

# IEEE Recommended Practice for Seismic Design of Substations

IEEE Power and Energy Society

Sponsored by the  
Substation Design Criteria Committee

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USA

IEEE Std 693™-2018  
(Revision of  
IEEE Std 693-2005)

# **IEEE Recommended Practice for Seismic Design of Substations**

Sponsor

**Substation Design Criteria Committee  
of the  
IEEE Power and Energy Society**

Approved 23 October 2018

**IEEE-SA Standards Board**

**Abstract:** Seismic design recommendations for substations, including qualification of different equipment types 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, IEEE 693™, loads, projected performance, required response spectrum, seismic protective devices, seismic qualification, shake table, static coefficient analysis, support structure, suspended equipment, time history

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## Introduction

This introduction is not part of IEEE Std 693-2018, IEEE Recommended Practice for Seismic Design of Substations.

This revision of IEEE Std 693-2005 was developed as a recommended practice for the seismic design of substations. This recommended practice emphasizes the seismic qualification of electrical equipment. Nuclear Class 1E equipment is not covered by this recommended practice, but it is covered by IEEE Std 344<sup>TM</sup>.

This recommended practice is intended to establish standard methods of providing and validating seismic withstand capability of electrical substation equipment. It provides detailed test and analysis methods for selected common equipment types of major equipment or components 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. This 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.

This revision of the recommended practice incorporates a number of substantive as well as editorial changes from the previous version. The most significant of these changes include the following:

- Shake-table test requirements for qualification of bushings have been modified;
- Conductor seismic loading effects are explicitly included as part of the qualification of certain equipment;
- Time history shake-table testing at the Performance Level is required for most equipment that are required to be qualified by the time history test method;
- Seismic loads for the design of anchorages of inherently acceptable equipment have been increased.

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 Scope

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

### 1.2 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. Instructions on how to include this recommended practice in specifications are provided. 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 without modification or removal of any requirement, except as allowed herein.

### 1.3 General

This recommended practice provides minimum requirements for the seismic design of substations and seismic qualification of equipment. Emphasis is on seismic qualification of electrical equipment and its anchorage. Instructions on the use of this recommended practice is provided in Clause 4.

There are several important goals of this recommended practice; one 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 qualification documentation. The intent of a uniform and consistent seismic qualification procedure is to enable manufacturers to incorporate seismic criteria into their design process and reduce the cost for qualification of substation equipment. Manufacturers can qualify their equipment once for a given qualification level and reduce the need for specialized testing. It should also improve earthquake performance by establishing clear performance criteria that take into account the dynamic characteristics of substation equipment.

Another goal of this recommended practice is to allow the user, or user's agent, to secure substation equipment that will have no significant structural damage and maintain electrical functionality at nominal operating conditions during and after a seismic event as specified herein.

This recommended practice establishes three qualification levels for earthquake performance. They are low, moderate, and high qualification levels. The user is required to determine the qualification level when purchasing the equipment.

## **1.4 Associated design references**

### **1.4.1 Electrical connections between equipment**

The design and implementation of electrical connections between equipment should be in accordance with the recommendations of this recommended practice and IEEE Std 1527<sup>TM</sup>.

### **1.4.2 Electrical equipment**

Electrical equipment and their associated anchorage should be designed in accordance with the requirements given within this recommended practice and ASCE 113.

### **1.4.3 Dedicated support structures**

Dedicated support structures, which are qualified together with the equipment, shall be designed in accordance with the requirements of this recommended practice as prescribed by the methodology used to qualify the supported equipment. All other support structures may be designed in accordance with this recommended practice or the requirements given in ASCE 113. Connection of the equipment to any support structure shall be designed in accordance with the requirements of this recommended practice.

### **1.4.4 Primary substation structures**

The seismic design of primary substation structures, (e.g., strain bus structures, A frames, rigid bus structures, etc.) is beyond the scope of this recommended practice and should be designed in accordance with the requirements given in ASCE 113. The anchorage of substation structures should be designed in accordance with ASCE 113.

### **1.4.5 Foundations**

Foundations are designed to have an adequate load capacity with limited settlement and lateral displacement by a civil or geotechnical engineer and the footing itself may be designed structurally by a civil or structural engineer. The primary design concerns are settlement and bearing capacity. When considering settlement, total settlement and differential settlement are normally considered. Foundation loads from the equipment may be designed in accordance with 6.6 or to the requirements of the relevant code in the jurisdiction of the utility and/or substation.

#### **1.4.6 Buildings**

Buildings should be designed in accordance with the requirements of the relevant code in the jurisdiction of the substation.

#### **1.5 Substation seismic design flow chart**

A flow chart (Figure 1) has been provided to help the user determine what clauses or annexes should be used for the seismic design of the substation.

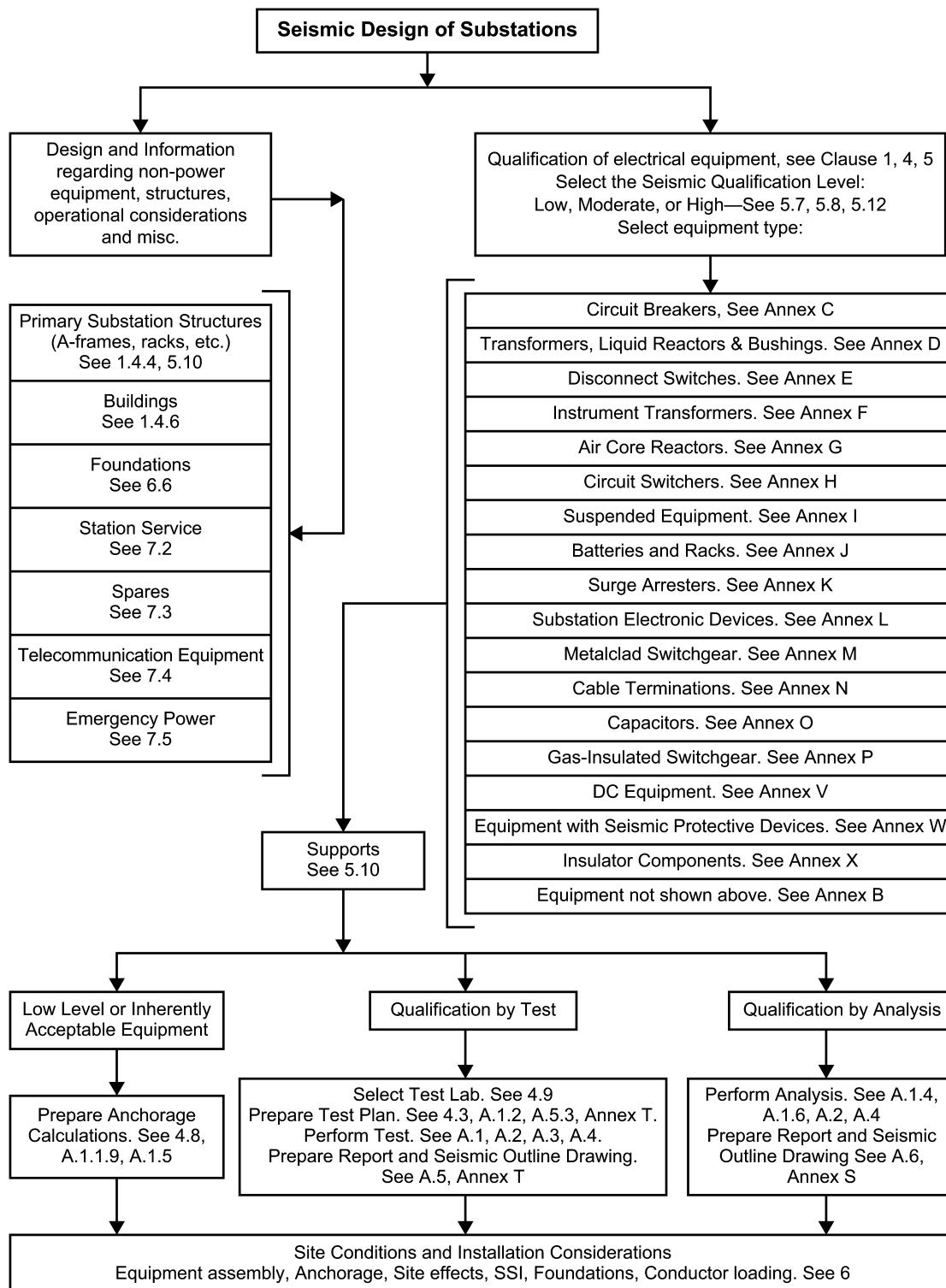


Figure 1—Using this recommended practice

## **1.6 Earthquakes and substations**

An earthquake is the sudden release of energy from rupture of geological faults in the earth's crust in which elastic strain has been accumulating: a sudden lateral or vertical movement of rock along a rupture (break) surface. The seismic waves that radiate from the rupture arrive at the earth's surface as a complex multi-frequency vibratory ground motion, having both horizontal and vertical components.

It is this ground shaking, surface faulting, and earthquake induced soil failure that can damage substation equipment.

The poor seismic performance of substations during previous earthquakes, coupled with society's demand for electrical service in a post-earthquake environment, lead to an increased focus on the earthquake survivability of substations.

The initial approach of providing earthquake engineering to substations was based on the approaches used in conventional building structures. However, the realization emerged that the seismic engineering of substations presented unique challenges that differed from buildings. Among these challenges are the need to maintain functionality, the unique materials (e.g., porcelain and composites), relatively low damping and high frequency dynamic characteristics (in comparison to building structures), and the effects of the interconnection of the equipment via electrical conductors.

## **1.7 Design/construction and quality assurance processes**

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 of plans and inspection of as-installed facilities to verify that the intentions of this recommended practice are preserved.

## **2. Normative references**

The following referenced documents are indispensable for the application of IEEE Std 693. The referenced documents must be understood and used in conjunction with this document. Therefore each referenced document is cited in text and its relationship to this document is explained. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ACI 318, Building Code Requirements for Structural Concrete and Commentary.<sup>1</sup>

ADM 1-516166, Aluminum Association, Aluminum Design Manual, Specification and Guidelines for Aluminum Structures.<sup>2</sup>

AISC Manual of Steel Construction.<sup>3</sup>

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<sup>1</sup> ACI publications are available from the American Concrete Institute, 38800 Country Club Drive, Farmington Hills, MI 48331, USA (<https://www.concrete.org>).

<sup>2</sup> ADM publications are available from the Aluminum Association, 1525 Wilson Boulevard, Suite 600, Arlington, VA 22209, USA (<http://www.aluminum.org>).

<sup>3</sup> AISC Publications are available from the American Institute of Steel Construction, 130 East Randolph, Suite 2000, Chicago, IL 60601, USA (<http://www.aisc.org>).

