



IEEE Recommended Practice for Seismic Design of Substations

IEEE Power Engineering Society

Sponsored by the
Substations Committee

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IEEE Power Engineering Society

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Abstract: Seismic design recommendations for substations, including qualification of each equipment type, are discussed. Design recommendations consist of seismic criteria, qualification methods and levels, structural capacities, performance requirements for equipment operation, installation methods, and documentation.

Keywords: anchorage, conductor, electrical equipment, damping, dynamic analysis, loads, projected performance, required response spectrum, seismic qualification, shake table, sine beat, static coefficient analysis, support structure, suspended equipment, time history

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Introduction

This introduction is not part of IEEE Std 693-2005, IEEE Recommended Practice for Seismic Design of Substations.

This revision of IEEE Std 693-1997 was developed as a recommended practice for the seismic design of substations. This recommended practice emphasizes the qualification of electrical equipment. Nuclear Class 1E equipment is not covered by this recommended practice, but it is covered by IEEE Std 344™.

This recommended practice is intended to establish standard methods of providing and validating the seismic withstand capability of electrical substation equipment. It provides detailed test and analysis methods for each type of major equipment or component found in electrical substations.

This recommended practice is intended to assist the substation user or operator in providing substation equipment that will have a high probability of withstanding seismic events to predefined ground acceleration levels. It establishes standard methods of verifying seismic withstand capability, which gives the substation designer the ability to select equipment from various manufacturers, knowing that the seismic withstand rating of each manufacturer's equipment is an equivalent measure.

This recommended practice is also intended to guide the manufacturers of power equipment in the seismic design and in demonstrating and documenting the seismic withstand capability of their product in a form that can be universally accepted.

Although most damaging seismic activity occurs in limited areas, many additional areas could experience an earthquake with forces capable of causing great damage. This recommended practice should be used in all areas that may experience earthquakes.

It is the hope of those who worked on the development of this recommended practice that these standard methods of verifying seismic withstand capability will lead to better earthquake performance and to lower qualification costs.

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IEEE Recommended Practice for Seismic Design of Substations

1. Overview

1.1 General

This recommended practice provides minimum requirements for the seismic design of substations, excluding Class 1E equipment for nuclear power generation stations. Seismic qualification of electrical equipment and its support is emphasized.

1.2 Scope

The recommended practice contains recommendations for the seismic design of substation buildings, structures, and equipment.

1.3 Purpose

This recommended practice is for new substations and planned additions or improvements to existing substations. It is not intended that existing substations must be retrofitted to these recommended practices.

For instruction on how to include this recommended practice in specifications, refer to 5.2.

IEEE Std 693 is designed as an integrated set of requirements for the seismic qualification of electrical power equipment. Users should use IEEE Std 693 as a whole. Do not modify or remove any requirement, except as allowed herein.

If any part of this recommended practice is removed, not met, or reduced, then neither the user nor the manufacturer may claim the equipment is in compliance with IEEE Std 693 and should not attach the seismic identification plate to the equipment. The user is strongly urged not to modify any of the requirements herein, including increasing or adding to the requirements.

The most important goal of this recommended practice is to provide a single standard set of design recommendations for seismic qualification of each equipment type. Design recommendations consist of seismic criteria, qualification methods and levels, structural capacities, performance requirements for equipment operation, installation methods, and documentation. The intent of a uniform and consistent seismic qualification procedure is to reduce the cost for qualification of substation equipment, because the

manufacturers can qualify their equipment once for each qualification level and eliminate specialized testing. It should also improve earthquake performance by establishing clear performance criteria that take into account the dynamic characteristics of substation equipment.

Three qualification levels are defined. They are low, moderate, and high. The user should determine the desired qualification level when purchasing the equipment. See Clause 8.

This recommended practice is divided into 8 Clauses (Clause 1 through Clause 8) and 22 Annexes (Annex A through Annex V). Clauses contain general seismic design requirements. Annex C through Annex P contain equipment-specific seismic design requirements and are located after the clauses. If the type of equipment to be qualified is not specifically addressed in Annex C through Annex P, the seismic design requirements of Annex B may be used, if applicable.

Annexes are titled normative or informative. Normative annexes are official parts of this recommended practice. Informative annexes include information only and are not an official part of this recommended practice.

The following references are recommended for seismic design of substation structures, foundations, and anchorage¹:

- *Buildings*: International Building Code (IBC), Mexican Code (MDOC/CFE), Uniform Building Code (UBC), or National Building Code of Canada (NBCC).
- *Anchorage design*: American Society of Civil Engineers (ASCE) Substation Structure Design Guide.

NOTE—Anchorage design requirements are found in the ASCE Substation Structure Design Guide. Anchorage requirements for equipment qualification are provided in this recommended practice.²

- *Foundation Design*: International Building Code (IBC), Uniform Building Code (UBC), Mexican Code MDOC/CFE, NBCC, or Canadian Foundation Engineering Manual [B6].³
- *Structures*: Strain Bus Structures, A-Frames, racks, box structures, rigid bus supports, and all other such substation structures. ASCE Substation Structure Design Guide.

The ASCE “Guide to Improved Earthquake Performance of Electric Power Systems,” ASCE Manual 96, is a guide that illustrates many methods of installing substation equipment and discusses their advantages. This guide will provide useful information for evaluating existing installation details for good earthquake performance.

The ASCE “Guide to Reliable Emergency Power for Lifelines and Critical Applications,” ASCE Manual, is a guide that discusses methods of selecting, installing, maintaining, and testing emergency power systems. It illustrates many methods of installation of emergency power equipment and discusses their advantages. This guide provides useful information for evaluating existing installation details for good earthquake performance.

1.4 How to use this recommended practice

Follow the flow chart Figure 1, and read the clauses and annexes noted.

¹ Information on references can be found in Clause 2.

² Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the recommended practice.

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

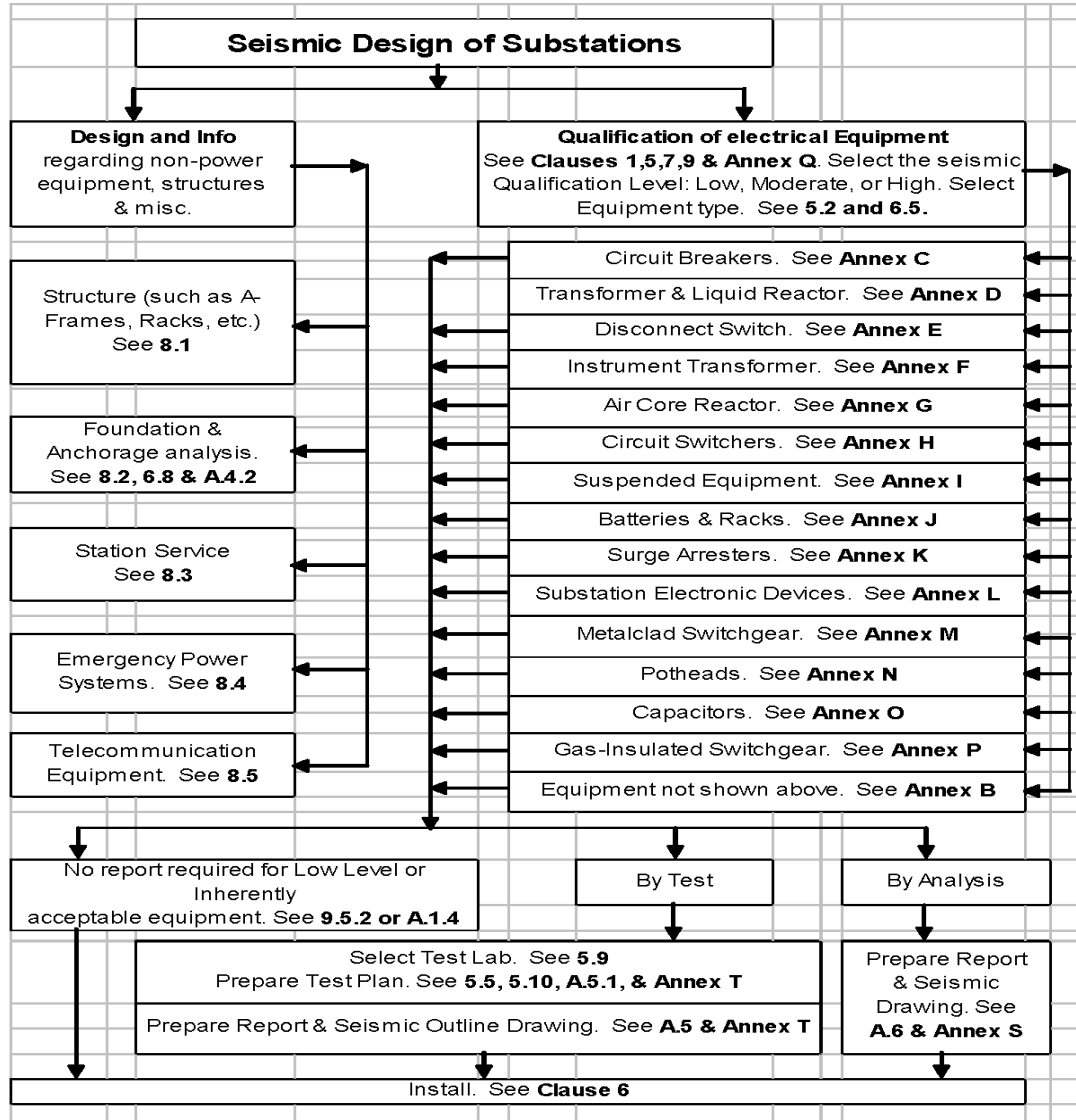


Figure 1—Using this recommended practice

1.5 Acceptance of previously qualified electrical equipment

Existing qualifications, including qualifications in conformance with other standards, may be acceptable and need not be repeated, provided the specialist who signs the report and the user agree in writing that the existing qualification adequately meets or exceeds the requirements of this recommended practice. However, the existing qualification report shall be augmented with a detailed explanation of the adequacy of the equipment to meet the requirements of this recommended practice. Changes to the report will be identified.

“Adequately” means that if the qualification was repeated using the requirements of this current recommended practice, in the opinion of the user and the specialist and based on the data in the existing qualification report, the equipment would meet or exceed the acceptance criteria of this current recommended practice.

Part of an existing qualification may be acceptable and need not be repeated provided the requirements stated here are met.

1.5.1 Acceptance of previous versions of IEEE Std 693

Equipment qualified to IEEE Std 693-1997 or later versions will be deemed to be in conformance with the current version of IEEE Std 693, and the qualification need not be repeated, unless a previous qualification test or analysis method is explicitly excluded by the current version. The qualification will be acceptable once the explicitly excluded part is done according to the current recommended practice and found acceptable according to A.5 or A.6. Additional documentation will be required if the current version requires additional documentation.

For a manufacturer to use a qualification from a previous edition of this recommended practice to qualify the equipment to the current version of this recommended practice, a supplemental report must be appended to the old qualification report explaining how sections excluded in the new version of the recommended practice will meet the adequacy criteria given in 1.5. The identification tag for the equipment supplied to that user can state that the equipment has been qualified to the current IEEE Std 693.

1.6 Earthquakes and substations

Earthquakes are caused by the sudden rupture of a geologic fault. Shock waves radiate from the fault fracture zone and arrive at the earth's surface as a complex multifrequency vibratory ground motion, having both horizontal and vertical components.

The response of buildings and structures to earthquake ground motion depends on factors, including their configuration, strength of construction, ductility, and their dynamic properties. Lightly damped structures having one or more natural modes of oscillation within the frequency band of ground excitation can experience considerable amplification of the forces, component stresses, and deflections.

Mechanisms that absorb energy in a structure, in response to its deformation, provide damping.

If two or more structures or equipment are linked together, such as through a conductor, they may interact with one another producing a modified response and interaction loads. Even when the link is sufficiently flexible to accommodate the relative displacement, forces may be transferred between the structures or equipment including dynamic effects. Therefore, particular care should be given to that design aspect so that the level of forces is minimized. However, provisions should also be taken in equipment design to take such forces into account. (See 5.9 and IEEE Std 1527-2006 [B23].) In particular, many items of substation equipment, for electrical reasons, are highly interconnected and often contain brittle, relatively low strength (compared with, e.g., steels), and/or low damping materials (e.g., porcelain). The conductors are often installed with very small slack. In these cases, after only a little relative motion occurs, damaging nonlinear interaction, including impacting between connected equipment will begin. Thus, items of substation equipment whose natural frequencies lie in the normal frequency range of earthquake ground motion are particularly vulnerable to damage by seismic events.

