—May lead to large sags for longer spans —Requires 45° or 90° connector hardware
3: Catenary	—Smaller elongation demand	—Simple —Most flexible of all configurations for the same ratio of elongation demand over available slack (however the inverse parabola is usually more flexible when formed as a half circle as prescribed in this guide) —Conventional installation with conventional hardware —Easy acceptance by field personnel as business as usual	—May lead to abrupt change of stiffness if all slack is used up —May lead to clearance violations if a large slack is required
4: Triple curvature	—Clearance problems with catenary —Large spans where inverse parabola not suitable	—May satisfy clearances not possible with catenary with same required slack —Takes conductor away from phase to ground radius clearance	—Limited in minimum span as may become too stiff —Requires 45° connector hardware —Not recommended with 90° hardware as may lead to bird caging

(New)

^aIn this table, clearances are used loosely to refer to phase to ground and the minimum safety clearance from ground, for equipment interconnected horizontally. The discussion with respect to clearances in this table may not apply to other types of arrangements, such as vertical phase-to-phase arrangement.

6.2.2 Other conductors and shapes

In addition to AAC conductors that are commonly used for interconnecting high voltage equipment, other flexible conductors may be used, such as ASCR and copper conductors. In the same way, other shapes than those described may be used; see Dastous and Der Kiureghian, “Application Guide for the Design of Flexible and Rigid Bus Connections between Substation Equipment Subjected to Earthquakes” in Clause 2 for examples. The methodology described in the following subclauses is applicable to these other types and shapes. Commonly used vertical drops have not been studied yet and are, therefore, not covered by the present standard; however, it is recommended that these should be designed with sufficient slack to allow for the expected relative displacement between their interconnection points.

6.2.3 Required conductor length, general requirements

Although the seismically induced equipment movements will initially be in the same direction, later movements may oppose each other, depending on the natural frequency of each piece of equipment. It is, therefore, necessary to choose a conductor configuration that will provide the necessary flexibility, in both the compression and tension directions, to accommodate the expected maximum differential displacement. Because configurations where the amount of available slack equals the elongation demand will become abruptly stiff when stretched close to that limit, an additional length is necessary so that the configuration provides the required flexibility for the entire range of expected motions.

The required conductor length for a flexible conductor is expressed as follows in Equation (12):

$$L_0 = L_1 + e_o + L_2 \quad (12)$$

(New)

where

L_0 is the necessary conductor length

L_1 is the straight-line distance between the attachment points

e_o is the elongation demand

L_2 is the flexibility slack

The flexibility slack is an additional provision for the conductor shape under consideration to avoid abrupt stiffening when stretched close to the elongation demand and to ensure that the loads transferred to the terminals are within equipment and terminal pad connection capacities. The determination of L_2 is detailed in Dastous and Der Kiureghian, "Application Guide for the Design of Flexible and Rigid Bus Connections between Substation Equipment Subjected to Earthquakes," and requires a flexibility analysis of the configuration under study. A calculation example to determine flexibility slack using the finite-element method is presented in Annex H. However in the absence of such study, the following values of L_2 are recommended as minimal for AAC for spans over 3 m:

- Configuration #1 (inverse parabola): 0 cm
- Configuration #2 (double curvature): 5 cm
- Configuration #3 (catenary): 0 cm
- Configuration #4 (triple curvature): 10 cm

These values were obtained by one utility for 1796 and 4000 kcmil AAC, and should be adequate for conductors of similar or smaller bending stiffness (see Table G.1 in Annex G for bending stiffness values of commonly used conductors). It is likely that larger values of L_2 might be required for stiffer conductors (with larger bending stiffness), such as steel reinforced aluminum conductors and conductors made of trapezoidal wires.

Also, for each conductor configuration, a minimum span exists below which the conductor becomes increasingly more rigid and, therefore, lacks the necessary flexibility to accommodate the expected differential displacement. Depending on the required amount of slack, some configurations may also sag in a way that will violate the clearance requirements. An extensive discussion of these topics is also presented in Dastous and Der Kiureghian, "Application Guide for the Design of Flexible and Rigid Bus Connections between Substation Equipment Subjected to Earthquakes."

Therefore, in addition to determining L_2 , the user must determine the following:

- The minimum span below which the configuration becomes too rigid
- The maximum span at which the configured shape will collapse under its own weight or under the additional effects of climatic loading, such as wind and ice whenever this applies
- The satisfaction of the clearance requirements

The methods to check these requirements are discussed for some configurations in the following subclauses.

6.2.3.1 Inverse parabola conductor length

Regarding configuration 1, the inverse parabola, it is recommended to form it as a half circle, whenever possible, because it will then be more stable to vertical loads, such as its own weight and additional ice loading if present. In terms of the parameters defined in Figure 6, the recommended length of the conductor in this configuration is as follows in Equation (13):