ANSI/NEMA C29.9, Wet Process Porcelain Insulators—Apparatus, Post Type.<sup>4</sup>

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

ASCE 4, Seismic Analysis of Safety-Related Nuclear Structures.<sup>5</sup>

ASCE 7, Minimum Design Loads for Buildings and other Structures.

ASCE 113, Substation Structure Design Guide.

ASTM F1554, Standard Specification for Anchor Bolts, Steel, 36, 55, and 105-ksi Yield Strength.<sup>6</sup>

IBC, International Building Code.<sup>7</sup>

IEC 60099-4, Surge arresters—Part 4: Metal-oxide surge arresters without gaps for ac systems.<sup>8</sup>

IEC 61462, Composite hollow insulators—Pressurized and unpressurized insulators for use in electrical equipment with rated voltage greater than 1000 V—Definitions, test methods, acceptance criteria and design recommendations.

IEC 62155, Hollow pressurized and unpressurized ceramic and glass insulators for use in electrical equipment with rated voltages greater than 1000 V.

IEC 62231, Composite station post insulators for substations with ac voltages greater than 1000 V up to 245 kV—Definitions, test methods and acceptance criteria.

IEC 62231-1, Composite station post insulators for substations with ac voltages greater than 1000 V up to 245 kV—Part 1: Dimensional, mechanical, and electrical characteristics.

IEC 62271-102, High voltage switchgear and controlgear—Part 102: Alternating current disconnectors and earthing switches.

IEEE Std 48<sup>TM</sup>, IEEE Standard Test Procedures and Requirements for Alternating-Current Cable Terminations 2.5 kV through 765 kV.<sup>9, 10</sup>

IEEE Std 518<sup>TM</sup>, IEEE Guide for the Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources.

IEEE Std 824<sup>TM</sup>, IEEE Standard for Series Capacitors in Power Systems.

IEEE Std 1036<sup>TM</sup>, IEEE Guide for Application of Shunt Power Capacitors.

IEEE Std 1527<sup>TM</sup>, IEEE Recommended Practice for the Design of Buswork Located in Seismically Active Areas.

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<sup>4</sup>ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42<sup>nd</sup> Street, 13<sup>th</sup> Floor, New York, NY 10036, USA.

<sup>5</sup>ASCE publications are available from the American Society of Civil Engineers, 1801 Alexander Bell Drive, Reston, VA 20191-4400.

<sup>6</sup>ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshocken, PA 19428-2959, USA.

<sup>7</sup>IBC publications are available from International Code Council, 900 Montclair Road, Birmingham, AL 35213-1206, USA.

<sup>8</sup>IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3 Rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (<http://www.iec.ch/>). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

<sup>9</sup>IEEE publications are available from The Institute of Electrical and Electronics Engineers, Inc., 445 Hoes Lane, Piscataway, NJ 08854, USA (<http://standards.ieee.org/>).

<sup>10</sup>The IEEE standards or products referred to in this clause are trademarks of The Institute of Electrical and Electronics Engineers, Inc.

IEEE Std C37.016<sup>TM</sup>, IEEE Standard for AC High-Voltage Circuit Switcher Rated 15.5 kV through 245 kV.

IEEE Std C37.06<sup>TM</sup>, Switchgear—AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Preferred Ratings and Related Required Capabilities.

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

IEEE Std C37.20.1<sup>TM</sup>, IEEE Standard for Metal-Enclosed Low-Voltage (1000 Vac and below, 3200 Vdc and below) Power Circuit Breaker Switchgear.

IEEE Std C37.20.2<sup>TM</sup>, IEEE Standard for Metal-Clad Switchgear.

IEEE Std C37.30.1<sup>TM</sup>, IEEE Standard for High-Voltage Air Switches for Alternating Current, Rated Above 1000 Volts.

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

IEEE Std C37.90.2<sup>TM</sup>, IEEE Standard for Withstand Capability of Relay Systems to Radiated Electromagnetic Interference from Transceivers.

IEEE Std C37.100.1<sup>TM</sup>, IEEE Standard for Common requirements for switchgear rate above 1000 Volts.

IEEE Std C37.122<sup>TM</sup>, IEEE Standard for Gas-Insulated Substations.

IEEE Std C57.12.00<sup>TM</sup>, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.13<sup>TM</sup>, IEEE Standard Requirements for Instrument Transformers.

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

IEEE Std C57.19.00<sup>TM</sup>, IEEE Standard General Requirements and Test Procedure for Outdoor Power Apparatus Bushings.

IEEE Std C57.21<sup>TM</sup>, IEEE Standard Requirements, Terminology, and Test Code for Shunt Reactors Over 500 kVA.

IEEE Std C62.11<sup>TM</sup>, IEEE Standard for Metal-Oxide Surge Arresters for Alternating Current Power Circuits.

MDOC-CDS, Manual de Diseño de Obras Civiles, de la Comisión Federal de Electricidad, Instituto de Investigaciones Eléctricas, México.<sup>11</sup>

National Building Code of Canada (NBCC).<sup>12</sup>

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<sup>11</sup> MDOC/CFE publications are available from the Civil Engineering Department, P.O. Box 1-475, 62001, Cuernavaca, Mor, Mexico.

<sup>12</sup> The National Building Code of Canada is available from the National Research Council of Canada, Institute for Research in Construction, Ottawa, Canada.

### 3. Definitions, acronyms, and abbreviations

#### 3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.<sup>13</sup>

**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 ( $\text{m/s}^2$ ) squared, and thus, it considers the full range of frequencies recorded over the duration of the given record.

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

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

where

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

**brittle material:** 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.

**bushing shake-table rated moment:** The measured moment observed at the insulator-flange interface corresponding to the prescribed shake table test. The maximum moment that the bushing can survive without damage, i.e., the moment capacity, will be equal to or greater than the shake-table rated moment.

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

**composite insulator:** An insulator composed of a fiber-reinforced core, with metal end fittings, and elastomer sheath and sheds.

**critical variables:** Strain, stress, and deflection determined at locations that indicate the seismic or structural capacity of a component.

**dedicated support:** A dedicated support is a structure designed exclusively to support only a single piece of substation equipment. Dedicated supports may be seismically qualified in conjunction with a specific piece of equipment by the prescribed methodology in this recommended practice for the supported equipment. Examples include a pedestal supporting a CVT or the entire structure supporting a disconnect switch.

**Design level:** The level of shaking or seismic event that is half the performance level. At this level of shaking or seismic event, qualified equipment should be fully functional and completely undamaged.

**ductile material:** Material that experiences considerable plastic deformation before fracture. Considerable plastic deformation is defined as 10% or greater in 5 cm (2 in) at failure in tension.

**dynamically equivalent or better support structure:** A functionally similar support structure that results in seismic demand of the equipment that is less than or equal to that occurring when mounting the equipment on a support with which the equipment has been seismically qualified.

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<sup>13</sup>*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>.

**equivalent terminal force (ETF) method:** Method of accounting for the effects of conductor interaction by applying a force to the terminal of equipment. These responses due to ETF are then added to the seismic responses of the unconnected equipment item. See A.1.6.3.

**flexible equipment:** Equipment, structures, and components whose lowest resonant frequency is less than 33 Hz.

**fragility testing:** Vibration testing of substation equipment to the minimum level of shaking at which the equipment will experience structural failure.

**g:** Acceleration due to gravity that is  $9.81 \text{ m/s}^2$  ( $32.2 \text{ ft/s}^2$ ).

**ground acceleration:** The acceleration of the ground resulting from the motion of a given earthquake. *See: peak ground acceleration.*

**high (0.5 g) design level required response spectrum:** A response spectrum used to qualify equipment using the design level seismic qualification approach. The spectrum is defined by halving the acceleration values shown in Figure A.1 for the high performance level required response spectrum.

**high (1.0 g) performance level required response spectrum:** A response spectrum that directly reflects the accelerations associated with the seismic qualification objective (refer to 5.2) at the high level. The spectrum is defined by the plots and equations detailed in Figure A.1.

**intermediate support:** The structural member or sub-assembly in between the equipment and primary substation structure. Intermediate supports may also act as the support for other pieces of equipment, or conductor pull off loads.

**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.

**maximum mechanical load (MML):** The largest service load allowed on a composite hollow insulator or bushing. The MML is within the reversible elastic range and is specified by the manufacturer. See IEC 61462 (Ed. 1.0) and R.1.2.4.

**moderate (0.25 g) design level required response spectrum:** A response spectrum used to qualify equipment using the design level seismic qualification approach. The spectrum is defined by halving the acceleration values shown in Figure A.2 for the moderate performance level required response spectrum.

**moderate (0.5 g) performance level required response spectrum:** A response spectrum that directly reflects the accelerations associated with the seismic qualification objective (refer to 5.2) at the moderate level. The spectrum is defined by the plots and equations detailed in Figure A.2.

**modified performance level required response spectrum:** These spectra are used for shake-table testing transformer bushings and are defined in D.5.2.1.d).

**moment amplification factor (MAF) method:** Method of accounting for the effects of conductor interaction by applying a factor to the seismic responses of a standalone unconnected equipment item. See A.1.6.2.

**normal operating load:** Any force, stress, or load resulting from equipment operation that can reasonably be expected to occur during an earthquake, except the loads given in 6.10 through 6.12.

**peak ground acceleration:** The peak ground acceleration is the maximum ground acceleration of any component of the time history.

**performance level:** The level of shaking or seismic event at which qualified equipment is anticipated to perform acceptably with little or no significant structural damage.

**performance level response spectrum:** A response spectrum that directly reflects the accelerations associated with the seismic qualification objective (refer to 5.2).

**polymer-housed surge arrester:** Arrester using polymeric and composite materials for housing.

**primary substation structure:** In the context of the support of substation electrical equipment, a primary substation structure shall be considered to be any other structure not deemed a dedicated support. Primary substation structures may also support rigid bus work or conductors.

**required response spectrum (RRS):** Response spectrum that defines the required level of input motion for a given level of qualification.

**resonant frequency:** Frequencies coinciding with the natural frequency of a system (at which the response amplitude is a relative maximum) are known as resonance frequencies. At these frequencies, even small periodic driving forces can produce large amplitude oscillations.

**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.

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

**seismic identification plate:** A physical plate to be placed on the equipment identifying it as having satisfied the requirements of this recommended practice. See A.7 for details on the data to be placed on the plate.

**seismic outline drawing:** A drawing dedicated to the depiction of key seismic qualification parameters of the equipment and meeting the requirements of either A.5.5 or A.6.4. See also Annex S and Annex T.

**seismic protective device:** A device such as a base isolator or damper that reduces seismic response by lowering the frequency and/or increasing the damping to a system.