1.7 Design and construction

It is recognized that a substation may not always be designed and constructed solely by a utility using its in-house expertise. A substation may be designed as a "turnkey contract." In between these two extremes lie many hybrid possibilities, including the involvement of consultants or architect-engineers as third parties.

After the substation is complete, the user should have procedures that ensure that the installed configuration and any subsequent modification or expansion of the substation is subject to proper review to verify that the intentions of this recommended practice are preserved.

1.8 The equipment at risk

The satisfactory operation of a substation during and after an earthquake depends on the survival, without malfunction, of many diverse types of equipment. Not only must individual equipment be properly engineered, but also their anchorage, services, and interconnections must be well designed. For critical areas, it may be prudent to have back-up facilities and protected spares in the event of failure due to earthquake-causing ground motion.

1.9 Mechanical loads

Seismic loads (horizontal and vertical, acting simultaneously) are superimposed on other preexisting loads or other loads that may occur due to the earthquake.

Preexisting loads and loads other than seismic loads include the following:

- a) Dead weight (gravitational load)
- b) Assembly loads, either deliberate (i.e., by design) or accidental (arising from manufacturing tolerances and assembly misalignment)
- c) Line pull (and other interconnections)
- d) Wind, snow, and ice loads
- e) Internal pressure (or vacuum)
- f) Thermal affects (stresses due to thermal expansion, plus influence on strength properties of materials over the full temperature range from minimum ambient to maximum ambient plus temperature rise due to load heating effects)
- g) Electromagnetic forces due to normal current and short-circuit current
- h) Operating mechanism forces and reactions to open and closed contacts

Of course, it is not reasonable to expect all of these loads to occur simultaneously.

2. Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ADM 1-516166, Aluminum Association, Aluminum Design Manual, Specification and Guidelines for Aluminum Structures, 2000 Edition.⁴

AISC Manual of Steel Construction, Load Resistance Factor Design (LRFD) Third Edition, 2003.⁵

AISC M016-1989, Manual of Steel Construction, ASD - 9th Edition, Including updates, which exclude the 1/3 increase of allowable stresses.

ANSI C37.06-2000, Switchgear—AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis —Preferred Ratings and Related Required Capabilities.⁶

⁴ADM publications are available from the Aluminum Association, 1525 Wilson Boulevard, Suite 600, Arlington, VA 22209, USA (<http://www.aluminum.org>).

⁵AISC publications are available from the American Institute of Steel Construction, One East Wacker Drive, Chicago, IL 60601-2001, USA (<http://www.aisc.org>).

⁶ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

ANSI C37.32-2002, High-Voltage Switches, Bus Supports, and Accessories—Schedules of Preferred Ratings, Construction Guidelines, and Specifications.

ANSI C93.1-1999, Power-Line Carrier Coupling Capacitor and Coupling Capacitor Voltage Transformers (CCVT)—Requirements.

ASCE, Substation Structure Design Guide.⁷

ASTM A36/A36M-04, Standard Specification for Carbon Structural Steel.⁸

ASTM A307-04, Standard Specification for Carbon Steel Bolts and Studs, 60,000 psi Tensile Strength.

ASTM F1554-04 Standard Specification for Anchor Bolts, Steel, 36, 55, and 105-ksi Yield Strength.

IBC-2003, International Building Code.⁹

IEEE Std 48™-1996 (Reaff 2003), IEEE Standard Test Procedures and Requirements for Alternating-Current Cable Terminations 2.5 kV through 765 kV.^{10, 11}

IEEE Std 518™ -1982 (Reaff 1996) (Withdrawn), IEEE Guide for the Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources.

IEEE Std 824™ -1994, IEEE Standard for Series Capacitors in Power Systems.

IEEE Std 1036™ -1992, IEEE Guide for Application of Shunt Power Capacitors.

IEEE Std C37.09™ -1999, IEEE Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

IEEE Std C37.20.2™ -1999, IEEE Standard for Metal-Clad Switchgear.

IEEE Std C37.90.1™ -2002, IEEE Standard Surge Withstand Capability (SWC) Tests for Protective Relays and Relay Systems Associated With Electric Power Apparatus.

IEEE Std C37.90.2™ -2004, IEEE Standard for Withstand Capability of Relay Systems to Radiated Electromagnetic Interference from Transceivers.

IEEE Std C37.122™ -1993, IEEE Standard for Gas-Insulated Substations.

IEEE C57.12.00™ -2000, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.13™ -1993, IEEE Standard Requirements for Instrument Transformers.

IEEE Std C57.16™ -1996, IEEE Standard Requirements, Terminology, and Test Code for Dry-Type Air-Core Series-Connected Reactors.

⁷ASCE publications are available from the American Society of Civil Engineers, 1801 Alexander Bell Drive, Reston, VA 20191-4400.

⁸ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA.

⁹IBC publications are available from International Code Council, 900 Montclair Road, Birmingham, AL 35213-1206, USA.

¹⁰IEEE publications are available from the Institute of Electrical and Electronics Engineers, Inc., 445 Hoes Lane, Piscataway, NJ 08854, USA (<http://standards.ieee.org/>).

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IEEE Std C57.19.00™ -2004, IEEE Standard General Requirements and Test Procedure for Outdoor Power Apparatus Bushings.

IEEE Std C57.21™ -1990 (Reaff 1995), IEEE Standard Requirements, Terminology, and Test Code for Shunt Reactors Over 500 kVA.

IEEE Std C62.11™ -1999, IEEE Standard for Metal-Oxide Surge Arresters for Alternating Current Power Circuits.

MDOC/CFE Manual de Diseño de Obras Civiles, de la Comisión Federal de Electricidad, Instituto de Investigaciones Eléctricas, México, 1993.¹²

National Building Code of Canada (NBCC), Eleventh Edition, 1995.¹³

NEHRP-2000 (National Earthquake Hazards Reduction Program), Recommended Provisions for Seismic Regulations for New Buildings [Federal Emergency Management Agency (FEMA), 2000].¹⁴

PSM Peligro Sísmico en México, II-UNAM, CENAPRED, CFE, IIE, México, 1996.¹⁵

Uniform Building Code, 1997.¹⁶

Wilson, E. L., Der Kiureghian, A., and Bayo, E. R., “A replacement for the SRSS method in seismic analysis,” *Earthquake Engineering and Structural Dynamics*, vol. 9, pp. 187–192, 1981.¹⁷

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B16] should be referenced for terms not defined in this clause.

3.1.1 Arias Intensity: A ground motion parameter that is a measure of the total energy associated with a ground motion record. The Arias Intensity is proportional to the integral over time of the acceleration squared (m/s), and thus, it considers the full range of frequencies recorded over the duration of the given record.

$$\text{Arias Intensity } A(t) = (\pi / 2g) \int_0^t a^2(\tau) d\tau$$

$$\text{Normalized Arias Intensity } I(t) = A(t) / A(\infty)$$

where $a(\tau)$ is the acceleration time history function.

¹²MDOC/CFE publications are available from the Civil Engineering Department, P.O. Box 1-475, 62001, Cuernavaca, Mor, Mexico.

¹³The National Building Code of Canada is available from the National Research Council of Canada, Institute for Research in Construction, Ottawa, Canada.

¹⁴The NEHRP publication is available from the Building Seismic Safety Council, 1201 L St., N.W., Suite 400, Washington, D.C. 20005, USA.

¹⁵PSM publications are available from the Instituto De Ingenieria, CD Universtaria, Coyoacan, 04510, Mexico, D.S.

¹⁶UBC publications are available from International Code Council, 4051 W. Flossmoor Rd, Country Club Hills, IL 60478-5795, USA.

¹⁷The *Earthquake Engineering and Structural Dynamics* publication available online from John Wiley and Sons, Inc. at <http://cajun.cs.nott.ac.uk/engineering/civeng.html>.

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

- Minimum bending radius being violated.
- Ends being twisted opposite to direction of twist.

3.1.3 biaxial testing: Testing simultaneously in two directions, i.e., one horizontal and one vertical direction.

3.1.4 brittle material components: A material that experiences limited or no plastic deformation before fracture. Limited deformation shall be taken as less than 10% in 5 cm (2 in) at failure in tension.

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

NOTE—See 5.9.3.

3.1.6 composite: Materials that refer to polymer impregnated fiber components used as insulators or bushings.

3.1.7 ductile material: Material that experiences considerable plastic deformation before fracture.

NOTE—See 3.1.4.

3.1.8 dynamically equivalent or better structure(s): A functionally similar structure that transmits seismic motions, such as translation and rotation, at the equipment interface equal to (equivalent) or less (better) than a structure to which a comparison is being made. Accelerations should include all possible axes of freedom.

3.1.9 first support: The primary aboveground support of a piece of equipment. For stand-alone equipment, the first support is the entire structure, such as a CVT pedestal or the entire frame for a disconnect switch. For racks or A-frames that support other equipment or carry pull-off loads, the first support is the member(s) upon which the equipment is attached and its connections.

NOTE—The rest of the structure is designed according to the ASCE Substation Structure Design Guide.¹⁸

3.1.10 flexible equipment: Equipment, structures, and components whose lowest resonant frequency is less than the cutoff frequency, 33 Hz, on the response spectrum.

3.1.11 fragility testing: Vibration testing of substation equipment to the minimum level of shaking at which the equipment will no longer operate as intended.

3.1.12 g: Acceleration due to gravity that is 9.81 m/s^2 (32.2 ft/s^2).

3.1.13 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.

3.1.14 load path: The route the loads follow through the equipment and support. It describes the transfer of loads generated by, or transmitted through, the equipment from the point of origin of the load to the anchorage.

¹⁸ Information on references can be found in Clause 2.

3.1.15 maximum mechanical load (MML): The largest service load allowed on a composite insulator or bushing. The MML is within the reversible elastic range and is supplied by the manufacturer.

NOTE—It is defined in IEC TC 36 WG07 Project 1462 Ed 1 (draft). See R.1.2.4.

3.1.16 normal operating load: Any force, stress, or load resulting from equipment operation that can reasonably be expected to occur during an earthquake, except short-circuit loads.

3.1.17 oil leakage load: The cantilever load applied to the top of any oil-filled component at which oil leakage begins.

3.1.18 projected performance: The estimated performance based on the value of critical variables (strain, stress, and deflection) determined from shake-table tests or analyses at the required response spectrum using acceptance criteria that assure the critical variables are equal to or less than their acceptance allowables.

NOTE—See A.2.

3.1.19 resonant frequency: A frequency at which a response peak occurs in a system subjected to sinusoidal forced vibration. This frequency is accompanied by a 90° phase shift of response relative to the excitation.

3.1.20 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.

3.1.21 rigid equipment: Equipment, structures, and components whose lowest resonant frequency is greater than the cutoff frequency, 33 Hz, on the response spectrum.

3.1.22 seismic outline drawing: A 280 mm × 432 mm (11 in × 17 in), A3, 216 mm × 280 mm (8½ in × 11 in), or A4 drawing that shows key information concerning the seismic qualification of the equipment. It shows information such as the resonant frequencies of the equipment, important loads, an outline drawing of the equipment, the center of gravity of the equipment, and other key information about the equipment.

NOTE—See A.5.3 and A.6.2.

3.1.23 specified mechanical load (SML): The bending moment load of a composite, which is ≥2.5 times the maximum mechanical load. After application of the SML load, the residual strain may be ±5% of the maximum strain (irreversible plastic phase), but no visible damage may occur. The SML is a load rating used for composite insulators. [adapted from IEC TC 36 WG07 Project 1462 Ed 1 (draft)]

NOTE—In the context of this recommended practice, the term will be used in reference to bending loads, but users should be aware that the terminology is also applicable to other loading directions. See R.1.2.4.

3.1.24 triaxial: Testing or analysis in two horizontal orthogonal directions and the vertical direction simultaneously.

3.1.25 zero period acceleration (ZPA): The acceleration level of the high-frequency, non-amplified portion of the response spectrum (e.g., above the cutoff frequency, 33 Hz). This acceleration corresponds to the maximum (peak) acceleration of the time history used to derive the spectrum.

NOTE—For use in this recommended practice, the ZPA is assumed to be the acceleration response at 33 Hz or greater.