**seismic qualification approach:** The solution path for seismic qualification. The two seismic qualification approaches used in this recommended practice are the design level approach and the performance level approach.

**seismic qualification level:** There are three levels of qualification, high, moderate, and low. The level at which equipment must be qualified is dependent upon the seismicity of the region where it will be in service.

**seismic specialist:** An individual who, through education, training, and experience, is capable of planning, performing, and documenting a seismic qualification as described in this recommended practice (A.5.2, A.6.2).

**specified cantilever load:** As defined in IEC 62231, the cantilever load that a solid core station post composite insulator can withstand for a short term.

**specified long-term load (SLL):** As defined in IEC 60099-4, the force perpendicular to the longitudinal axis of an arrester, allowed to be continuously applied during service without causing any mechanical damage to the arrester.

**specified mechanical load (SML):** A rated load a composite insulating product (insulator or housing) can withstand for 1 min. It is predominantly associated with cantilever loads. The SML is equal to or greater than 2.5 times the maximum mechanical load (MML) for a composite hollow insulator.

**specified short-term load (SSL):** As defined in IEC 60099-4, the greatest force perpendicular to the longitudinal axis of an arrester, allowed to be applied during service for short periods and for relatively rare events without causing any mechanical damage to the arrester.

**standalone configuration:** The configuration of an equipment item that is not connected by conductors to equipment. The seismic qualification of the equipment is usually performed in the standalone or unconnected configuration. See 6.9.

**test response spectrum (TRS):** The response spectrum that is calculated from the time history motion recorded at the base of equipment in a time history (shake table) test.

**triaxial:** Test or analysis procedure in which the effects of vertical and two horizontal orthogonal components of earthquake are applied simultaneously.

**zero period acceleration (ZPA):** The acceleration level of the high-frequency, non-amplified portion of the response spectrum. This acceleration corresponds to the maximum (peak) acceleration of the time history used to derive the spectrum. For use in this recommended practice, the ZPA is assumed to be the acceleration 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/allowable strength 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
DCV	duty cycle voltage (rating)
DFR	digital fault recorders
E	earthquake loads or seismic loads; modulus of elasticity
EPDM	ethylene propylene diene copolymer
EPM	ethylene propylene copolymer
ETF	equivalent terminal force

FACTS	flexible alternating current transmission systems
FRP	fiberglass reinforced polymer
GIS	gas insulated switchgear
HVDC	high voltage direct current
IEC	International Electrotechnical Commission
IED	intelligent electronic devices
IBC	International Building Code
IT	instrument transformer
LTR	laboratory test report
LRFD	load and resistance factor design
MAF	moment amplification factor
MDOC/CFE	Manual de Diseño de Obras Civiles de la Comisión Federal de Electricidad
MML	maximum mechanical load
NBCC	National Building Code of Canada
PGA	peak ground acceleration
PSD	power spectral density ( $g^2/Hz$ vs. frequency)
RRS	required response spectrum
RTU	remote terminal unit
SCL	specified cantilever load
SDOF	single degree of freedom
SED	substation electronic devices
SER	sequence of events recorders
SLL	specified long-term load
SML	specified mechanical load
SR	silicone rubber
SRSS	square root of the sum of the squares
SSI	soil-structure interaction
SSL	specified short-term load
TRS	test response spectrum
VT	voltage transformer
W	wind loads
ZPA	zero period acceleration

## 4. Instructions

### 4.1 Format of this recommended practice

This recommended practice is divided into seven clauses (Clause 1 through Clause 7) and 25 annexes (Annex A through Annex Y). Clauses contain general seismic requirements. Annex C through Annex P and Annex V 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 and Annex V, the seismic requirements of Annex B may be used, if applicable.

Sections of the document that are deemed “normative” establish requirements of the recommended practice. Whereas sections of the document deemed “informative” are included for information purposes only.

All the clauses of the document (Clause 1 through Clause 7) are to be considered as being normative. Annexes can be either normative or informative. For any particular annex, the designation of it being either normative or informative will be in parenthesis immediately before the annex title.

### 4.2 Standardization of criteria

IEEE Std 693 is designed as an integrated set of requirements for the seismic qualification of electrical substation equipment. Users should use IEEE Std 693 as a whole. Do not modify or remove any requirement, except as allowed herein (refer to 5.8.3).

If any part of this recommended practice is changed, removed or not met, then neither the user nor the manufacturer may claim the equipment is in compliance with this recommended practice and should not attach the seismic identification plate to the equipment.

### 4.3 Specifying this recommended practice in user's specifications

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 and Annex V, such as circuit breaker, disconnect switch, or suspended wave trap, otherwise Annex B must be referenced.

NOTE—The electrical section of the user's specifications should define the detailed electrical requirements (e.g., voltage, BIL, creep lengths).<sup>14</sup>

- 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 4.4, 5.7, 5.8, and 5.12.
- d) Equipment's in-service configuration. The user or user's agent should specify:
  - 1) Whether the equipment be supplied with or without a support.

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<sup>14</sup> Notes to text, tables, and figures are for information only and do not contain requirements needed to implement the standard.

- 2) The configuration, height of the support, and any other specific detailing requirement, if furnished with a dedicated or intermediate support.
  - 3) The details of the support structure including anchorage points, if the manufacturer is responsible for qualifying the equipment on any other support, including primary substation structures.
- e) 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, Annex V, and Annex W.

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

The test plan schedule requirements should be omitted from the Annex B template if the qualification is by analysis.

#### **4.4 Selection of qualification level for a region**

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. In the event of equipment malfunction following an earthquake, equipment from other substations or standard spares can be moved and installed in the substation that experienced the loss. Equipment inventory management may be simplified by employing the fewest number of different qualification levels.

When selecting or standardizing a seismic qualification level for a region, the qualification level should be based on the highest seismicity within the region being considered. Refer to 5.7 and 5.12.

#### **4.5 Acceptance of previously qualified electrical equipment**

##### **4.5.1 Acceptance of previous qualifications from other standards**

Equipment that is in conformance with other standards may be acceptable and need not be requalified. However, a supplemental report shall be prepared by a seismic specialist. The supplemental report must provide detailed explanation and documentation that shows that the previous qualification adequately meets or exceeds the requirements of this recommended practice. “Adequately” means that the previous qualification can be used to meet or exceed the requirements of the current recommended practice, in the opinion of the user and the seismic specialist.

##### **4.5.2 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 specifically excluded by the current version.

The equipment that is excluded by the current version are the following:

- Bushings that are required to be qualified by time history testing (by D.5.5)

- Equipment utilizing composite insulators that have not passed the shed seal test (by A.4.6)
- Equipment 110 kV and above with conductor load effects, and qualified by means other than the static pull test (by A.1.6)
- Surge arresters 90 kV DCV and above with conductor load effects (by A.1.6.)
- Inherently acceptable equipment—anchorage calculations (by A.1.5)

For equipment that is excluded by the current version as listed above, a supplemental report shall be prepared by the seismic specialist to be able to qualify the equipment to the current version of the recommended practice. The qualification will be acceptable provided the issues that cause the exclusion can be shown to be satisfied in the previous qualification or additional analysis or tests that are performed. The supplemental report shall clearly identify the report applicable to the previously qualified equipment. The manufacturer shall furnish to the user, the supplemental report, and the seismic report for the previously qualified equipment.

#### **4.5.3 Seismic identification plate**

When previously qualified equipment has satisfied the requirements of 4.5, the manufacturer shall furnish a seismic identification plate in accordance with A.7.2. The manufacturer of such equipment shall provide to the user a supplemental report/letter that includes depiction of the seismic identification plate.

### **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 4.6.10. 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 annex specified technique. Qualification techniques with recognized options are limited to those listed in 4.6.2 through 4.6.10.

It should be noted that these are manufacturers' options only. The user is not to exercise these options. The qualification shall be done according to the requirements of A.1, and the acceptance requirements shall be according to the requirements of A.2 or A.4 as applicable.

#### **4.6.2 Option to static analysis**

When static analysis is specified, the manufacturer has the option of substituting it by dynamic analysis, time history analysis, or time history testing (design or performance level), 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 it by the static coefficient analysis method as defined in A.1.4.6, provided a static coefficient of 1.5 is used and all other requirements are met.

#### **4.6.4 Option to dynamic analysis (time history analysis or testing)**

When dynamic analysis is specified, the manufacturer has the option of substituting it by the time history analysis or time history test (design or performance level) and its associated acceptance criteria in lieu of the analytical method, provided all other requirements are met.

#### **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 analysis, or time history test (design or performance level) as an alternative method of analysis, provided all other requirements are met.

#### **4.6.6 Option to time history analysis**

When the time history analysis is specified, the manufacturer has the option of time history test (design or performance level) as an alternative method of analysis, provided all other requirements are met.

#### **4.6.7 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 (refer to Figure A.1 of Figure A.2) provided all other requirements are met.

#### **4.6.8 Option to design level test**

When design level testing (refer to 5.4.2) is specified, the manufacturer has the option of testing using performance level testing (refer to 5.4.1).

#### **4.6.9 Option to pull test**

When a pull test is specified, the manufacturer has the option of substituting the time history test and its associated acceptance criteria in lieu of the pull test, provided all other requirements are met.

#### **4.6.10 Option to test to the design level**

For some equipment types and configurations, testing at the performance level can be limited by the size and capacity of available shake table facilities, the unique configuration of the equipment to be tested, and the hazard involved with testing such equipment at high levels. For these types of equipment it is permissible to test to the design level (time history test) in lieu of testing to the performance level. The equipment types and configurations for which this option is allowed for qualification are detailed in Annex C through Annex P, Annex V, and Annex W.

### **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 have varying operating characteristics, such as current, voltage, BIL, etc. and may be combined into groups for qualification purposes. The most seismically vulnerable piece of equipment of each group shall be tested or analyzed, in accordance with the requirements of this recommended practice. 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 a supplemental seismic report. The supplemental report shall clearly identify the report applicable to the most seismically vulnerable equipment of the group. The manufacturer shall furnish the following reports to the user: the supplemental seismic report for the grouped item(s), and the seismic report for the most seismically vulnerable equipment of the group.

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. If qualification by test is required then it is acceptable to substitute the test with a dynamic analysis using a finite element analysis model that has been calibrated with the results from the original shake-table test. The qualification level demonstrated by the finite element analysis shall not exceed that of the item qualified by time history test. Note that additional equipment may be added to a grouping at any time. For example, an existing surge arrester, model number "Reference," has been qualified, and sometime later, a candidate surge arrester, model number "Candidate," is required. If surge arrester "Candidate" can be shown to be less vulnerable than surge arrester "Reference;" then surge arrester "Candidate" can be grouped with the qualification of surge arrester "Reference," provided the user or user's agent agree as discussed above.

When determining whether an equipment item is suitable for grouping and less vulnerable than the most seismically vulnerable member of a group, the assessment should include but not be limited to the following considerations:

- Mass and stiffness of the equipment
- Geometry (e.g., general configuration, height, location of center of mass)
- Use of identical or very similar components
- Dynamic response of the equipment
- Magnitude of conductor load effects
- Strength of load-carrying elements
- Differences that may influence functionality
- Support structure
- Anchorage details

The manufacturer shall determine the following information for each item that is qualified by group and report the results on the seismic outline drawing for the equipment.

- a) Anchorage loads
- b) Peak terminal deflections

A seismic outline drawing shall be provided for the "Reference" equipment item that is seismically qualified. A list of the "Candidates" equipment in the grouping shall be provided in the seismic report.

## **4.8 Inherently acceptable equipment**

Post-earthquake observations have demonstrated that equipment with lower voltage ratings (i.e., less than 35 kV) generally perform well during earthquakes. Equipment can only be deemed inherently acceptable if it is within the classification ratings, and similar in operation and construction, of Annex C through Annex P, and Annex V, and fulfills all the requirements of A.1.5.

## **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, acceleration, weight, and overturning moment. Thus, the size and weight of equipment that can be tested may be restricted at some facilities (see 4.11).

Equipment identified in this recommended practice as requiring shake-table testing can be fully tested by many 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 equipment utilizing certain types of seismic protective devices (see 4.13).

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.

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.

When performance level testing is planned, the laboratory shall be warned that the equipment may be tested to the ultimate strength limits and thus it may be prudent to consider additional safety measures (refer to 5.4.1.1).

Minimum requirements for testing laboratories shall be as follows (for equipment with lowest resonant frequency  $> 1.4 \text{ Hz}$ ):

- a) The weight of the equipment shall not exceed the capacity of the table.
- b) The table shall be capable of enveloping the RRS for the equipment weight at frequencies of 0.70 times the lowest resonant frequency of the equipment, and all resonant frequencies up to 33 Hz, except the 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  $4 \text{ Hz} \times 0.70 = 2.8 \text{ Hz}$  and above.) See 4.13 for testing of low frequency equipment.
- c) The test laboratory equipment shall be capable of identifying resonant frequencies from at least 1 Hz in both horizontal directions and the vertical direction.
- d) The laboratory's control and function equipment shall be capable of performing all of the tests required by this recommended practice.
- e) The test laboratory personnel shall be experienced in performing testing work.
- f) The test laboratory shall be capable of producing the test data necessary to complete the laboratory test report to be used as an appendix to the qualification report by this recommended practice.

## **4.10 Witnessing of shake-table testing**

The shake table tests shall be witnessed by the qualified seismic expert who will be responsible for preparing the seismic qualification report.

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.

## **4.11 Equipment too large to be tested in its in service configuration**

Equipment too large to be mounted completely on the shake-table (e.g., gas-insulated switchgear) may be broken into sub-assemblies and tested separately, provided the parts tested produce conservative results, and the conservatism may be demonstrated by analysis or test. The test or analysis concept must be approved by seismic specialist and the user or user's agent, before it may 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.

## **4.12 Table extension frame**

Where a piece of equipment is geometrically too large to fit on a shake table, an alternative to the testing of sub-components is to use a table extension frame. The table extension frame should meet the following criteria:

- a) The table extension frame should be rigid. The check for rigidity should be that the TRS on the top of the table extension frame, with the equipment installed (at the equipment interface) should be similar in frequency content and amplification to the TRS at the shake table top. If significant peaks are observed, the table extension frame is not rigid and does not serve the purpose. The table extension frame should be designed and analyzed before testing. The rigidity of the test frame should be assessed through analysis and then verified through the testing method described herein.
- b) The table extension frame should not introduce significant rocking motion at the interface of the extension frame and equipment.

If a table extension frame is used, the TRS is defined as the motion at the equipment interface with the table extension frame and not at the top of the shake table.

## **4.13 Low-frequency testing**

Equipment with natural frequencies below 1.4 Hz may require special techniques. If it is apparent or reasonably possible that resonant frequencies exist below 1.4 Hz, testing below 1.4 Hz shall be done. The following technique 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 or constant sine 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.

## **4.14 Report templates**

The template given in Annex S should be used for the static coefficient method, static, dynamic, and time history analyses. The template given in Annex T should be used for time history shake table 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 customary unit format.

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

# **5. Seismic criteria for qualification of electrical substation equipment**

## **5.1 General introduction**

This clause describes:

- a) The seismic qualification objective.
- b) The seismic qualification approaches.
- c) Qualifications by test.
- d) Qualifications by analysis.
- e) Damping.
- f) Design and performance level testing.
- g) The response spectra.
- h) Other types of seismic criteria.
- i) The influence of support structures on the seismic response of equipment.
- j) Equipment mounted on an intermediate support.
- k) Equipment mounted in upper elevations of a building.
- l) Selecting a seismic level for qualification.

## **5.2 Seismic qualification objective**

### **5.2.1 General**

The objective of this recommended practice is to allow the user, or user's agent, to secure substation equipment that will have no significant damage (refer to 5.2.2) and maintain electrical functionality at nominal operating conditions during and after a seismic event as specified herein. This goal is termed the "seismic qualification objective."

The intent of the seismic qualification objective is to maintain the electrical functionality of a substation during and after an earthquake. Some damage is tolerated, provided that it is not significant structural damage (refer to 5.2.2).

Equipment that has survived a performance level earthquake defined in this recommended practice might have been weakened despite the fact that it demonstrated continued operability during and immediately after the event. It is acknowledged that, after withstanding the initial earthquake, a subsequent significant load may cause further damage to the equipment that may render it inoperative. Examples of significant loads may include high wind conditions, electrical faults, or large ice/snow conditions. The consideration of these types of subsequent events is beyond the scope of this document.

It is therefore important that any tolerated damage (damage not deemed to be significant damage) be repaired such that the equipment is restored to its full capacity in an expedient manner after an earthquake.

### **5.2.2 Significant damage**

Significant damage, a major criterion for judging the attainment of the seismic qualification objective, will be assessed in the context of the following:

- a) *Failure to maintain functionality*: Significant damage will have been deemed to have occurred if the equipment ceases to perform its primary electrical function.
- b) *Excessive yielding or fracture*: Significant damage will have been deemed to have occurred if yielding is to the extent such that it is judged that the equipment has a possibility of imminent collapse at nominal electric operating conditions. It is important to realize that yielding is permitted provided that it does not impair electrical functionality or pose a risk of imminent collapse. Fracture of a component is considered significant damage.

### **5.2.3 Uncertainties in achieving the seismic qualification objective**

Beyond the uncertainties associated with predicting and quantifying any naturally occurring event (refer to 5.8.3), the seismic qualification objective is a goal that is associated with the following uncertainties;

- a) *Variability in materials*: The inherent variability in material properties means that, statistically, components may perform at less than the expected capacity.
- b) *Uncertainties in the locations of critically stressed components*: If the locations of the highest stresses within the equipment are not accurately identified, then the monitoring during testing or the evaluation in analysis may overestimate the performance capabilities of the equipment.
- c) *Uncertainties in equipment response*: The response of the equipment to the dynamic loading may not be as anticipated or inelastic behavior may occur. It is therefore possible that the equipment may experience more severe loading than anticipated.
- d) *Seismic characteristics associated with the size of earthquakes considered, but not characterized in the evaluation, such as soil liquefaction, ground subsidence, lateral spreading, and soil-structure interaction*.

Consequently, as a result of these potential uncertainties, it is possible that the equipment may suffer premature failure in an earthquake or when attempting to test at the performance level.

## 5.3 Seismic qualification approaches

### 5.3.1 Specification of seismic qualification approaches

Two qualification approaches are defined herein: the “performance level qualification approach” (see 5.3.4) and the “design level qualification approach” (see 5.3.5).

To help ensure uniformity of qualification procedures for any specific type of equipment, the seismic qualification approach is established in each particular equipment annex. In addition to being equipment-specific, the seismic qualification approach is also dependent on either nominal system voltage or maximum rated voltage, depending on the type of equipment.

For a particular voltage level, the equipment annex will also specify the required method of qualification (e.g., test or analytical qualification method).

### 5.3.2 Comparison of response spectra for the performance level approach and design level approach

The accelerations of the response spectra used for the design level approach at the moderate and high seismic qualification levels are half of the performance level spectra at any given frequency and level of damping.

The ratio of 2 between the design and performance levels represents the inverse of the minimum allowable stress ratio for brittle materials. And for ductile materials, the factor 2 is based on the factors of safety built into the allowable strength design, conservative estimates of damping, and energy dissipation that is expected to accompany the equipment/support response at higher levels of loading.

### 5.3.3 Criteria for establishing the seismic qualification approaches and methods

Qualification methods specified in each equipment annex (refer to 5.3.1) are established from the following criteria:

- a) *Voltage level*: Higher voltage equipment has historically and theoretically demonstrated an increased vulnerability to seismic damage. Thus, the greater the rated voltage level for any given type of equipment requires a more stringent qualification procedure. Note that the qualification methods are based on the rated voltage, or nominal system voltage, not the extremes of operating voltage.
- b) *Historical performance*: Historical performance of general types of equipment (e.g., disconnect switches) have demonstrated the susceptibility of the equipment to seismic damage and the suitability of specific qualification methods.
- c) *Equipment importance*: Equipment critical to the function of the substation requires a more stringent qualification method.
- d) *Reasonableness of requirements*: Seismic qualification methods must be achievable. Methods, materials or processes must not be experimental or unreasonably expensive.
- e) *Linearity*: Equipment that utilizes non-linear components to reduce seismic loading must have a qualification method that accounts for the non-linearity.

### **5.3.4 Performance level seismic qualification approach**

#### **5.3.4.1 General**

Equipment qualified by the “performance level approach” attains the seismic qualification objective through application of seismic qualification methods using the performance level spectrum as input. A performance level response spectrum directly reflects accelerations associated with the seismic qualification objective for a given seismic qualification level (Moderate or High).

#### **5.3.4.2 Performance level testing**

Equipment qualified using a performance level approach in conjunction with testing is said to have been subjected to “performance level testing.” Performance level testing will utilize a performance level response spectrum which will be termed the “performance level required response spectrum.” A “test response spectrum” will be evaluated for sufficiency in comparison to the required response spectrum. The test response spectrum is developed from time-history shake-table records.

#### **5.3.4.3 Performance level analysis**

This document does not address the complexities of performing an analytical qualification of equipment at the performance level. While a performance level analysis may be needed to properly evaluate some types of highly non-linear systems (e.g., suspended equipment or base isolated equipment that are beyond the scope of Annex I and Annex W) this recommended practice does not provide acceptance criteria for analytically qualifying equipment at the performance level. For such cases, the acceptance criteria used for the analytical qualification shall be adherent to the seismic qualification objective, consistent with industry practice and agreed upon by the end user prior to proceeding with the analysis.