3.2 Abbreviations and acronyms

ACI	American Concrete Institute
ADM	Aluminum Design Manual
AISC	American Institute of Steel Construction
ASCE	American Society of Civil Engineers
ASD	allowable stress design
AWS	American Welding Society
BIL	basic impulse insulation level
CG	center of gravity
CQC	complete quadratic combination
CT	current transformer
CVT	capacitor voltage transformer
D	dead load
DFR	digital fault recorders
E	earthquake loads or seismic loads
EPDM	ethylene propylene diene copolymer
EPM	ethylene propylene copolymer
FRP	fiberglass reinforced polymer
GIS	gas insulated switchgear
IED	intelligent electronic devices
IBC	International Building Code
IT	instrument transformer
LTR	laboratory test report
LRFD	load resistance factor design
MDOC/CFE	Manual de Diseño de Obras Civiles de la Comisión Federal de Electricidad
MML	maximum mechanical load
NBCC	National Building Code of Canada
NEHRP	National Earthquake Hazards Reduction Program
PGA	peak ground acceleration
PSD	power spectral density (g^2/Hz vs. frequency)
RRS	required response spectrum
RTU	remote terminal unit
SDOF	single degree of freedom
SED	substation electronic devices
SER	sequence of events recorders
SML	specified mechanical load
SR	silicone rubber
SRSS	square root of the sum of the squares
SSI	soil-structure interaction
TRS	test response spectrum
UBC	Uniform Building Code
VT	voltage transformer
W	wind loads
ZPA	zero period acceleration

4. Instructions

4.1 General

This recommended practice provides qualification requirements for substation equipment and supports manufactured from steel, aluminum, porcelain, and composites. Should other material, such as timber, structural plastics, concrete, or glass, be specified, the user or the user's agent should provide the acceptance criteria. Any acceptance criteria proposed by the manufacturer shall first be accepted by the user or user's agent, before it can be used by the manufacturer in the qualification.

4.2 Specifying this recommended practice in user's specifications

For equipment to be qualified to this recommended practice, this recommended practice must be used in its entirety. The user or user's agent must not add additional requirements to their specifications, nor remove requirements given herein from their specifications. Nor should the user or user's agent attempt to cut-and-paste sections from this recommended practice to create a specification.

The user or the user's agent should supply the following information in their equipment specifications to the manufacturer:

- a) The type of equipment shall be stated, and the name must match one of the types of equipment described in Annex C through Annex P, such as circuit breaker, disconnect switch, suspended wave trap, and so on, or Annex B must be referenced.

NOTE—The electrical section of the user's specifications should define the detailed electrical requirements, including voltage, BIL, creep lengths, and so on.

- b) A statement that the equipment shall be qualified according to the requirements of this recommended practice.
- c) The seismic qualification level required (i.e. high, moderate, or low). To determine the qualification level, refer to 8.6.
- d) Equipment's in-service configuration. The user or user's agent should
 - 1) Specify that the equipment be supplied with or without a support.
 - 2) If without a support, the requirements of 5.5 shall be followed.
- e) The user or user's agent should provide any necessary information, such as allowables or acceptable codes for wood, plastics, or other material not provided for in this recommended practice.
- f) The user should include a schedule of due dates for completion of the test plan, testing (if needed), and the report.

The templates given in Annex U may be used in preparing seismic qualification specifications for Annex B through Annex P.

The specification templates are given in English. It may be translated into other languages.

For example, filling in the template in Annex U, the user's specifications for Annex C through Annex P may read as follows:

The surge arresters and support structure shall be qualified according to the requirements of IEEE Std 693-2005. The surge arresters and support shall meet the requirements of the high seismic qualification level. (Structure height and information discussed in item d) of 4.2 must be included if the support structure is required.) The test plan shall be submitted within 35 calendar days of award of contract, and the test shall be completed within 75 calendar days of award of contract. The report shall be submitted within 21 calendar days after testing is complete.

For example, filling in the template in Annex U, the user's specifications for Annex B may read as follows:

The voltage divider and support shall be qualified according to the requirements of IEEE Std 693-2005. The voltage divider and support shall meet the requirements of the moderate seismic qualification level and shall be qualified according to Annex B. Qualification shall be by time history testing. No functional tests are required. The test plan shall be submitted within 35 calendar days of award of contract, and the test shall be completed within 75 calendar days of award of contract. The report shall be submitted within 21 calendar days after testing is complete.

Note that additional information is required, because this latter example is for Annex B.

Structure height and information discussed in item d) of 4.2 must be included if a support structure is required. The test plan schedule requirements should be omitted from the Annex B template, if the qualification is by analysis.

4.3 Standardization of criteria

The user should not include additional or different seismic requirements in their specifications for equipment. This recommendation provides for a uniform and consistent seismic qualification procedure and allows multiple users to take advantage of pre-qualified equipment with the goal of distributing the cost among the users. This also allows the manufacturer to design the equipment to a standard set of requirements.

4.4 Selection of qualification level

This recommended practice provides three levels of qualification that should encompass the needs of most users. Experience has shown that it is good practice to specify the same criteria for all like equipment in all substations within a reasonably large geographical area, even if some of the substations within the area have moderately higher or slightly lower expected levels of ground shaking. There are several reasons for this. The most important reason is interchangeability. Should equipment malfunction or in the event of an earthquake, be lost and need to be replaced quickly, equipment from other substations can be moved and installed in the substation that experienced the loss. Also, keeping the same criteria for all like equipment will simply make it easier to keep track of equipment and its qualification level.

Following this practice makes economical sense. There are savings to be had by specifying fewer levels for the same equipment. The manufacturer only needs to design and manufacture fewer modifications of the same equipment. Also, the equipment supplied to slightly different areas is generally the same equipment with possible minor modifications.

4.5 Witnessing of shake-table testing

Potential users should witness the shake-table testing. If the equipment is being qualified for a specific purchaser, it is suggested that additional potential users also be invited, with the approval of the purchaser.

The names of the witnesses should be included in the report, with the approval of the witnesses.

4.6 Optional qualification methods

4.6.1 General

The manufacturer may replace an annex-specified qualification method with an optional qualification method listed in 4.6.2 through 4.6.7. The intent of the optional qualification methods is to return either a more conservative or a more precise determination of the seismic loads than the original required technique. Qualification techniques with recognized options are limited to those listed in 4.6.2 through 4.6.7.

It should be noted that these are manufacturers' options only. The user is not to exercise these options.

4.6.2 Option to static analysis

When static analysis is specified, the manufacturer has the option of substituting dynamic analysis, time history testing, or sine beat testing according to the requirements of A.1 and the acceptance requirements of A.2 as appropriate, provided all other requirements are met.

4.6.3 Option to dynamic analysis (static coefficient analysis)

When dynamic analysis is specified, the manufacturer has the option of substituting the static coefficient analysis method as defined in A.1.3.2, provided a static coefficient of 1.5 is used and all other requirements are met. This method allows a simpler technique in return for added conservatism. Under this alternative method, a determination of natural frequencies and damping is not required. Where natural frequencies are normally shown or provided in the report and seismic outline drawing, the note "Optional analysis" should be shown.

4.6.4 Option to dynamic analysis (testing)

When dynamic analysis is specified, the manufacturer has the option of substituting the time history test or sine beat test and its associated acceptance criteria in lieu of the analytical method, provided all other requirements are met. The testing shall be done according to the requirements of A.1, and the acceptance requirements shall be according to A.2.

4.6.5 Option to static coefficient analysis

When the static coefficient analysis is specified, the manufacturer has the option of substituting dynamic analysis, time history, or sine-beat testing as an alternative method of analysis, provided all other requirements are met. The qualification shall be done according to the requirements of A.1, and the acceptance requirements shall be according to A.2.

4.6.6 Option to use a greater acceleration

The manufacturer may use an acceleration greater than that specified or a response spectrum that envelops the required response spectrum as discussed in A.1.2.2, provided all other requirements are met.

4.6.7 Option to test at the performance level

When testing is specified, the manufacturer has the option of testing at the performance level, which is twice the RRS level. For sine beats, the acceleration level is increased by a factor of 1.2; that is, for the moderate seismic level, the peak acceleration is 0.3g, and for the high seismic level, it is 0.6g. All other requirements shall be met, except as allowed in A.2.6.

When an analysis or pull test is specified, the manufacturer has the option of testing at twice the RRS level specified, provided all other requirements are met. The testing shall be done according to the requirements of A.1, and the acceptance requirements shall be according to A.2.6.

Equipment tested at twice the RRS level shall not be provided to the user, unless the user accepts in writing the tested equipment.

4.6.8 Option to pull test

When a pull test is specified, the manufacturer has the option of substituting the time history test or sine beat test and its associated acceptance criteria in lieu of the pull test, provided all other requirements are met. The testing shall be done according to the requirements of A.1, and the acceptance requirements shall be according to A.2.

4.7 Qualifying equipment by group

Equipment that differs structurally or dynamically, including different voltage class, BIL, and equipment type, shall require a separate qualification, except as allowed herein.

Often, equipment of the same type, such as bushings, surge arresters, or instrument transformers, are very similar structurally, but of varying current, voltage, BIL, and so on. Equipment such as these may be combined into groups for qualification purposes, with the most seismically vulnerable piece of equipment of each group being analyzed or tested. That qualification would then apply to all equipment in that group. It shall be demonstrated analytically or by test that the equipment in that group is structurally similar and that the most seismically vulnerable equipment was tested or analyzed. The manufacturer shall include the demonstration work in the seismic report. The user or the user's agent reserves the right to refuse the grouping, if they do not agree with the technical merit of the demonstration analysis. Should this happen, a review of the analysis should be conducted to determine if the reason for rejection can be resolved. If it cannot be resolved, grouping may not be used, and the equipment shall be qualified separately.

Note that additional equipment may be added to a grouping at any time. For example, an existing surge arrester, model number "Existg," has been qualified, and some time later, a new surge arrester, model number "New," is required. If surge arrester "New" can be shown to be less vulnerable than surge arrester "Existg"; then surge arrester "New" can be grouped with the qualification of surge arrester "Existg," provided the user or user's agent agree as discussed above.

A seismic outline drawing shall be provided for the most seismically vulnerable piece of equipment. A seismic outline drawing need not be provided for the other pieces of equipment in the grouping. A list of the other equipment in the grouping shall be provided in the seismic report. Note that the data provided on the seismic outline drawing are only applicable to the equipment tested or analyzed. For the other equipment in the grouping, it is the user's responsibility to adjust the data, such as deflections or base loads, if needed.

4.8 Inherently acceptable equipment

The following types of equipment are deemed inherently acceptable and can be qualified by the requirements of A.1.4:

- Electric motors
- Engine generators

4.9 Shake-table facilities

Due to the design and capacities of the incorporated actuators and servo valves, all shake-tables have limitations in displacement, velocity, and acceleration. Thus, the size and weight of equipment that can be tested is restricted.

Equipment identified in this recommended practice as requiring shake-table testing can be fully tested by most commercial tables according to the requirements of this recommended practice, with the possible exception of equipment with low resonant frequencies. Such equipment may include tall slender cantilever type equipment, such as live tank circuit breakers or current transformers, or base isolated equipment. Equipment with natural frequencies below 1 Hz may require special techniques. If it is apparent or reasonably possible that resonant frequencies exist below 1 Hz, testing below 1 Hz shall be done. The following approaches may be used: Although the broad-band signal may be reduced below 1 Hz and at the equipment fundamental natural frequency, it will generally be possible to add a low amplitude sine beat signal to the time history at the equipment fundamental frequency to raise the test response spectrum above the RRS. Note that the sine beat may have to be longer duration, but lower amplitude than the typical sine beat used in a sine beat test.

If equipment limitations at the test laboratory require deviations from this recommended practice, the deviation shall be approved by the user or user's agent. (It is suggested that the deviations be discussed with the potential user witnesses discussed in 4.5.)

All safety requirements as determined by the testing laboratory shall be followed. A safety line with sufficient slack to decouple the safety line from the equipment during testing should be attached to the equipment during testing, and appropriate precautions should be followed for testing pressurized equipment.

Minimum requirements for testing laboratories shall be as follows:

- a) The table shall be biaxial with triaxial preferred.
- b) The weight of the equipment shall not exceed the capacity of the table.
- c) The table shall be capable of enveloping the RRS for the equipment weight at frequencies of 0.75 times the lowest resonant frequency of the equipment, and all resonant frequencies up to 33 Hz, except shake-table need not be capable of testing below 1 Hz. (Example: Lowest resonant frequency is 4 Hz. Table shall be capable of testing equipment weight at $4 \text{ Hz} \times 0.75 = 3 \text{ Hz}$ and above.)
- d) The test laboratory equipment shall be capable of identifying resonant frequencies from at least 1 Hz in both horizontal directions and the vertical direction.

- e) The laboratory's control and function equipment shall be capable of performing all of the tests required by this recommended practice.
- f) The test laboratory personnel shall be experienced in performing testing work.
- g) The test laboratory shall be capable of producing the test data necessary to complete the test report as required by this recommended practice.

4.10 Equipment too large to be tested in its in-service configuration

Gas-insulated switchgear and other equipment too large to be mounted completely on the shake-table may be broken into sub-assemblies and tested separately, provided the parts tested produce conservative results, and the conservatism can be demonstrated by analysis or test. The test or analysis concept must be approved by utility witnesses or the user or user's agent, before it can be used. The sub-assemblies removed may be simulated by adding weights and/or support to the part tested, provided it can be demonstrated by analysis or test that the additional weight and/or support effectively replicate the missing equipment sub-assemblies. This procedure should be repeated for all sub-assemblies until all are tested. Seismically and structurally independent equipment sub-assemblies may be tested independently.

All components that can interact, such as the individual columns of one phase of a live-tank circuit breaker, should be tested or analyzed as a unit.

4.11 Report templates

The manufacturer shall use the template given in Annex S for the static coefficient method and static and dynamic analysis. Annex T shall be used for time history and sine beat testing. Annex S and Annex T provide a checklist for the manufacturer to follow to help ensure that no information or requirement is inadvertently omitted. The templates also provide the user with a standard format for the many reports the user will need to review and maintain. Annex S and Annex T are presented in metric unit format and in English unit format.

Additional sections or appendices may be added, as required. If an existing section or appendix is not required, list the section number or appendix letter and note N/A.

5. Installation considerations

5.1 General

This clause discusses the effect that the parameters of installation may have on the equipment qualification and earthquake performance. Installation parameters can have a significant effect on the way equipment will respond and perform during an earthquake. Some equipment installation parameters can affect the motion that the equipment will experience during an earthquake. This is true of both equipment that is installed and operating or spare components in storage. Installation parameters can either amplify or attenuate the equipment response to an earthquake. Important installation parameters include equipment assembly, site response characteristics, SSI, support structures, base isolation, suspended equipment, anchorage, and conductor loading from the conductor dynamic and adjacent equipment interaction.

5.2 Equipment assembly

The proper assembly of equipment and its components in accordance with the manufacturer's guidelines (e.g., tightening bolts to required torque levels, minimizing the conductor loading on insulators, ensuring that components are properly aligned, following anchorage recommendations, etc.) is critical to achieving the intended seismic performance of the equipment. It is the responsibility of the user or user's agent to ensure that the equipment is properly installed except in the case when the manufacturer undertakes the responsibilities of erection. It is also crucial that all future field alterations be approved by an engineer familiar with the seismic design and criteria of the equipment. A statement reflecting this should be included on the manufacturer's installation drawings.

Where the difference in post-insulator length can induce assembly stresses, insulators should be shimmed to limit unnecessary assembly stresses.

5.3 Site response characteristics

Site effects are dependent on the dynamic properties of the geologic formations at and around the site and are influenced by factors including bedrock quality, soil type and depth, liquefaction potential, surface and bedrock topography (including the presence of sedimentary basins), and near-fault effects. The impact of site effects on the motion from an earthquake is usually considered in detailed hazard assessments. Site effects can result in dynamic amplification or attenuation between the bedrock and the soil immediately surrounding the foundation of the equipment of interest. Generally speaking, due to the usual frequency content of earthquakes, hard rock sites tend to have less severe motion of engineering significance than do softer sites of alluvium or saturated clays or silts. It is the responsibility of the user to ensure that site response characteristics are reflected in the RRS.

5.4 Soil-structure interaction

SSI occurs when the soil deforms due to the loading to the soil from the equipment-foundation system responding to an earthquake. The soil-foundation system may become a significant component in the dynamic properties of the equipment-foundations-soil system, which may increase or decrease the motion the equipment experiences during an earthquake. SSI occurs with certain combinations of equipment mass and size, foundation type and configuration, and soil properties. Transformers and liquid-filled reactors are especially susceptible to SSI. The rocking motion of transformers can cause increased acceleration and displacement of components high in the equipment, such as bushings and lightning arresters. SSI is generally not considered in the design of substation equipment, unless specifically requested by the user. SSI increases where there are high accelerations, heavy equipment, high centers of gravity, or soft sites.

5.5 Support structures

Support structures can have a very significant effect on the motion that the supported equipment will experience during an earthquake. The acceleration that the equipment experiences on a structure can be several times more severe than the ground acceleration. During qualification, it is generally desirable to have the equipment mounted or modeled in the identical manner as it would be in its in-service configuration. However, the following reasons are typical for not qualifying the equipment in its in-service configuration:

- *The equipment will be used on a variety of supports.* When equipment is to be used on a variety of supports, the user often cannot design the support until electrical requirements are established. Yet the equipment must be qualified or an existing qualification should be used, if possible.

- *Existing supports.* Adequate supports already exist that are different from those used in the equipment qualification. That is, the qualification for the equipment already exists, and the supports used in the qualification are different from those to be used by the user.
- *Support height unknown.* The exact height of the pedestals is not known at the time the equipment is purchased.
- *Better supports to be used.* The support to be used by the User is dynamically better (i.e., will transmit lower accelerations to the mounted equipment) than the support tested or analyzed.
- *Equipment height.* The height of the equipment makes it impractical to test inside a test laboratory.

When the equipment cannot be mounted for testing or modeled for analysis in the identical manner as it would be in its in-service configuration, the following methods may be used.

5.5.1 Modifying existing qualified support

When the user intends to install the equipment on supports different from those used in an existing qualification, the existing qualification will be acceptable if the support used is dynamically equivalent (Definition 3.1.8) or better than that used in the existing qualification. The user's designer shall design the support to meet all of the requirements of this recommended practice and shall demonstrate due consideration of all electrical and structural functions that were served by the original equipment support structure. The user may assign the design requirement to the manufacturer in the specification. If the user intends to install the pre-qualified equipment on a support other than that used in the existing qualification, then the user needs to inform the manufacturer of his/her intent to use a dynamically equivalent or better support.

5.5.2 Qualification on multiple supports

[If the support parameters (i.e., height, etc.) are not known, 5.5.4 must be used.]

When equipment will be mounted on a variety of pre-designed or pre-defined supports, the qualification will be acceptable if the equipment is mounted or modeled on the most seismically vulnerable configuration of the equipment/structures to be used.

It is the responsibility of the user to determine which support is deemed "most seismically vulnerable."

5.5.3 Qualification without support—support parameters known

When the equipment is tested without the support, the shake-table base acceleration shall be amplified to replicate the effects of the support, including the effects of translation, rotation, and torsional accelerations. The amplification value used in testing shall be the amplification value found multiplied by 1.1.

It is the responsibility of the user to supply the design and effects of the support to the manufacturer. The manufacturer shall include the effects of the support in the shake-table test. Or the manufacturer may fabricate a support structure and test the equipment on the actual support.

Only the user may exercise this option, except the case in which the equipment and support will not fit in the test laboratory. In this case, the manufacturer may exercise this option. Should the manufacturer exercise this option, the manufacturer shall determine the effects of the support and include the support effects in the test.

5.5.4 Qualification without support—support parameters not known

When equipment will be mounted on a support or a variety of supports and the parameters of the support(s) are not known, the qualification will be acceptable if the equipment is mounted or modeled without the support and the qualification is conducted at 2.5 times the requirements specified in this recommended

practice. The manufacturer shall include an amplification of 2.5 in the shake-table test or analysis. The users shall design the structures, once the parameters become known such that the supports do not amplify the loads at the base of the equipment greater than 2.25 times the base accelerations and the support(s) shall meet all requirements of this recommended practice. When adding the amplification factors, the user should consider the complexity of the support motions, which may include translation, torsion, and rotation of the equipment.

5.6 Base isolation

The support structure dynamics can figure heavily in the qualification strategy of equipment. Base isolation is an earthquake damage mitigation strategy that relies on a support structure to lessen the severity of earthquake-induced accelerations. Base isolators have been successfully used. However, relying on base isolation devices introduces the following concerns:

- a) The damping or frequency characteristics of the system may change over time, due to creep or relaxation of materials, exposure to the elements, and other causes.
- b) The device or attachment may, over time, require maintenance.
- c) Should the device be removed for any reason, such as maintenance of the equipment, it may not be reinstalled properly.
- d) Very large displacements may result, causing electrical clearance problems.

Base isolation shall not be allowed, unless the considerations and problems listed below and in A.7 are resolved.

Historically, there have been significant problems with existing base isolation designs that use conical-shaped disked springs (washers). Base isolation systems should be tested, nonlinearly if necessary, to assure they perform as intended. The design of this type of base isolating device should be very carefully considered before using for the following reasons:

- The springs (washers) have been known to change characteristics, usually due to environmental effects, such as corrosion, dust, or other material collecting between the washers. (This type of device should be sealed from the environment.)
- The springs have been known to change characteristics due to fatigue or improper tensioning.
- To remove the equipment from its stand, this type of spring assembly usually must be entirely disassembled.
- The expected response of the springs may not be achieved if improperly pretensioned.
- Base isolation systems must be capable of accommodating displacements associated with performance level excitations.
- The base isolation device shall have sufficient restoring capabilities to return the equipment to its original position after a performance level event.

5.7 Suspended equipment

Equipment that is suspended often takes on the dynamic characteristics of base-isolated equipment. As a consequence, it may not be subjected to the peak levels of the horizontal ground motion acceleration. On the other hand, just as with base-isolated equipment, it may experience significant vertical acceleration and horizontal displacements and may be subject to large loads associated with snubbing action of restraints. In the case of suspended equipment, instances of displacements over a meter have been observed during a significant earthquake. The large motions may cause significant nonlinear effects due to interaction with conductor connections with inadequate slack. The dynamics of the upper support point may also influence the response and loads on support and restraint points. (It is expected that most suspension mounting

structures are nonrigid in at least one direction.) These interactions can cause large connection point loads. Suspended equipment has included wave traps, capacitor voltage transformers, capacitors, and thyristor valves. Requirements for suspended equipment other than thyristor valves are given in Annex I. Suspended thyristor valves shall be qualified on a case-by-case basis.

There are four basic components to a suspended mounting configuration. They are as follows:

- The equipment
- A suspension system
- A restraint system
- Electrical connections

To achieve the intended seismic performance of the suspended equipment, the user must adequately design the suspension system, restraint system, and the electrical connections.

Figure 2 is provided to assist the user in understanding the terms used in conjunction with suspended equipment. It does not represent the only configuration. For example, the restraint system need not be below the equipment and both the suspension and the restraint systems may consist of more than one line.

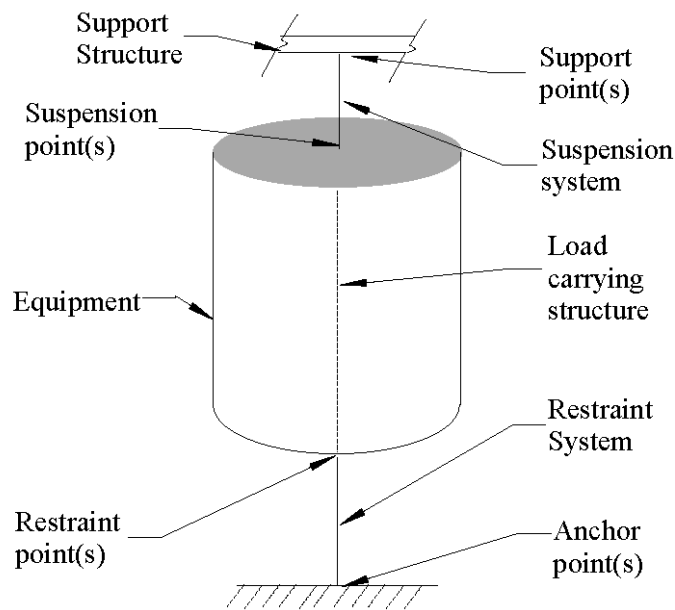


Figure 2—Definitions

There are numerous possible configurations for the mounting of suspended equipment, but seismically proven designs generally adhere to the following concepts:

- a) *Equipment.* Suspended equipment shall meet the requirements of Annex I.
- b) *Suspension system.* The purpose of the suspension system is to support the weight and loads imparted by the suspended equipment, the restraint system, and the suspension system. The suspension system consists of all hardware between the support point(s) and the equipment's suspension point(s) (I.1.4.2). The suspension system must be constructed such that it allows the suspended equipment to oscillate about the upper support point(s).