### **5.3.5 Design level seismic qualification approach**

#### **5.3.5.1 General**

Equipment qualified by the “design level approach” attains the seismic qualification objective by projection from a “design level response spectrum.” A design level response spectrum reflects accelerations that are half those associated with the seismic qualification objective for a given seismic qualification level (refer to 5.3.2).

Seismic qualification can only be made by successfully demonstrating that the equipment’s measured or calculated response (e.g., stress, load, deflection, etc.) to the design level response spectrum are within the allowable limits defined herein. The allowable limits are established such that extrapolation of the equipment performance to the accelerations associated with the performance level can be made while maintaining the seismic qualification objective.

#### **5.3.5.2 Design level testing**

Equipment qualified using a design level approach in conjunction with testing is said to have been subjected to “design level testing.” Design level testing will utilize a design level response spectrum which will be termed the “design level required response spectrum.” A “test response spectrum” will be evaluated for sufficiency in comparison to the required response spectrum. The test response spectrum is developed from time-history shake-table records.

### **5.3.5.3 Design level analysis**

Equipment qualified using a design level approach in conjunction with analysis is said to have been subjected to “design level analysis.” Design level analysis will utilize a design level response spectrum which will be termed the “design level required response spectrum.” The required response spectrum may either be:

- a) Used directly in the analysis e.g., response spectrum analysis.
- b) Used as a measure of sufficiency of time-history earthquake records used for analysis.

## **5.4 Seismic qualification methods with respect to test qualifications**

### **5.4.1 Performance level testing**

#### **5.4.1.1 Conditions for performance level testing**

The following conditions shall apply when conducting performance level testing:

- a) *Acceptability of tested equipment:* Equipment subjected to performance level testing shall not be provided to the user unless the user accepts in writing the tested equipment.
- b) *Safety precautions:* When performance level testing is planned, the test facility shall be warned that the equipment may be tested to the limits of performance and thus it may be prudent to consider additional safety measures. Some precautions may include tethering equipment so that it does not fall and hit the shake table if it fails, and providing protection to the shake table if an oil leak develops in the equipment.

#### **5.4.1.2 Advantages of performance level testing**

Performance level testing has the following two significant advantages over design level testing (and all analysis qualifications) as follows:

- a) *Greater assurance of performance:* Performance level testing substantially reduces uncertainty related to the structural behavior of critically stressed components. It is therefore possible, in all other qualification methods, that an unanticipated failure mechanism is overlooked and that the oversight is critical in nature.
- b) *Assurance of functionality:* Performance level testing is the only qualification method that can assure the seismic qualification objective of equipment functionality. This is by virtue of the principles that electrical functionality can neither be extrapolated from tests nor can it be established by analysis.

#### **5.4.1.3 Disadvantages of performance level testing**

Performance level testing has the following disadvantages in comparison to design level testing as follows:

- a) *Safety concerns:* Performance level testing may involve subjecting the equipment to loads that approach the strength capacity of brittle materials. This may constitute an unacceptable safety risk, which can be reduced through the use of design level tests.
- b) *Serviceability concerns:* The performance level testing may involve testing to an extent whereby the equipment may be damaged or deemed unacceptable for future service. If this tested equipment

is placed in service, this may constitute an unacceptable operational risk, which can be reduced through the use of design level tests.

- c) *Financial concerns:* Performance level testing may involve testing to an extent whereby the equipment may be damaged or deemed unacceptable for future service. This may constitute an unacceptable financial risk, which can be reduced through the use of design level tests.
- d) *Test facility limitations:* Performance level testing of certain types of equipment may require acceleration levels (especially at low frequencies) that cannot be achieved by typical test laboratories. Whereas a design level test may be feasible at typical test laboratories.

## **5.4.2 Design level testing**

### **5.4.2.1 Conditions for design level testing**

Ideally, all equipment would be qualified utilizing performance level testing; however, this may not always be possible for the reasons outlined in 5.4.1.3. Design level testing may be used unless performance level testing is required by this recommended practice.

### **5.4.2.2 Design level test assumptions in the context of the seismic qualification objective**

Yielding of components is permitted when subjected to performance level testing (refer to 5.2.2) and such plasticity can introduce nonlinear response. However, for flexible equipment, all of the design level test qualification methods given in this recommended practice theoretically imply a linear response with regard to the evaluation of the acceptance criteria (refer to A.2.1).

The application of the acceptance criteria, as specified in A.2, to the equipment response (e.g., stress, load, deflection, etc.) from a design level test is expected to provide an acceptable projection of equipment performance to the acceleration levels associated with the seismic qualification objective.

## **5.4.3 Specification of performance level testing or design level testing**

The applicability of performance level testing or design level testing shall be as specified in each equipment annex (refer to 5.3.1).

Equipment that is specified to be qualified by performance level testing shall not be qualified by design level testing irrespective of presence of any of the conditions listed in 5.4.1.3.

For equipment that is specified to be qualified by design level testing, the manufacturer can elect to exercise the option to performance level test (refer to 4.6).

## **5.5 Seismic qualification methods with respect to analytical qualification**

### **5.5.1 General**

It is the intent of this recommended practice that equipment qualified by analysis to a given design level would remain functional after a seismic event corresponding to a level of shaking twice that actually qualified. This level is defined as the performance level. As equipment qualified to a seismic qualification level is tested or analyzed to a Required Response Spectrum (RRS) that is only half the performance level,

it is assumed by this recommended practice based in the design criteria that the actual projected performance would be at the performance level. This projected performance must be sufficient such that equipment qualified to a design level would likely perform satisfactorily if it was to be tested to the performance level. The performance levels and the corresponding design levels are related to each other by a factor of two. As the design level qualifications allow for testing at a RRS that is less than the performance level, the performance level objective is provided for in the acceptance criteria specified in A.2.1.

### **5.5.2 Design level analysis assumptions in the context of the seismic qualification objective**

The seismic qualification objective permits yielding of components, (refer to 5.2.2) when subjected to performance level loading. Such plasticity is normally non-linear in nature. However, for flexible equipment, all of the design level analytical qualification techniques given in this recommended practice assumes a linear response.

The projection of the equipment response from a design level analysis to the performance level using linear assumptions is expected to be conservative due to the low assumed damping required for use in the analysis and increase damping and energy dissipation that occurs at higher level loadings.

The acceptance criteria, as specified in A.2, are expected to result in equipment performance meeting the seismic qualification objective.

### **5.5.3 Specification of design level analysis**

Design level analysis (see 5.3.5.3) shall be used for all equipment qualified by analysis unless otherwise specified. The applicability of analysis for qualification shall be as specified in each equipment annex.

For equipment that is specified to be qualified by design level analysis, the manufacturer may apply any of the appropriate optional qualification methods given in 4.6.

## **5.6 Damping with respect to seismic qualification methods**

### **5.6.1 Damping parameters**

#### **5.6.1.1 General**

The specification of damping is an important parameter in all seismic qualification methods for flexible equipment. The items to consider when specifying damping are described in 5.6.1.2 through 5.6.1.5.

#### **5.6.1.2 Response effects**

Damping is known to have a significant effect on the magnitude of acceleration that equipment can withstand. In general, the larger the damping ratio, the less the equipment will accelerate. This relationship is reflected by the damping equations associated with the required response spectra defined in this recommended practice.

### **5.6.1.3 Stress relationship**

It is generally assumed, for hysteresis damping, that damping increases as stress increases. This relationship is important for design level qualifications as:

- a) The prescribed damping is expected to be conservative (refer to 5.6.2.1) unless increased damping can be justified by physical testing.
- b) The damping values determined through testing are typically made at low levels of stress relative to the stress that would be associated with equipment loading at the performance level and is therefore presumed conservative.

This assumed conservatism in damping is relied upon in the projection of design level qualification methods to the seismic qualification objective (refer to 5.4.2.2 and 5.5.2).

### **5.6.1.4 Material dependence**

It is generally assumed that hysteresis damping varies with material type. However, the correlation of damping to material type is not made within this document for the sake of conservatism.

### **5.6.1.5 Structural system dependence**

It is generally accepted that the types of construction (materials and connection details) influences the level of damping. However, no distinction is made between construction or equipment types for the sake of conservatism.

## **5.6.2 Assumed damping magnitudes for analysis**

### **5.6.2.1 Damping associated with design level analysis**

Damping must be conservatively applied in an analysis because of its significant effect on equipment response.

A damping ratio of 2% (damping) may be assumed for all design level analysis.

### **5.6.2.2 Damping values beyond the assumed 2% damping magnitude**

Should the manufacturer claim any damping above the prescribed damping values given in 5.6.2.1, then the elevated damping shall be corroborated by one of the tests specified in A.1.1.6.

The damping determined in tests may not be extrapolated. When tests for the determination of damping are made at reduced levels of excitation, the resulting measured damping shall not be extrapolated to a higher level of damping on the premise that higher levels of excitation may result in higher levels of damping.

## **5.6.3 Damping associated with testing**

A test qualification, as opposed to analytical qualification, has no specified assumption of equipment damping. The equipment will dissipate energy at its inherent damping level commensurate with the level of excitation, induced stress, material type, and structural system type.

#### **5.6.4 Damping associated with matching the required response spectra**

A level of damping is used generically with establishing the sufficiency of the time-history data used in conjunction with time history analysis and testing.

This recommended practice requires that time histories be developed such that the resulting spectra envelop the required response spectra (refer to 5.3.4 and 5.3.5) using 5% damping. This process is called “matching” (refer to A.1.2.6).

The value of 5% damping is utilized for matching because of the following:

- It has been shown to be more conservative in comparison to matching at 2% damping.
- Its use is prevalent in reference standards (ASCE 7, ASCE 113) for definition of response spectra.

### **5.7 Seismic qualification levels**

#### **5.7.1 General**

A seismic qualification level is defined as the magnitude of seismic excitation to which equipment must maintain the seismic qualification objective. This recommended practice recognizes three seismic qualification levels: high, moderate, and low.

Qualification levels are closely associated with ZPA of the response spectrum. For the high qualification level, the horizontal ZPA associated with the seismic qualification objective is 1.0 g. For the moderate qualification level, the ZPA associated with the seismic qualification objective is 0.5 g. For the low qualification level, there is no horizontal ZPA associated with the seismic qualification level.

The selection of the seismic qualification level is the responsibility of the user and is normally based on an assessment of site geophysical parameters, risk assessments, and economics.