To allow the necessary freedom of motion and yet control the attitude of the suspended equipment, the upper connection of the suspension system to the upper support point(s) and the lower connection of the suspension system to the equipment suspension point(s) must each have rotational freedom about any horizontal axis.

- c) *Restraint system.* All seismically qualified equipment that is suspension mounted should have a restraint system. The purpose of the restraint system is to control oscillation (i.e., maintain electrical clearances of the suspended equipment), without unduly increasing the equipment acceleration and to maintain a continuous downward force upon the suspension system. The restraint system encompasses all of the hardware from the suspended equipment's restraint point(s) (I.1.4.2) to the anchorage point(s), which are normally below the equipment.

The restraint system must be constructed such that it continuously maintains the electrical clearances of the suspended equipment. It is prohibited to have slack in either the suspension or the restraint system, neither initially nor as the system moves in an earthquake. Therefore, the restraint system must not go slack. Past field experience has proven that designs with initial slack or lines that go slack in an earthquake have experienced impact damage.

For reasons identical to those given for the suspension system, the connection of the restraint system to the equipment restraint point(s) must allow rotational freedom about, and translational freedom in, any horizontal axis. The connection of the restraint system to the anchorage point(s) must allow rotational freedom about any horizontal axis.

The restraint system is usually attached to anchors located below the equipment, but the restraint system need not be below the equipment. However, restraint systems must be capable of maintaining a continuous downward load upon the suspension system throughout a seismic event (to avoid any slack in the suspension system). For restraint systems that are not below the equipment, maintaining a continuous downward load typically entails the incorporation of axial stiffness into the suspension system to prevent vertical displacements. Without axial stiffness, the insulators may go slack, resulting in the equipment bouncing and causing impact loads.

A recommended, but not compulsory, type of restraint system is to incorporate a spring-damper mechanism. Care should be exercised not to over-damp the restraint system, thereby increasing the acceleration of the equipment.

A suspension system can have coincident restraint functions. This is done by providing full rotational freedom at the support and suspension points, using rigid insulators and providing adequate flexibility of movement of the conductor to allow free movement of the equipment. It is key to ensure that no contact arises due to potential large deflections of the system and to prevent any slack from occurring in the suspension system.

- d) *Electrical connections.* To allow the necessary freedom of motion of the suspended equipment, the equipment's electrical connections must be made with suitably flexible conductors, which do not impede the free oscillations of the equipment. Also, the displacements of the entire suspended configuration should be accounted for when designing clearances with neighboring equipment or structures.

Typically, electrical conductors do not serve as part of the suspension or restraint systems. However, for certain equipment types [e.g., capacitor voltage transformers (CVTs)], the electrical conductor may provide the structural support. This is acceptable provided there are independent connectors at either end of the conductor capable of transferring the mechanical loads and the conductor can accommodate the structural loads.

The combination of unique requirements for a suspension mounted system (e.g., suitable structures from which to suspend the equipment, restraint anchorage points, physical clearances, and conductor terminals) may dictate the design of the suspended equipment. If this is the case, the user should provide the following information in their specification:

- The number and locations of the suspension and restraint points on the equipment.
- The direction and magnitude of the normal operating restraint load(s) at the restraint point(s).

5.8 Anchorage

Providing adequate anchorage is often the most cost-effective measure that can be implemented to improve the earthquake performance of equipment. It is important, as in the case of a support structure, that the anchorage used in the qualification closely simulate the in-service anchorage. Welded anchorage normally allows for a simpler and stiffer anchorage configuration and can be stronger than bolted anchorages.

It is the responsibility of the manufacturer to supply a product with the capability of being secured by a fastening method condoned by the user (either welded or bolted). The manufacturer shall state the anticipated seismic loads (shear, tension, compression, bending, if applicable) in combination with normal loads at the footprint(s) of the equipment. It is the responsibility of the user to ensure that the connection between the manufacturer's equipment and the immediate support (either a foundation, support structure, or other piece of equipment) is made so that it will properly transfer the anticipated load combinations.

The recommended equipment anchorage is made by welding the base to structural steel members embedded in or firmly anchored to a concrete foundation. The manufacturer designs the welds, including the size, location, and type, and shows them on the manufacturer's installation drawing and on the seismic outline drawing. All welds and welders should conform to applicable American Welding Society (AWS) specifications, such as ANSI/AWS D1.1 [B1].

If bolts are to be used, their size, strength, location, and materials should be shown on the manufacturer's installation drawings and on the seismic outline drawing.

The size and strength of the anchor systems (welds or anchor bolts) should be determined using either the ASD or the LRFD method, as described in A.2.1. It is recommended that mild ductile steel be specified, such as ASTM A36, ASTM 1554-36, or ASTM A307, and that the design requirements of the ASCE Substation Structure Design Guide be followed. The depth of embedment and the type of bonding to that portion of the anchor system within the foundation is to be determined by the user and should produce a strength greater than the strength of the anchor bolts. The intention here is to ensure that the bolt is weaker than the concrete so that the beginning of failure, should it occur, will be ductile. The strength of the steel portion of the anchor depends on the steel properties and the size of the anchor. The strength of the embedded portion of the anchorage depends on its embedment length, strength of concrete, proximity to other anchors, distance to free edges, and size of head at the embedded end of the anchor. Consideration should be given by the user to any unequal distribution of dynamic earthquake loading on the anchor bolts.

All anchor systems must withstand the forces resulting from the design earthquake in addition to other existing loads (refer to 1.8).

When designing equipment foundation anchoring systems, it is recommended that the anchor system be reviewed for adequacy to withstand the cyclic nature of the seismic forces. The anchor must withstand the shear, uplift, and compressive forces resulting from the design earthquake. Any anchoring system (e.g., expansion type, adhesive type, etc.) must be certified by the manufacturer as being acceptable for use in seismic applications. The manufacturer's recommendations for safety factors, embedment lengths, pullout design, and edge shear design should be reviewed, modified, and applied as required by the designer, taking into account the objectives of this recommended practice (refer to 8.2).

In the past, it has been considered good engineering practice not to use mechanical fasteners that rely on friction or wedging action to anchor equipment against earthquake loading. Although certain types of mechanical fasteners perform acceptably for tension and shear static loads, historical experience suggests that these types of anchors should not generally be used for tension and shear vibrating loads. In all cases, use caution and investigate qualification testing and *in situ* experience for these types of anchors.

Refer to A.4.2 for further information.

5.9 Conductor induced loading

Subclause 5.9.3 provides a brief overview of methods of decoupling equipment to minimize the effects discussed in 5.9.1 by providing flexible conductoring between equipment. Subclause 5.9.2 discusses observed displacements. For a detailed discussion of this topic, refer to IEEE Std 1527-2006 [B23].

5.9.1 Interconnection with adjacent equipment

All equipment, whether installed and operating or stored as spares, may be adversely affected by impacting an adjacent moving or stationary component. Therefore, care must also be given to the placement of important components so that failure or movement of adjacent components does not cause damage that would lessen the ability of a facility to operate.

Equipment that is interconnected by conductors must have some provision in the installation (e.g., sufficient flexible line slack) that allows for any relative deflection between the equipment that will occur during an earthquake. Likewise, in rigid bus installation, it is necessary to incorporate adequate flexibility to permit axial or longitudinal movement of individual major equipment assemblies while avoiding the transfer of excessive forces between the individual components.

5.9.2 Observed component displacements

Based on analyses, tests, and forensic engineering after earthquakes, it has been determined that individual items of major equipment and bus supports move by varying degrees depending on their mass, mounting height, type, and size of support structure, and so on. This movement results in the need for specific flexible bus configurations.

Depending on the equipment's resonant frequency and damping, it may experience small to large displacements at its conductor connection point. Table 1 represents typical values calculated for 2% damping.

The lower bound displacement in Table 1 is related to equipment with mass concentrated at their top, such as live tank circuit breakers or CVTs. The upper bound is related to equipment with mass and stiffness more evenly distributed. An average displacement value for most equipment supported on supports or pedestals is 1.3 times the lower bound value.

5.9.3 Decoupling equipment through flexible bus-work

The typical movements (displacements) given in Table 1 are for informational purposes only and should not be used in design. Equipment movement is dependent on equipment configuration. The displacement found in the qualification should be used in the design. The user is cautioned that deflections found from an RRS qualification method must be multiplied by two so that the values represent the ground acceleration. Wherever possible the design should provide additional slack or movement between equipment over that found in the qualification; that is, the required length should be less than the actual length.

Table 1— Typical equipment displacements for moderate and high qualification levels

Fundamental frequency (Hz)	Qualification level Displacements (mm)	
	Moderate	High
1.0	375–750	750–1500
2.0	100–200	200–400
3.0	45–90	90–180
5.0	16–32	32–64
8.0	6–12	12–24
10.0	3–6	6–12

The necessary conductor length between interconnected components can be estimated as follows:

$$L_o = L_1 + 1.5(\max u(t)) + L_2 \quad (1)$$

where

- L_o is the minimum required conductor length. Note that the equivalent equation given in IEEE Std 1527-2006 [B23] is slightly different. This recommended practice is the more conservative approach.
- L_1 is the straight line between connected points.
- $\max u(t)$ is the maximum relative displacement between equipment.
- L_2 is the additional provision for conductor configuration under consideration.

The value $\max u(t)$ can be estimated, using the maximum standalone displacements (u_n and u_m) of the equipment, by one of the following methods:

- a) *Absolute sum—preferred method.* Add displacements directly

$$\max u(t) = u_n + u_m \quad (2)$$

- b) *SRSS.* Add displacements using the square root sum of the squares

$$\max u(t) = \sqrt{u_n^2 + u_m^2} \quad (3)$$

- c) *CQC.* Combine displacements using the complete quadratic combination¹⁹

$$F = \sqrt{\sum_n \left(\sum_m f_n \rho_{nm} f_m \right)} \quad (4)$$

where

- F is the peak value of a response quantity (e.g., force or displacement)
- f_n is the modal response quantity associated with mode n
- f_m is the modal response quantity associated with mode m

$$\rho_{nm} = \frac{8\sqrt{\zeta_n \zeta_m} (\zeta_n + r \zeta_m) r^{\frac{3}{2}}}{(1 - r^2)^2 + 4\zeta_n \zeta_m r (1 + r^2) + 4(\zeta_n^2 + \zeta_m^2) r^2}$$

¹⁹ See Wilson et al. in Clause 2.

ρ_{nm} simplifies when all modal responses have identical damping ratios to

$$\rho_{nm} = \frac{8\zeta^2(1+r)r^{3/2}}{(1-r^2)^2 + 4\zeta^2r(1+r^2) + 8\zeta^2r^2}$$

where

- ρ_{nm} is the cross-modal coefficient
- r is the ratio of modal frequencies = ω_m/ω_n , $r \leq 1$
- ζ is the damping ratio

$$\max u(t) = \sqrt{u_n^2 - 2\rho_{nm}u_nu_m + u_m^2}$$

Table 2 provides a comparison study among the three methods given above. A damping value of 2% was used for consistency. As observed from cases A and B, it is not the frequency that defines the combined deflections, but the ratio $r = f_1/f_2$. It is also clear from cases B through E that the difference between the SRSS and CQC is significant only when the frequencies of the two pieces of equipment are almost identical. As observed from cases B and F, the difference between the SRSS and the CQC decreases significantly when the deflection difference between the two pieces of equipment becomes significant. (That is, instead of 64 to 10 for case B, it is only 50 to 45 for case F.) In most cases, there is a significant difference between the absolute sum method and the SRSS and CQC methods. However, the user should use the absolute sum method whenever possible. All connection configurations transmit loads, including well-designed loops. The user should concentrate on designing the best slack configuration that does not violate electrical restrictions.

Table 2— Calculations examples for the maximum relative displacement ($\max u(t)$)

Case	f_1 (Hz)	f_2 (Hz)	u_1 (cm)	u_2 (cm)	$r = f_1/f_2$	ρ_{12}	$(\max u(t))$		
							Absolute	SRSS	CQC
A	1.0	1	50	40	1.00	1.000	90	64	10
B	10.0	10	50	40	1.00	1.000	90	64	10
C	9.5	10	50	40	0.95	0.378	90	64	51
D	9.0	10	50	40	0.90	0.126	90	64	60
E	8.5	10	50	40	0.85	0.057	90	64	62
F	10.0	10	50	5	1.00	1.000	55	50	45

An example of Equation (1), using method a), and Figure 3 is as follows: For the installation of an adjacent circuit breaker and disconnect switch, the deflection of the circuit breaker is 55 mm and the deflection of the disconnect switch is 75 mm. When combined, the total deflection equals 130 mm for the out-of-phase scenario.

Example data:

- Equipment #1 (circuit breaker) displacement: 55 mm
- Equipment #2 (disconnect switch) displacement: 75 mm
- Straight-line distance between equipment: 3000 mm

Equation (1):

- a) $\max u(t) = 55 \text{ mm} + 75 \text{ mm} = 130 \text{ mm}$.
- b) $L_I = 3000 \text{ mm}$.
- c) $L_2 = 800 \text{ mm}$. The user selected configuration 1 (Figure 3) and after testing concluded that the addition length required was 800 mm. (See below for an explanation of L_2 .)
- d) $L_o = 3000 \text{ mm} + 1.5 \times 130 \text{ mm} + 800 \text{ mm} \approx 4000 \text{ mm}$ or 4 m.

To determine whether configuration 1 is acceptable, check the following: A full half-circle arc with a diameter of 3 m (the clear distance between equipment) would yield a conductor length of 4.71 m ($\pi d/2$ or $\pi \times 3 \text{ m}/2 = 4.71 \text{ m}$). Therefore, the required length is less than the arc length ($4.0 \text{ m} < 4.71 \text{ m}$), so configuration 1 is acceptable (Figure 3).

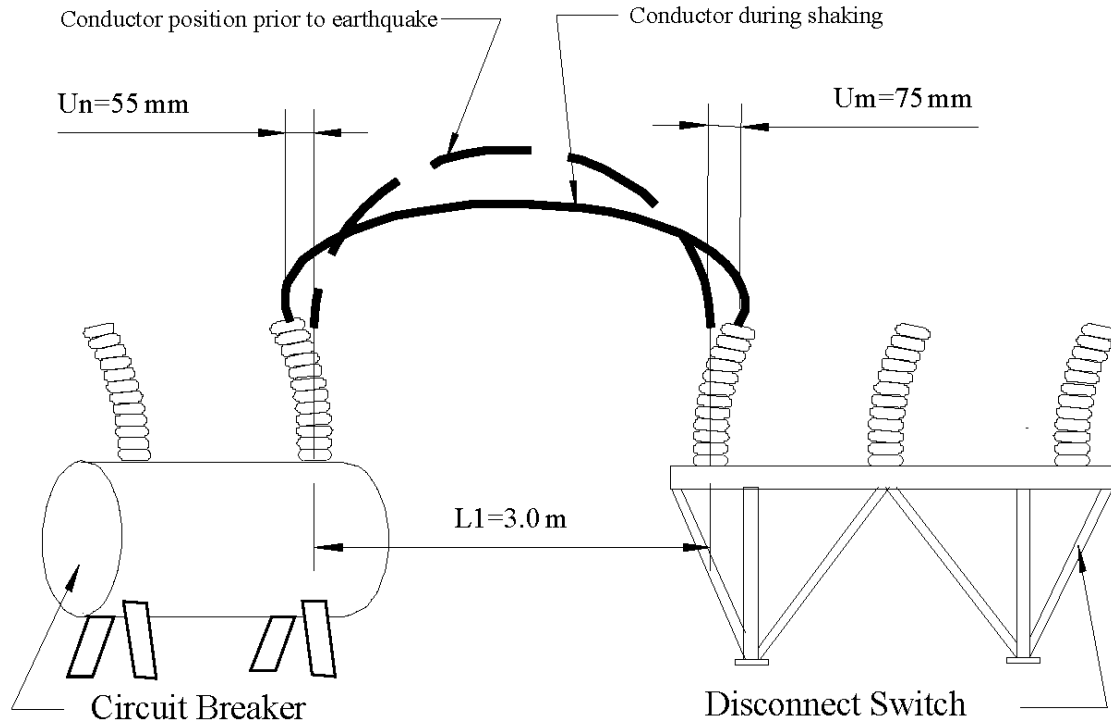


Figure 3—Example using configuration 1

To understand the necessity for step c), L_2 , it is necessary to recognize two points: (1) The conductors are pre-bent to the configurations shown in Figure 4, such that the conductor does not add load to the equipment, except the dead weight of the conductor. (2) All configurations, including configuration 1, have rigid moment connections between the conductor and the insulator at both ends of the conductor. A high-voltage conductor is stiff and takes significant force to bend sharply. If the end connections between the conductor and insulator were pin connected, then the equipment insulators could move apart the full length of the conductor, or in this case 4.71 m. But the ends are moment connected. Therefore, as the insulators move apart, the conductor bends exerting a moment and a force onto the insulator (Figure 3 and Figure 4). Obviously, the stiffer the conductor, the greater the effect the bending of the conductor has due to the fixed-end-moment boundary conditions. The user must test or take into consideration the conductor shape, number of bundle conductors, the distance between the ends of conductors, and the stiffness of the conductor in determining how much additional conductor length is required. The conductor end connection displacing forces (Figure 4) should remain at or below a reasonable force level so not to adversely impact the equipment. In this case, the user determined that an additional length $L_2 = 0.8 \text{ m}$ was needed for the conductor under consideration. For a discussion of L_2 , refer to IEEE Std 1527-2006 [B23].

Only the longitudinal motion (for the equipment/device to equipment/device length) is important for the flexible conductor. For the rigid conductor, both longitudinal and transverse motion can be important.

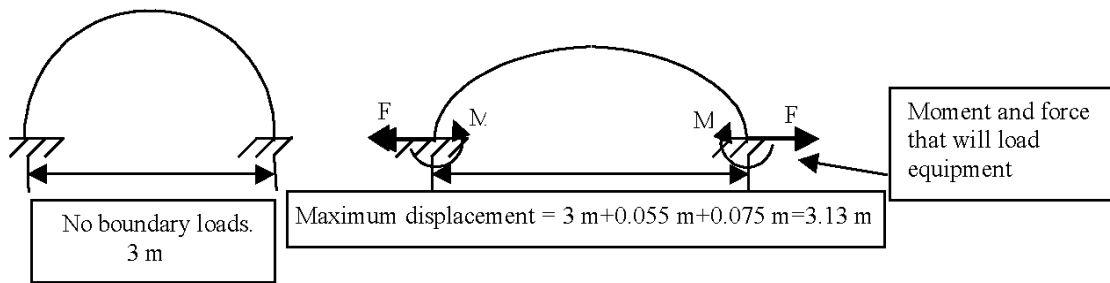


Figure 4—Loads from displacement

5.9.4 Conductor installation

The stranded bare conductor, although considered to be flexible, will not allow sufficient movement between equipment unless adequate length is included. The minimum distance between the termination points for which the stranded bare conductor may be used is determined by the minimum-bending radius of the conductor. The distance between termination points will determine the configuration of the conductor.

In addition to establishing the required amounts of differential movement, it is necessary to choose a practical conductor configuration that will provide the necessary limited flexibility. The flexible connection shall be configured to avoid compromising voltage gradients across bus and equipment insulators and to maintain the established phase-to-phase and phase-to-ground air insulation clearances.

It is generally not good practice to simply install a tension conductor to the equipment, even with significant sag. As the result of analysis and tests aimed at establishing the flexibility characteristics of standard all-aluminum conductors, four basic configurations (see Figure 5) and adaptations of each were found to be suitable. Other configurations are presented in IEEE Std 1527-2006 [B23]. The configurations are intended to provide the necessary conductor stretch and compression without applying excessive force to the bus and equipment terminations. The dimensions of configurations adequate for an application are determined according to voltage (clearances), conductor size (bending radius), equipment differential movement, and vertical and horizontal separation of the termination points (V and H).

Adding conductor length normally decreases dynamic load, but it can result in violation of required electrical clearances.

Some suggested configurations are shown in Figure 5.

It is recommended that conductor connections be configured to conform to a shape that has given good testing and/or earthquake performance, such as those shown in Figure 5.

The right end of configuration 2 exhibited basketing during lateral load testing, which simulated wind loads on the conductor. However, basketing has not been noticed in actual installations.

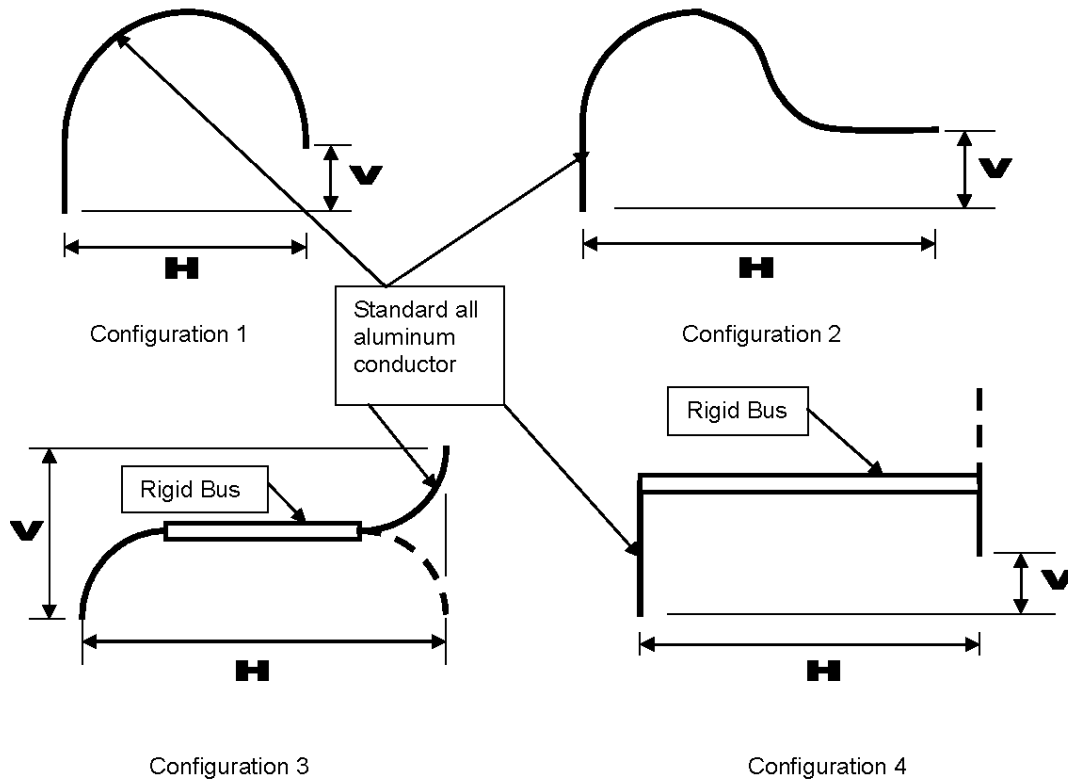


Figure 5—Basic slack configurations

5.9.5 Weight of conductor (static) and conductor dynamic loads

The weight of the conductor (static) and conductor dynamic loads does not seem to have been a significant cause of failure during past earthquakes when the conductor is installed according to the recommendations of 5.9.2 through 5.9.4.

When the conductor is strung from another component, the conductor weight may exert a longitudinal force due to catenary action. Depending on the amount of sag, this force can be significant. During an earthquake, the conductor responds dynamically. This dynamic response can be significant.

Based on earthquake performance and installations meeting the recommendations of 5.9.2 throughout 5.9.4, equipment need not be designed for concurrent earthquake, conductor weight (static), except as provided in A.1.1, and conductor dynamic loads.

5.10 Short-circuit loads

Short-circuit conditions typically produce a high fault current that in turn produces electromagnetic forces between conductors carrying the current. Depending on the spacing of the conductors, the generated forces can be significant. The greater the current and the smaller the conductor spacing, the greater the force generated.

The short-circuit force exists as long as the current flows and ceases when the current flow ceases. The faster the system recognizes there is a fault and opens the circuit via circuit breaker operation, the less the system will respond and be stressed.

Sometimes by the time the earthquake shaking reaches a substation, the substation is de-energized due to damage in other substations, circuit breaker operation in adjoining substations, or faulting along the lines leading into the substation causing the substation circuit breakers to open.