#### **5.7.2 High seismic qualification level**

##### **5.7.2.1 High seismic performance level qualification**

Equipment that is qualified in accordance with this practice is said to be qualified to the high seismic performance level when the required response spectra used in a performance level qualification corresponds to the “High Performance Level Required Response Spectrum” depicted in Figure A.1.

##### **5.7.2.2 High seismic design level qualification**

Equipment that is qualified in accordance with this practice is said to be qualified to the high seismic design level when the required response spectra used in a design level qualification corresponds to the “high design level.”

### **5.7.3 Moderate seismic qualification level**

#### **5.7.3.1 Moderate seismic performance level qualification**

Equipment that is qualified in accordance with this practice is said to be qualified to the “moderate seismic performance” level when the required response spectra used in a performance level qualification corresponds to the “Moderate Performance Level Required Response Spectrum” depicted in Figure A.2.

#### **5.7.3.2 Moderate seismic design level qualification**

Equipment that is qualified in accordance with this practice is said to be qualified to the “moderate seismic design” level when the required response spectra used in a design level qualification corresponds to the “moderate design level.”

### **5.7.4 Low seismic qualification level**

Equipment that is qualified in accordance with this practice and using the low seismic qualification criteria is said to be seismically qualified to the low seismic level. The low seismic level represents the performance that can be expected when good construction and seismic installation practices are used, but when no special consideration is given to the seismic performance of the equipment.

Minimum foundation loading and anchorage requirements are specified in 6.6.9 and A.1.1.9.

## **5.8 Response spectra**

### **5.8.1 Spectral shape**

Irrespective of seismic qualification level or seismic qualification method, the spectrum shape is consistent. The shape is a broadband response spectrum that attempts to account for the effects of earthquakes in different areas, encompassing magnitude/distance combinations, and considering site conditions ranging from rock to soft soil as described in ASCE 7.

### **5.8.2 Spectral amplitude**

Spectral amplitudes represent what is deemed to be a reasonable response. The resulting magnitude does not envelope the spectra from all of the historical earthquakes used in its derivation. Furthermore, it is cautioned that the resulting accelerations of an actual earthquake may exceed the accelerations of the response of the spectra contained herein at some frequencies.

### **5.8.3 Special cases**

#### **5.8.3.1 Exceptions**

The spectra contained in this recommended practice are expected to be suitable for most substation site conditions; however, they may be inadequate when any of the following exceptional situations exists:

- a) Near field conditions (refer to 6.4.4).

- b) Very soft soil sites (refer to 6.4.2).
- c) Equipment in the upper floors of buildings (refer to 5.11).
- d) Hill sites (refer to 6.4.3).
- e) Subduction zone earthquakes (refer to 5.8.3.2).
- f) Sites where geotechnical evidence shows that the standard spectra are inadequate.

### **5.8.3.2 Subduction zone earthquakes**

Qualification spectra of this recommended practice do not specifically account for the parameters (frequency and duration) of a subduction zone earthquake. Historical seismic performance of equipment subjected to subduction earthquakes and that were qualified using spectra similar to those specified in this recommended practice have performed well during this type of earthquake. Research on subduction earthquakes versus crustal earthquakes is ongoing. Until otherwise determined it is believed that qualification per this recommended practice will provide acceptable performance. Additional information on subduction earthquakes is provided in 6.4.5.

### **5.8.3.3 Site-specific spectra**

Should any the conditions in 5.8.3 exist at a particular substation, the user is recommended to develop and use a site-specific spectrum.

The user may claim compliance to this practice if the resulting site-specific spectrum envelopes a performance level response spectrum of this standard. However, compliance can only be stated to the appropriate seismic qualification level with no claim to any additional capability.

## **5.9 Discussion of other seismic design criteria**

### **5.9.1 Building codes**

It has been a common practice to cite a building code with regard to the seismic design of substation equipment. The application of building code methodologies, including non-building structures, to substation structures can be problematic. Some of the issues that may be encountered with building codes, and whereby contrasts to the approach taken in this recommended practice, are as follows;

- a) The primary objective of building codes is typically to protect the public by averting structural collapse. Building codes frequently achieve this objective by allowing the building's structural elements to dissipate earthquake energy through substantial levels of inelastic behavior. This recommended practice includes a functionality aspect considered where by, in addition to the structural aspects, equipment is expected to be operational during and after an event.
- b) In general, the nomenclature and definitions developed for building type of construction are not directly applicable to substation equipment (e.g., soft story, elevation irregularity, etc.). As a result, the application of a building code to electric substation equipment can be subject to considerable interpretation and may involve very fundamental parameters. Since this recommended practice is specifically written for substation engineering, it is succinct and is less susceptible to variances in interpretation.
- c) There is a tendency for building codes, especially with regard to dynamic analysis, to emphasize the expected low natural frequency response (typically < 1 Hz) of buildings. This tendency frequently manifests itself in period calculations and in the shape of the spectra. In contrast, the

spectra specified by this recommended practice envelope the response expected by most substation equipment (generally > 1 Hz).

- d) The seismic design criteria in building codes often reflect the damping levels expected from general construction methods (typically about 5%). In comparison, the damping expected from substation equipment can be significantly lower, and this is reflected in the general 2% assumption used in this recommended practice (refer to Q.2.2).
- e) Building codes tend to address the materials that are prevalent in general construction. Typically, little or no guidance is given for materials that are ubiquitous in substation design (e.g., porcelain, fiberglass, cast aluminum, etc.). In contrast, this recommended practice considers the materials used in substation equipment.

Building codes are useful for providing insight into the seismic hazard of a geographic location (users are cautioned that the probabilities of exceedance should be understood). Guidance for utilizing seismic hazard information to select a qualification level is given in 5.12.

It is noted that some building codes recognize the unique nature of substation equipment and guide users accordingly.

### **5.9.2 Intensity and magnitude scales**

Intensity scales (e.g., Mercalli, Modified Mercalli) are methods of subjectively describing the collateral effects of an earthquake. In general, the subjective nature of intensity scales does not serve as a sound basis for engineering design. Magnitude scales indicate the size of earthquakes and the energy released. Earthquake ground motion parameters for engineering purposes may be determined from various ground motion prediction equations using magnitude, distance to a given site from the earthquake source, fault characteristics, site soil conditions, and other factors.

## **5.10 Influence of support structures on seismic response of equipment**

### **5.10.1 Types of supports**

Support structures such as dedicated supports, intermediate supports, and primary substation structures can significantly alter the dynamics of the earthquake motion experienced by a piece of equipment when compared to that of the identical equipment mounted directly on a foundation. Among the effects are the potential changes in accelerations, displacements, and stresses. Subclause 5.10 addresses the influence of the support structure on the qualification of equipment as well as the qualification of the support structure itself.

Because of the potentially significant effects of a support structure, 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 are typical reasons for not qualifying the equipment in its in-service configuration:

- a) 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.
- b) Existing dedicated support structure: A dedicated support structure already exists but is different from the dedicated support used in an existing equipment qualification.
- c) Support details unknown. The exact details of the support are not known at the time the equipment is purchased.

- d) Better support is to be used. The support to be used by the user is dynamically better (see 5.10.5) than the support tested or analyzed.
- e) Total height. The height of the equipment mounted on the dedicated support makes it impractical to test inside a test laboratory.

The support structure must be designed for the seismic demand loads and dynamic characteristics of the combined equipment/support structure. For equipment that is mounted on a support structure, the combined system may be qualified by one of the following:

- Analyze and/or test the combined system (refer to 5.10.2).
- Qualify the equipment using an analytically-derived, modified input motion that allows for the effects of the support structure (refer to 5.10.3).
- Qualify the equipment using a modified input motion ( $2.5 \times \text{RRS}$ ) that conservatively allows for the effects of most support structures (refer to 5.10.4).

Each of these scenarios is discussed in more detail in 5.10.2 through 5.10.7.

### **5.10.2 Qualification of equipment with support**

This method covers situations where design details of the dedicated support are known. Qualification by analysis can be achieved by detailed modeling of both the equipment and the dedicated support. Qualification by testing can be achieved by testing of the combined system. From analysis or test results, internal member and component forces and stresses are obtained and used for design and qualification purposes.

### **5.10.3 Qualification of equipment without the support structure when support parameters are known**

This method covers situations where the equipment must be qualified by testing, and the dedicated support structure is too large or complex to be included in the test set-up. For these situations, a combined analytical model of the dedicated support and the equipment must be developed. This model must be dynamically analyzed subject to the RRS, and the resulting acceleration response spectra at the base of the equipment must be extracted in all three orthogonal directions. The spectra shall be calculated using the requirements of A.1.2.6.c). The testing is then conducted subject to the extracted analytical output at the interface of equipment and the dedicated support, multiplied by factor of 1.1 to allow for any uncertainties. The dedicated support is then designed to the member forces and stresses as derived from the analysis of the combined system in accordance with requirements of this recommended practice. Note that this process may be iterative, as the support member sizes may vary from the initial design to accommodate resulting stresses. Equipment testing shall only be conducted when the design details of the dedicated support are finalized and a final analysis is performed providing the control acceleration response spectra at the interface of the equipment and the dedicated support.

The method described above may also be applied to situations where an assembly of the equipment and intermediate support may have to be tested together to capture localized effects of support conditions at the equipment base. In these situations, the analytically determined acceleration spectra at the interface of the intermediate structure and primary structure will be used as target spectra for testing.

#### **5.10.4 Qualification of equipment without the support structure when support parameters are not known**

This method covers the situation where equipment is to be mounted on a support structure whose design details are not known at the time of qualification of the equipment. In such cases, the equipment shall be qualified to  $2.5 \times \text{RRS}$  to allow for potential dynamic amplification of the input acceleration as a result of the presence of the support structure. Once the design details of the support are known, the support shall be checked analytically by the user or user's agent for the design level loading defined in this recommended practice, allowing for dynamic interaction between the equipment and the dedicated support.

#### **5.10.5 Dynamic equivalency of a dedicated support**

In the circumstance where qualification exists for a combination of an equipment item and an associated dedicated support, but circumstances (refer to 5.10.1) dictate that the same piece of equipment is desired on an alternative dedicated support, the concept of "dynamic equivalency" may prove that proposed new combination is seismically qualified. Dynamic equivalency of the proposed combination of equipment and dedicated support shall be demonstrated through analytical methods by ensuring that the following conditions are met:

- a) When it is not practical to test the equipment/structure assembly to demonstrate equipment functionality, and yet, some level of assurance of equipment functionality is required, the following analytical procedure may be used. Demonstrate that the 2% damped response spectra at the interface of the equipment and the new support structure is 10% below the 2% damped response spectra at the interface of the qualified equipment and the original support structure, for all three orthogonal directions. This enveloping must be demonstrated both in amplitude and frequency content.
- b) When equipment functionality is not required to be demonstrated, the seismic response (acceleration at center of mass of equipment, reaction at the base of the equipment, and stresses in critical parts of the equipment) is less than those obtained from the configuration of the equipment supported on the qualified support. If terminal displacements are an important consideration in equipment acceptance criteria, then the resulting terminal displacements should also be lower from employing a dynamically equivalent support.