Short-circuit loads have not been shown to be a significant cause of failure during past earthquakes. Equipment need not be designed for concurrent earthquake and short-circuit loading.

5.11 Wind and ice loads

Wind and ice loads do not seem to have been a significant cause of failure during past earthquakes.

Wind and ice loads can be significant on electrical equipment, especially if they are due to the loading on conductors.

Equipment need not be designed for concurrent earthquake and wind and ice loads.

6. Qualification methods: an overview

6.1 General

Static analysis, static coefficient analysis, dynamic response spectrum analysis, time history testing, sine-beat testing, and static pull testing are methods used in this recommended practice to qualify electrical equipment. This clause explains these methods. This clause does not provide qualification requirements. The requirements for the qualification methods are given in Annex A through Annex P. However, this clause discusses time history dynamic analysis, which the user may use as discussed within.

To qualify equipment to withstand earthquakes, the following dynamics factors should be considered:

- a) *The expected magnitude of the excitation.* The geographical region, local site and soil conditions, historical seismic data, and degree of conservatism should all be considered when establishing the expected magnitude of excitation.
- b) *The configuration of the equipment.* In general, taller, heavier, high-voltage equipment has lower natural frequencies and is more susceptible to seismic excitations, which results in higher stresses and motions. Therefore, simpler calculation methods are generally acceptable for lighter, higher frequency, or low-voltage equipment.
- c) *The functional aspects of the equipment during and after a seismic event.* This is influenced by the importance of the equipment and level of acceptable risk. For important equipment, it may be advisable to demonstrate by test that components such as equipment mechanisms, relays, and contacts operate without malfunctioning before, during, and after a design earthquake. Refer to 6.6 and Clause 8 for more detailed information. Review of previous seismic performance or testing of similar equipment is recommended.

The use of seismic response spectra as a means for qualifying equipment either by calculation or by test has become the most widely accepted and powerful method. Figure A.1 and Figure A.2 give the RRS for high and moderate levels, respectively.

The maximum acceleration response of equipment with modes in the range of 1.1 Hz to 8 Hz is as indicated by these spectra. The response levels are also a function of damping, the less damping the higher the response. Equipment modes above 33 Hz are considered to be rigid and to respond at the constant ZPA level of the required spectrum.

6.2 Analysis methods

6.2.1 Static analysis

For rigid equipment (refer to Definition 3.1.21), with all modal frequencies above 33 Hz, apply a multiple of the ZPA at the center of gravity in each principal axis direction simultaneously and calculate the combined resulting stresses and anchorage loads. See A.1.3.1 for further requirements.

6.2.2 Static coefficient analysis

This type of analysis usually applies to equipment having a few important modes in the seismic range. A factor of 1.5 times the peak g value from the RRS is to be applied according to the mass distribution in each principal axis direction (vertical and two horizontal) simultaneously, unless otherwise specified in the annexes, and calculate the combined resulting stresses and anchor loads. The 1.5 factor accounts for multimode effects. Refer to 4.6.3 and A.1.3.2 for more details.

6.2.3 Response spectrum dynamic analysis

For complex structures with many modes in the seismic range, a detailed finite element model is needed. The RRS method is used with damping ratio determined in accordance with A.1.1.3 or a conservatively low value (e.g., 2%) is used. The lower frequencies of the mathematical model should, if possible, also be verified by simple-bump or other specified test methods. The loads and modal stresses are combined using the SRSS method, or closely spaced modes (within 10% of lower modes) are added directly and then the remaining modes are added using the SRSS method. An alternative method for combining modes is the CQC technique. (For requirements, see A.1.3.3.) Residual mass effects at the CG should be included.

6.2.4 Time history dynamic analysis

This method is a powerful tool when evaluating multiple, interconnected equipment or when studying equipment too large to test. Note that this method is intended as a qualification method for electrical equipment, only if the user specifically requires it, because it requires proper definition of the time history.

In linear analysis, a time history representing a seismic event can be applied to a linear finite element model to calculate the instantaneous stresses, deformations, and loads. Modal reduction techniques can be used to reduce models to important lower modes and degrees of freedom, and then calculations can be made more readily.

A time history as above can be applied to a finite element model having nonlinear elements representing important nonlinearities in equipment. It is more time-consuming and costly and requires direct time integration of all degrees of freedom. Modal or modal reduction methods do not apply in general unless nonlinearities are treated as pseudo-forces. The behavior of nonlinear elements may also differ significantly under different input time histories, even when the input time histories match the same response spectrum. For this reason, the use of multiple time histories may be needed. This is an approximate method requiring considerable engineering judgment.

6.3 Testing methods

Historically, testing has been done using a variety of test methods, as follows:

- a) Single sine frequency
- b) Continuous-sine
- c) Sine beat
- d) Decaying sine

- e) Multiple-frequency
- f) Time history
- g) Random motion
- h) Random motion with sine beats
- i) Combination of multiple sinusoids
- j) Combination of multiple sine beats
- k) Combination of decaying sinusoids, and others plus combinations of any of the above.
- l) Pull test

An important consideration, regarding methods that envelop the RRS, is that the calculated TRS of the table motion at the test facility envelops the RRS in a manner similar to that of an actual earthquake. That is, it envelops the RRS with amplitudes, frequencies, and energy levels that occur in a similar simultaneous manner.

The method of attaching equipment to the test table should be the same or equivalent to that used on the actual foundation or supporting structure. Strain bolts are recommended to measure anchorage loads.

Direction categories for testing include biaxial and triaxial. Primarily for device testing, it is important to introduce cross-effects due to the earthquake disturbance. Hence, multiple tests are required in different directions (orientations) of each system when biaxial testing is performed. Because the triaxial method requires only one test position, the consequent stress fatigue effects will be at a minimum in the equipment tested in this manner.

A biaxial machine with 100% horizontal and 80% vertical motion can be used in lieu of a triaxial table by mounting the equipment at 45° to the table motion with the table motion increased by 40% to meet the RRS in both directions simultaneously, which will simultaneously excite the two orthogonal principal directions. This process reduces the number of tests, but the magnitude of motion applied to the equipment in the direction of table motion may be too severe. The severity is dependent on the geometry and type of equipment.

Instrumentation to measure accelerations at the overall CG is recommended, but not mandatory. If the CG is outside the equipment, the closest practical location on the equipment should be used. The results can be used to calculate and verify foundation loads and the seismic performance of equipment on other supports.

The resonant frequency search test is for the determination of resonant frequencies and damping of equipment. The data obtained from the test may be an essential part of an equipment qualification; however, the test does not constitute a seismic test qualification by itself.

Instrumentation of the table should be such that rotational accelerations of the table (about the X, Y, and Z axes) can be determined at moderate excitation levels so that the excitation can be adjusted to more accurately represent the higher RRS motions or the facility should quantify the rotational characteristics with similar equipment installed.

After testing to the desired level is completed, a frequency search should be repeated and evaluated to look for unexpected changes of system frequencies indicating the presence of equipment damage. A shift in frequency of more than 20% from the pre-vibration search indicates the need for careful inspection for damage, but it does not disqualify a unit.

6.4 Special test cases

Generic testing beyond specified requirements (overtesting) may be accomplished by broadening the specification to include a wide variety of applications. However, it can produce a severe test motion and

care must be taken to avoid costly damage. Generic or overtesting if done carefully can lead to improved seismic designs at reasonable costs.

Fragility testing can be used to determine the ultimate capability of equipment. Such information serves to prove adequacy for more drastic earthquake disturbances and may conclusively show the weak link, which may result in improved seismic capability. It also provides experimentally derived information on the seismic margin of the equipment.

Where the equipment was not tested before installation, on-site testing can be accomplished by portable shaking devices. It has the advantage of including the effects of attachments or modifications made to the equipment and limited foundation and soil effects, but it is not typical of earthquake random type motion. However, the results can be used to update and improve calculations (models).

6.5 Qualification method for specific equipment

The table of contents of this recommended practice lists annexes for equipment types found in substations. Depending on the complexity of its structure, historic performance, and importance, a specification has been provided for either calculations or tests necessary to qualify each piece of equipment to withstand an earthquake. The annexes contain a recommended qualification outline for the listed equipment.

6.6 Functionality of equipment

The functional aspects of specific equipment are defined in the “Operational requirements” and the “Acceptance criteria” of the annexes. The ultimate requirement for the particular equipment is to be capable of functioning before, during, and after a seismic event. This requirement can only be verified by testing to a level equivalent to the particular seismic event and performing the required functions before, during, and after the test. Switches, linkages, relays, and so on must remain functional, or they must change state as required to perform their function, which includes both mechanical and electrical integrity requirements.

Functional requirements are only verified to the actual level of the test. On the other hand, structural requirements can be satisfied by lower levels of testing and extrapolating results to higher levels by comparing the actual stress measurements with the allowables provided failure modes are known and stresses at appropriate locations are measured.

6.7 Qualification by seismic experience data

Procedures for qualifying certain types of equipment through the use of actual earthquake experience have been developed in the nuclear power industry. The use of earthquake experience data as a qualification method is addressed in IEEE Std 344™-2004 [B17] and in subsequent revisions of that standard under development at the time of this writing.

Earthquake experience data typically applies to categories of equipment rather than to specific items. The documented performance record of the equipment category must demonstrate that there is no tendency for significant structural seismic damage over the range of ground shaking experienced in actual earthquakes.

This documented performance record consists of an inventory of equipment within the particular category that has experienced substantial earthquake ground motion, for which the post-earthquake condition of the equipment can be verified. This inventory of earthquake-affected equipment comprises a database for the equipment category.

The use of experience data may be considered as an alternative to testing and analysis only when the following criteria have been met:

- a) The particular type of equipment can be shown to have no tendency for significant structural damage or performance degradation for the specified level of ground motion.
- b) The specified ground motion is less than or comparable with the range of ground motions experienced by sites reviewed in compiling the database.
- c) Items of equipment qualified by experience data must be shown to be generally represented by the equipment category for which an adequate database has been compiled. Representation means that a specific equipment item must fit within the database range of size, mass, and capacity; must be similar in operation and construction (including its support); and must contain no significant design differences compared with database equipment that might be sources of weakness under seismic loading. The equipment item need not be represented within the database by the specific manufacturer and model.
- d) An adequate database inventory for a particular category of equipment should include about 50 examples (i.e., about 50 items of similar equipment) that have experienced earthquake ground motion comparable with or greater than the predicted level for the substation site. This database inventory should include multiple sites and multiple earthquakes.
- e) The earthquake performance record for the category of equipment must demonstrate that there is no tendency for seismic damage in past earthquakes, or that sources of seismic damage are precluded by design or installation provisions for the particular item to be qualified.
- f) Experience data may be used only when approved by the user or user's agent of the substation equipment.

Experience data can only be used to demonstrate the ability of equipment to survive the earthquake and remain operable afterward. It cannot be used to ensure that equipment such as circuit breakers, relays, or contacts will maintain correct operational state during shaking.

Procedures for qualification by experience data have been developed by the nuclear power industry for certain categories of equipment powered at voltages up to about 15 kV. These procedures are supported by an existing database of adequate size and detail and a standard set of restrictions and requirements for reviewing specific equipment items. These procedures are discussed in Annex Q and in the EPRI/SQUG standard [B10]. Qualification by experience data requires appreciable expertise; it is suggested that the standards developed by the nuclear industry be used whenever possible.

6.8 Response spectra

A response spectrum is a plot of maximum response (displacement, velocity, or acceleration) versus a system characteristic (frequency or period and damping ratio) for a single degree-of-freedom oscillator for a particular applied load, such as an earthquake acceleration time history. Computation of a response spectrum is shown in Figure 17 in Chopra [B7]. The response, for each single degree-of-freedom oscillator, to the acceleration time history is calculated by numerical evaluation of the Duhamel integral or by numerical solution of the equation of motion. The maximum response of each oscillator is plotted as a function of damping ratio and period or frequency. After plotting the maximum responses for a sufficient number of frequencies or periods at a specified damping ratio, a response spectrum is created. The damping ratio can be changed to develop a family of response spectra.

The response spectra used in this recommended practice are intended to reasonably envelop anticipated earthquakes. Different earthquakes will have different response spectra. Strong motion accelerometers in different locations for the same earthquake will likely record different acceleration time histories and thus may have different response spectra.