All comparison parameters shall be evaluated at the level of damping assumed in the existing qualification. Once dynamic equivalency is demonstrated, the equipment is considered qualified when mounted on the proposed dedicated support.

#### **5.10.6 Qualification of equipment on multiple dedicated support designs**

When equipment will be mounted on a variety of pre-defined dedicated supports, then qualification by group (refer to 4.7) will be acceptable if the equipment is tested or modeled on the most seismically vulnerable configuration of the equipment/structures to be used.

When the equipment is mounted on user supports, it is the responsibility of the user to determine which support is deemed most seismically vulnerable.

#### **5.10.7 Qualified equipment mounted on an intermediate support**

When equipment is qualified by testing or analysis without a support (support parameters not known), sometimes the equipment is mounted on an intermediate support, such as a beam or truss, in between the equipment and the primary substation structure, such as a dead-end or rack substation structure. Substation structures, intermediate supports and their connections to the primary substation structure should be

designed in accordance with ASCE 113. The connection of the equipment to the intermediate support shall be designed in accordance with this recommended practice.

Equipment mounted on intermediate support of a primary substation structure is likely qualified to  $2.5 \times$  RRS (since support parameters are generally not known at time of equipment qualification).

However, user may opt to install equipment (previously qualified on a dedicated support) on a primary substation support using an intermediate support. This installation is allowed, as long as it is demonstrated the combination of primary substation structure (including intermediate support) are dynamically equivalent (see 5.10.5) to the qualified dedicated support which was the support for the original equipment qualification.

## **5.11 Qualification of equipment mounted within a building**

The RRS spectra provided in this recommended practice reflect free field (or ground) conditions and therefore do not include the influence of the dynamic characteristics of building response. One of the following alternatives, as agreed by the user and the manufacturer, may be used to define the spectra modified for the effects of building response that are used for equipment qualification:

- a) The user must provide a 2% damped response spectrum that represents the position-specific response within the building to the unreduced (elastic) design spectrum as determined according to the building code. Alternatively this may be developed by the manufacturer, with the agreement of the user.
- b) The user states that, in lieu of the position-specific spectrum of 5.11.a), building response effects be accounted for by multiplying the RRS of Figure A.1 or Figure A.2, as appropriate, by a factor of 2.5 for the purpose of equipment qualification.

The seismic design of the building itself should be in accordance with the relevant code in the jurisdiction of the substation (refer to 1.4.6).

## **5.12 Selecting the seismic level for seismic qualification**

### **5.12.1 General considerations**

The selection of seismic level for seismic qualification involves risk management. The acceptance or aversion of risk can only be judged by the user, thus the selection of seismic level should only be done by users.

A degree of judgment and advanced planning is needed in selecting the qualification level to be used. The hazard for a particular site should not be expected to fall directly on the high, moderate, or low seismic qualification level and a decision to take more risk or less risk will need to be made. Also, many operational factors will need to be considered when selecting equipment to go into the active inventory of an operating utility. Therefore, it is recommended that the user should evaluate all sites in its entire service territory and establish a master plan, evaluating which sites correspond to the high, moderate, or low qualification levels (see 4.4).

As the performance level of equipment is often projected from tests conducted at the design level or analyses, there is uncertainty as to the true performance level. To reduce the risks of unfavorable performance associated with this uncertainty, the user may wish to assign the high qualification level to sites with a PGA less than, but approaching, 0.5 g.

If new information becomes available about the seismic risk in the service area, this information should be considered in selecting the qualification level.

### **5.12.2 Site-specific seismic hazard method**

The site-specific hazard method is the preferred method and can be used at any site. This method uses site-specific soil data to determine the seismic hazard. Typically, this involves a geotechnical engineer familiar with site-specific seismic hazard analysis.

The procedure to select the appropriate seismic qualification level (high, moderate, or low) for a site consists of the following steps:

- a) Establish the mean plus one standard deviation peak ground acceleration and response spectra associated with the maximum credible earthquake that can impact the substation. As an alternative, the 2% probability of exceedance in 50-year mean peak ground acceleration and response spectra can be used. In developing the peak ground acceleration and response spectra, local site conditions shall be considered.
- b) The resulting peak ground acceleration values should be used to select the qualification level (high, moderate, and low) as follows:
  - 1) If the peak ground acceleration is equal to or less than 0.1 g, the low qualification level should be used.
  - 2) If the peak is greater than 0.1g but equal to or less than 0.5 g, the moderate qualification level should be used.
  - 3) If the peak is greater than 0.5 g, the high qualification level should be used.
- c) Use of one of the three qualification levels given in this recommended practice and the corresponding required response spectra is encouraged. Use of different utility specific criteria may require requalification of the equipment and does not meet the intent of this recommended practice in regard to uniformity.

In this procedure, it is assumed that the accelerations at the predominant frequencies of the equipment as given by the site specific response spectra are below those that are given by the response spectral shape in Figure A.1 anchored to the projected performance level PGA of 0.5 g for moderate qualification, or to the projected performance level PGA of 1.0 g for high qualification. If the accelerations of the site-specific spectra are higher at the predominant frequencies of the equipment, qualification to a higher level or to site-specific spectra may be appropriate.

### **5.12.3 Seismic exposure map method**

#### **5.12.3.1 General**

Users of this recommended practice in countries other than the United States, Mexico, and Canada should consult an equivalent seismic exposure map procedure. It is recommended that the map procedure be developed using a method similar to that described in the following clauses. The method should yield results similar to or more conservative than 5.12.2. If maps do not exist, the earthquake hazard method for specific sites is recommended. The seismic exposure map method for the United States, Canada, and Mexico are described in 5.12.3.2, 5.12.3.3, and 5.12.3.4, respectively.

### **5.12.3.2 United States**

Ground motion parameters presented in ASCE 7 may be used for sites in the United States with the following procedure:

- a) Locate the project site on the maps for Maximum Considered Geometric Mean ( $MCE_G$ ) Peak Ground Acceleration (PGA) provided in ASCE 7-16 Chapter 22 and determine the corresponding PGA. Locating a specific site on these maps may be difficult as the maps have been produced to a large scale. The use of the USGS website listed below is recommended to determine the site-specific PGA. The mapped PGA values are for a Site Class B and have been calculated as the lesser of the uniform-hazard (2% in 50 year) probabilistic and deterministic PGA values that represent the geometric mean of two horizontal components of ground motion. The deterministic PGA and site-specific  $MCE_G$  Peak Ground Acceleration have been determined in accordance with ASCE 7-16 Chapter 21.
- b) Determine the site class (A, B, C, D, E, or F) in accordance with ASCE 7-16 Chapter 20.
- c) Determine the Site Coefficient ( $F_{PGA}$ ) corresponding to the PGA and Site Class using ASCE 7-16 Chapter 11.
- d) Calculate the peak ground acceleration adjusted for site class  $PGA_M$  in accordance with ASCE 7-16 Equation 11.8-1:  $PGA_M = F_{PGA} \times PGA$ .

Alternatively, the  $PGA_M$  for a specified latitude and longitude may be determined from the detailed maps and on-line application available at the USGS website <https://earthquake.usgs.gov/designmaps>.

If the peak ground acceleration,  $PGA_M$ , is equal to or less than 0.1 g, the low qualification level should be used. If the peak ground acceleration is greater than 0.1 g but equal to or less than 0.5 g, the moderate qualification level should be used. If the peak ground acceleration is greater than 0.5 g, the high qualification level should be used.

### **5.12.3.3 Canada**

Ground motions presented in the National Building Code of Canada (NBCC) 2015, may be used. NBCC provides peak horizontal accelerations and 5% damped peak spectral accelerations for a probability of exceedance of 2% in 50 years (i.e., 2475-year return period).

To select the appropriate seismic qualification level, follow the steps outlined below:

- a) Determine the site peak ground acceleration for NBCC Reference Site Class C ( $PGAc$ ).
- b) For sites in listed locations, refer to NBCC Volume 1, Division B, Appendix C.
- c) For sites not listed, peak accelerations can be obtained from the Geological Survey of Canada website (<http://earthquakescanada.nrcan.gc.ca>) by specifying the latitude and longitude of the site.
- d) Determine the site ground classification (Class A, B, C, D, E, or F) in accordance with NBCC.
- e) Determine the site acceleration-based coefficient,  $F_a$ , in accordance with NBCC.
- f) Estimate the site peak ground acceleration adjusted for site ground classification by  $F_a \times PGAc$ .
- g) Use the site peak ground acceleration adjusted for site ground classification to select the seismic qualification level. If the peak ground acceleration is equal to or less than 0.1 g, the low qualification level should be used. If the peak ground acceleration is greater than 0.1 g, but equal to or less than 0.5 g, the moderate qualification level should be used. If the peak ground acceleration is greater than 0.5 g, the high qualification level should be used.

#### **5.12.3.4 Mexico**

To select the appropriate seismic qualification level for electrical facilities use the latest edition of Manual de Diseño de Obras Civiles, Comision Federal de Electricidad (MDOC-CDS), the following procedure should be used:

- a) Using the site location and the program PRODISIS<sup>15</sup>, determine the rock acceleration  $a_0^r$ .
- b) Determine the seismic zone (Zone A, B, C, or D).
- c) For electrical substations located in Zone B or D, assign qualification level as follows:
  - 1) For electrical substations located in Zone B, use the moderate qualification level.
  - 2) For electrical substations located in Zone D, use the high qualification level.
- d) For electrical substations located in Zones A and C, perform the following steps:
  - 1) Determine the soil type of the site substation according to section 3.1.5 of MDOC-CDS-2015, (soil types I, II, or III).
  - 2) Determine the Site Factor  $F_{sit}$  according to table 1.9 of MDOC-CDS-2015.
  - 3) Using the program PRODISIS, determine the rock acceleration  $a_{EPR}^r$  for a return period of 2475 years for Zone A and 975 years for Zone C.
  - 4) Obtain the peak ground acceleration at site substation:  $PGA = F_{sit} \times a_{EPR}^r$ .
  - 5) If the PGA is  $\leq 0.1$  g, use the low qualification level, otherwise,
  - 6) If  $0.1$  g  $<$  PGA  $<$   $0.5$  g, use the moderate qualification level, otherwise,
  - 7) If the PGA  $\geq 0.5$  g, use the high qualification level.