For shake table testing, a displacement time history can be fed to actuators or hydraulic rams that shake the table. Accelerometers can be located on the shake table to measure the acceleration time histories. These

acceleration time histories can be evaluated to create test response spectra at specified damping ratios. If the test response spectra envelop the required response spectra at the same percent of damping, then the testing is acceptable.

Response spectra are used to calculate responses (strain, velocity, displacement, acceleration) for each natural frequency or mode shape in a dynamic analysis. After the maximum response for each mode shape is determined, the maximum total response can be calculated. The maximum total response is not obtained by adding the response variable of each mode shape, because different modes will obtain their maximum values at different times. The superposition of modal maximums is an upper bound on the actual total response and will significantly overestimate the response for most cases. This recommended practice, uses SRSS or CQC for combining modal maximums to obtain the total response.¹⁴

6.9 Damping

Damping is a characteristic of a structure. Damping should not be associated with a particular device or material (e.g., if a structure with a particular damping device/material achieves “x” percent damping, it cannot be assumed that the same level of damping can be achieved with that same device/material on a different structure).

Damping is in fact mode specific, but in the context of this recommended practice, the term is generalized to one single value. This generalized value of damping is applicable to all modes of vibrations and in any direction of movement and should therefore be conservative in nature (e.g., if a structure achieves a value of “x” percent damping in one axis and “y” percent damping in another axis, the lower value of the two damping values should be assumed as the generalized value).

Damping characteristics of a structure may change with the level of stress of the materials in the structure. All levels of damping associated with this practice should be associated with levels of stresses below the allowable material stresses mandated herein.

A maximum damping value of 2% can be assumed on all equipment and structures.

Claims of any damping beyond 2% must be substantiated by testing (A.1.1.3). Historically, the determination of damping of substation equipment has been focused on the damping associated with the horizontal response of equipment and with particular emphasis on the lower modes of vibration. This practice seems to have resulted in designs that have performed adequately in earthquakes and is thus condoned in this recommended practice.

7. Design considerations

7.1 Structural supports, excluding foundations

The structural support requirements provided herein are applicable to the equipment’s “first support.” (See Definition 3.1.9.) All other support structures should be designed according to the ASCE Substation Structure Guide. Connection of the “first support,” including connections of the first support to ASCE designed supports, shall be designed according to the requirements of this recommended practice.

7.2 Foundation analysis

This subclause applies to the design of foundations and the analysis of the soil. It does not apply to anchorage. See ASCE Substation Structure Design Guide and A.4.2 for anchorage.

As an option to 7.2.1 and 7.2.2, the user may design the foundations to appropriate codes.

7.2.1 Pad type foundation supporting flexible equipment

Pad type foundations supporting flexible equipment may be designed using loads that are less than the foundation loads found in the qualification of the equipment and support. Foundation can be analyzed to the following:

$$F_p = 0.33 \times I_p \times W_p \text{ for High Qualification areas} \quad (5)$$

$$F_p = 0.2 \times I_p \times W_p \text{ for Moderate Qualification areas} \quad (6)$$

F_p is the lateral load applied at the center of gravity of the equipment/support; I_p is the importance factor, as defined by the ASCE Substation Structure Design Guide; and W_p is the weight of the equipment/support. As always, the dead weight of the equipment and foundation should be considered a vertical load. Normal operating loads, if applicable, should be included. F_p can be used for overturning and determining the loads on the soil. This method requires using working allowables for the soils, instead of ultimate.

7.2.2 Pad type foundations supporting heavy or rigid equipment

Pad type foundations supporting heavy or rigid equipment, such as transformers, may be designed to the same criteria as flexible equipment. Special care should be exercised when designing the foundation and evaluating the soils. Poor or marginal soils may require that engineered fill or piles be placed under the foundation. Limited settlement, rocking, cracked, and/or damaged foundations have been observed after earthquakes.

7.2.3 Pier and pile type foundations

Pier and pile type foundations supporting equipment should be designed to the loads found in the qualification process for the equipment and support. However, the soil may be analyzed by the same criteria and loads as the pad type foundations.²⁰

If the electrical support structure is designed to act as an integral unit at the high and moderate performance levels and is located on multiple foundations, then consideration should be given to connecting the foundation with grade beams to minimize differential foundation displacement due to an earthquake.

7.3 Station service

Station service is one key element necessary to bring earthquake-damaged substations back on line. The station service normally comprises lower voltage equipment (except the transformer high-voltage side), and experience has shown that such equipment is generally inherently rugged. However, station service has been lost in earthquakes, which can often be traced to inadequate attention to detail. The following checklist can be used when designing the station service:

- a) Verify that all equipment and supports are adequately anchored to the foundations.
- b) Verify that all equipment is decoupled by providing adequate slack or jumper loops in the conductors and interconnections with rigid bus.
- c) Verify that equipment meets the requirements of Annex B through Annex P.
- d) Verify that the support structures are rugged.
- e) Verify that there are no weak hinge points in the structures.

²⁰The equation factors of 7.2.1 should be increased as deemed necessary by the engineer for tall, top-heavy pedestal-type equipment and support.

- f) Verify that the bushings and their mounting fittings to the equipment are adequately designed.
- g) Verify that there are no objects, such as trees or branches, which are outside of the station service area but can fall into the station service area.
- h) It is desirable, if practicable, to place the station service equipment on one solid foundation. If liquefaction or soil settlement occurs, damage can be minimized using this technique. Also, differential movement between equipment is minimized.
- i) All items, including “non-critical” items (such as light poles), that are within or near the station service area that have the potential of falling on station equipment or energized bus, should be considered as critical and designed not to fail, because their failure could cause the station service to fail.
- j) Verify that no damage will result from the swinging of any suspended or hung equipment or article.

7.4 Emergency power systems

7.4.1 Station and other batteries

7.4.1.1 Station batteries

Experience in moderate and large earthquakes (magnitudes 6.4 and above) has shown that area-wide blackouts can occur well beyond areas of direct earthquake damage; thus, it is recommended that critical substations should have emergency generating systems. In the aftermath of an earthquake, travel times to deliver mobile emergency generating systems may be four or more times longer than normal.

Station batteries are needed for normal and emergency operation of control systems and emergency operation of communication systems. The capacity reserve of the battery, that is, the number of hours the battery can supply emergency load, typically ranges from 2 h to 6 h. Emergency generating systems can provide vital loads for an extended duration. For critical sites without emergency generating systems, battery capacity reserve should be determined by the time it would take to supply emergency power with a mobile generator.

During the life of a battery, it electrochemically degrades and its internal structure weakens. The service life of batteries is sensitive to their operating temperature. Their life is typically reduced by about half for every 10 °C above the rated operating temperature of 25 °C. The end of a battery's service life is usually defined when it can no longer provide 80% of its published capacity. Thus, for a battery to meet its load requirement at the end of its service life, it must have a published capacity of 125% of its design load. Optimum battery performance and service life can be achieved by implementing a surveillance and maintenance program for the type of battery in service (Refer to IEEE Std 450™-2002 [B18] and IEEE Std 484™-2002 [B19] for vented lead-acid batteries, IEEE Std 1106™-2005 [B20] for vented nickel-cadmium batteries, and IEEE Std 1187™-2002 [B22] for valve regulated lead-acid (VRLA) batteries).

7.4.1.2 Other batteries

Substations may have batteries in addition to station batteries for starting an engine generator, radio communications, and microwave communications. These batteries are usually much smaller than station batteries but should still be restrained so that they do not impact adjacent equipment, fall, or move so that power connections are damaged.

7.4.2 Emergency generating systems

The performance of emergency generating systems after earthquakes has not been good for several reasons. These reasons include inadequate anchorage of the engine-generator or fuel supply system, overturning or malfunction of the engine-generator control system, fouled fuel, uncharged starting batteries, or overloading of the system. Detailed discussion of issues related to the selection, installation, operation, maintenance, and testing of emergency generators is contained in the ASCE “Guide to Reliable Emergency Power for Lifelines and Critical Applications” [B1].

The most common problems with emergency generators are easily avoided, as follows:

- a) *Generator anchorage.* Engine generators are often mounted on vibration isolation systems to keep vibrations of the engine generator from getting into the engine support structure. In most cases, these isolation systems are not necessary. If they are used, it is vital that the system that is supported be restrained so that its motion is limited and that it cannot fall off of its support system. Some isolation systems have self-contained restraints, but they are often made of cast iron and fail under earthquake induced loads. It is also important to provide all utility connections, such as the fuel line, control lines, power lines, and cooling water lines, with adequate slack and flexibility. Combustion air ducts and exhaust piping should incorporate flexible sections.
- b) *Securing engine-generator-starting batteries.* Frequently, in otherwise well-engineered emergency power facilities, batteries that are used to start the engine generator are unanchored. In an earthquake, unanchored batteries can be damaged and, hence, unavailable to start the emergency engine. Batteries should be secured so that they cannot fall or slide and impact against each other or their support structure.
- c) *Day tank anchorage.* Day tanks are small tanks located near the engine generator and fed from the main storage tank. Typically they consist of a closed fuel tank sitting in a second open tank. Although the overall system is typically anchored to the floor, the closed tank may not be anchored to the open tank in which it sits. In this case, fuel lines provide the restraint to secure the tank. The load path for all system components should be evaluated for adequate strength and limited flexibility.
- d) *Fouled and contaminated fuel.* If diesel fuel is used, it should be treated with additives to prevent growth of micro-organisms and changed periodically, about every five years. Fouled fuel will clog injectors and filters. Under some conditions, partially filled tanks will allow water to condense and contaminate the fuel. Low pour point fuels (Diesel 1) have been found to be more stable in long-term storage than higher pour fuels (Diesel 2).
- e) *Posted manual operating instructions.* Several conditions can prevent an engine from starting. For example, relays used to control and protect the engine may malfunction due to earthquake-induced vibrations. It is important that detailed instruction be posted near the engine for starting the units. These instructions should indicate the proper position for all switches and valves and sequence of actions needed to start the engine.
- f) *Annually compare engine-generation capacity to its load.* Annually review electrical load on the engine generator to ensure that it is below its capacity. The load calculation should include the increased demand associated with inductive loads such as starting motors.
- g) *Annual verification of starting batteries and charger.* Annually verify that the starting batteries are charged and the charging unit is operating properly.
- h) *Tested at rated capacity.* The complete system should be tested at its rated capacity for several hours at least once a year. Preferably this should be done by simulating loss of normal station service and applying all emergency loads. If this is not practical, a load bank should be employed.

7.5 Telecommunication equipment

Three features common to telecommunication equipment can cause poor performance in earthquakes. They are as follows:

- a) *Flexible anchorage details of communication equipment racks.* Telecommunication equipment racks are typically anchored to the floor by four bolts through large aluminum angles in front and back. Although this anchoring method may have adequate strength, it is very flexible. These racks can experience earthquake-induced motions of many centimeters at the top of the rack. It is important that cable connections be provided with adequate slack to accommodate these motions. These motions can be greatly reduced by providing an upper brace to the rack by attaching the top of the rack to an overhead cable tray. The design should also prevent stretching or pinching of cables between cable trays or between rack and cable tray.
- b) *Communication cable trays.* Cable trays commonly used by the communication industry are constructed so that sections are connected with friction clips. If these trays are used to brace equipment racks, positive connections should be used in their assembly.
- c) *Communication equipment circuit board or pack restraints.* Communication equipment often contains circuit boards, or circuit packs, that plug into a motherboard mounted in the equipment chassis. These boards should have positive restraints to prevent them from vibrating loose. The restraints can be provided by circuit board retractors with locks or with other means to restrain the boards.

8. Seismic performance criteria for electrical substation equipment

8.1 Introduction

This clause describes

- a) Three seismic qualification levels (high, moderate, and low).
- b) The RRS and/or requirements for each qualification level.
- c) The substation equipment performance that can be expected for each qualification level.
- d) The projected performance and how the performance levels and qualification levels are related to each other.
- e) Guidelines to the equipment user or user's agent on how to select the appropriate qualification level.

8.2 Objective

The objective of this practice is to allow the user to secure individual equipment that will be completely undamaged and will continue to function after being subjected to the shaking described by the RRS for a given level, as specified in 8.3. It is further anticipated that the equipment will perform acceptably after ground shaking equivalent to the corresponding performance level, as described in 8.4 with little or no significant structural damage, and that most equipment will continue to function. However, some minor damage may occur and a small amount of equipment may not fully function after shaking to the performance level. (See 6.6 for a discussion of electrical function.)