## **6. Design for site conditions and installation considerations**

### **6.1 General**

Installation parameters may have a significant effect on the way equipment will respond and perform 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 methods, site response characteristics, soil-structure interaction, support structures, seismic protective systems, suspended equipment, anchorage, and conductor loading effects resulting from dynamic interaction with the adjacent equipment.

### **6.2 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, implementation of anchorage recommendations, etc.) is critical to achieving the intended seismic performance of the equipment.

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<sup>15</sup> PRODISIS is a seismic hazard mapping tool referenced in MDOC-CDS and can be obtained from La Comisión Federal de Electricidad de México, at the following address: Rio Ródano num. 14, Col Coauhtémoc, C.P 06598, Mexico, D.F.

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.

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

## **6.3 Anchorage**

### **6.3.1 General**

Anchorage constitutes the attachment of the equipment or the equipment support, to either a foundation, another piece of equipment, intermediate support, or a building. In specialized cases, anchorage may be needed to more than one of the aforementioned categories [e.g., suspended equipment could be anchored to an intermediate support (suspension system) and a foundation (restraint system)].

All equipment within the scope of this recommended practice shall be installed with anchorages that are capable of transmitting the seismic and normal operating loads to the foundation, the (connecting) equipment, intermediate support, or building to which it is attached (refer to A.4.3, A.4.4).

### **6.3.2 Historical experience**

Performance in historical earthquakes has shown that anchorage failure is a common cause of equipment failure. However, anchorages have also been cited as being a cost-effective measure to improve the seismic performance. The recommendations herein are intended to encompass these historical perspectives.

### **6.3.3 Design principles**

The following principles apply to the seismic design of anchorages:

- a) The anchorage must be capable of resisting the projected seismic loads simultaneously with the relevant mechanical loads.
- b) The anchorage must be capable of resisting cyclic loading due to earthquake actions.
- c) Ductile failure of anchorages is preferred. However, non-ductile anchorage design is permitted when the design satisfies the requirements of ASCE 113.

### **6.3.4 Recommended anchorage types**

#### **6.3.4.1 Welded anchorage**

Welded anchorages are made by welding the equipment or support structure base to structural steel members embedded in, or firmly anchored to, the foundation. Welded anchorage normally allows for a simpler and stiffer configuration and can be stronger than anchor rods. Welded anchorages are the preferred method for anchoring transformers.

#### **6.3.4.2 Anchor rods**

An alternative method for anchorage to concrete is to use cast-in-place anchor rods. Anchor rods shall be designed in accordance with the ductile or non-ductile anchor rod design requirements of ASCE 113. Materials shall be as specified in A.4.3.

#### **6.3.4.3 Threaded fasteners**

Threaded fasteners may be used to anchor a piece of equipment to a support structure, an intermediate support, or a building. It is recommended that the fasteners meet the requirements of A.4.4.

#### **6.3.4.4 Post-installed anchors**

Historical experience suggests that post-installed mechanical anchors that rely on friction or wedging action may have lower capacities than those derived from static tests due to the cyclic nature of earthquake loads and the detrimental effects of concrete cracking. Similar concerns generally also apply to chemical anchors. The user should specify post-installed anchors that are approved for seismic loading by a recognized agency in the jurisdiction of installation, and design such anchors in accordance with procedures that account for concrete cracking and cyclic loading described in ASCE 113, and the design principles of 6.3.3.

### **6.3.5 Manufacturers responsibilities**

It is the responsibility of the manufacturer to:

- a) Design the equipment with the capability of being secured by a recommended fastening method that takes into consideration magnitude and dynamic nature of the load.
- b) Provide the reaction loads at each anchorage location (axial force, shear forces, and moments for seismic and non-seismic load cases).
- c) In the case of threaded fasteners and anchor rods, justify the size, strength, location, and materials of the fasteners and show these details on the seismic outline drawing.
- d) In the case of welds, justify the weld pattern, weld sizes, and electrode types and show these details on the seismic outline drawing. Welding shall conform to the American Welding Society (AWS) specifications D1.1 [B2] or D1.2 [B3].
- e) Adhere to the requirements of A.4.3.2 and A.4.3.3.

### **6.3.6 Users responsibilities**

It is the user's responsibility to:

- a) Provide an anchorage capable of resisting the supplied reaction loads.
- b) In the case of anchor rods, the provisions of the ASCE 113, Substation Design Guide shall be followed.
- c) In the case of welds, base materials shall be provided that are suitable for welding and are of suitable thicknesses. Certified welders are to weld according to the weld details provided by the manufacturer.
- d) In case of post-installed anchors, the user shall ensure that anchors used are approved for seismic loading by a recognized agency in the jurisdiction of installation.
- e) Adhere to the requirements of A.4.3.4 and A.4.3.5.

## 6.4 Site response local topography, near-field effects, and subduction zone earthquakes

### 6.4.1 General

This clause deals with site conditions that may affect ground motions used for design. These effects may influence the selection of the seismic qualification level (low, moderate, or high) and therefore must be evaluated by the user.

### 6.4.2 Site response effects

Site response is dependent on the dynamic properties of the geological formations at and around the site. Influences include bedrock quality, soil type and depth, liquefaction, surface and bedrock topography. 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. Sites located near streams or former streambeds can experience liquefaction and lateral spreading, the latter of which can severely increase the displacement demand on conductor connections to the equipment. Such large permanent ground displacements may require the use of special foundation systems, ground improvement, or other mitigating measures.

### 6.4.3 Local topographic effects

Local topography refers to nearby large scale topographic features such as old lake beds, sedimentary basins, and hills or ridges. The presence of such features may cause large responses which are beyond those reflected in the response spectra given in Figure A.1 and Figure A.2. The conditions are not common, but should always be evaluated.

### 6.4.4 Near-field effects

Near-field effects are associated with ground motions at sites within 32 km (20 miles) of the causal fault. These effects are characterized by long period, large amplitude motions which are a particular concern for equipment having resonant frequencies below 1 Hz. Very high vertical motions may also occur at near-fault sites. The vertical accelerations at these sites may, in some cases, exceed the horizontal accelerations. The possibility of near-field effects should always be evaluated as these phenomena are not reflected in the response spectra given in Figure A.1 and Figure A.2. In these situations, a site-specific input motion should be considered.

### 6.4.5 Subduction zone earthquakes

Subduction earthquakes are a type of convergent boundary earthquake caused by the oceanic crust of one plate being pushed downward beneath the crust of another oceanic or continental plate. Since the crusts have large compressive strengths, the energy built up prior to failure can be large and consequently the earthquakes tend to be powerful. Beyond the magnitude of shaking, the duration of subduction earthquakes can be relatively long.

The application of spectral shapes presented in Figure A.1 and Figure A.2 may result in qualified equipment that have lower margins against failure when subjected to subduction zone earthquakes

compared to crustal earthquakes. The possibility of subduction earthquakes needs to be evaluated when determining seismic requirements.

## **6.5 Soil-structure interaction**

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. Very large 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 surge arresters. SSI may increase responses where there are high accelerations, heavy equipment, high centers of gravity, or soft sites. SSI is generally not considered in the design of substation equipment, unless specifically requested by the user. The user may wish to consider a site-specific SSI analysis (see ASCE 7-16, Chapter 19) in the presence of the characteristics noted above.

## **6.6 Foundation analysis**

### **6.6.1 General**

The recommended seismic demand loads for foundation design are described herein. Historical seismic performance suggests that anchorage design should be based upon inertial forces generated by the equipment, whereas the foundation itself may be designed to lesser loads. Foundations designed for relatively low levels of seismic loading have performed well even in large earthquakes. Such lower demand loads for foundation design are attributed to higher damping and the energy dissipation that occurs at the soil/foundation interface. Foundation demand loads described below correspond to the Design Level unless otherwise noted. Requirements for the design of foundations are provided in ASCE 113.

### **6.6.2 Geotechnical information**

A geotechnical investigation should be performed and a geotechnical report prepared for the substation to assess the site conditions, and develop design and construction recommendations for the installation of the electrical equipment foundations.

### **6.6.3 Foundation types**

There are various types of equipment and support structures, having a wide variety of ground line reactions. The foundations used to support these structures depend upon characteristics of the soil information, soil design recommendations, code requirements, constructability concerns, and preferences of the design engineer. Some common foundation types used in substations are:

- a) Spread footings.
- b) Mat foundation or slabs on grade.
- c) Drilled piers (cast-in-place concrete).
- d) Driven piles (steel or concrete).

Foundations are designed to transfer the loads imposed on equipment and support structures to the supporting soil or rock. These demand loads are resolved into forces on the foundation including bearing (vertical downward), uplift (vertical upward), and shear (sliding) and overturning moment.

#### **6.6.4 Foundation design forces**

The design of foundations for equipment may include the following forces:

- a) Dead loads.
- b) Seismic loads.
- c) Operating loads.
- d) Construction loads.
- e) Other loads: wind, snow, and ice loads.

All or some of the loads listed above should be considered in analysis and design of foundations. This recommended practice only addresses seismic loads.

#### **6.6.5 Earthquake component combination for foundation loads**

The demand forces from horizontal and vertical components of earthquake should be combined in accordance with ASCE 113.

#### **6.6.6 Foundation supporting flexible equipment**

Foundation supporting flexible equipment may be designed using loads that are less than the foundation loads determined from the qualification of the equipment and support (see 6.6.1). Foundations may be analyzed to the following:

For high qualification areas (horizontal):

$$F_{p\_h} = (0.75) \times I_p \times W_p \quad (1)$$

For high qualification areas (vertical):

$$F_{p\_v} = (0.6) \times W_p \quad (2)$$

For moderate qualification areas (horizontal):

$$F_{p\_h} = (0.375) \times I_p \times W_p \quad (3)$$

For moderate qualification areas (vertical):

$$F_{p\_v} = (0.3) \times W_p \quad (4)$$

where

$F_{p\_h}$  is seismic horizontal load

$F_{p\_v}$  is seismic vertical load

$I_p$  is seismic importance factor as defined by ASCE 113

$W_p$  is effective seismic weight of equipment and support

$F_{p\_h}$  shall be applied at 2/3 of the equipment/support height, and  $F_{v\_h}$  shall be applied at the center of gravity of the equipment.

### 6.6.7 Foundation supporting rigid equipment

Foundations supporting rigid equipment, such as transformers, may be designed using loads that are less than the foundation loads determined from the qualification of the equipment. Foundation may be analyzed to the following:

For high qualification areas (horizontal):

$$F_{p\_h} = (0.5) \times I_p \times W_p \quad (5)$$

For high qualification areas (vertical):

$$F_{p\_v} = (0.4) \times W_p \quad (6)$$

For moderate qualification areas (horizontal):

$$F_{p\_h} = (0.25) \times I_p \times W_p \quad (7)$$

For moderate qualification areas (vertical):

$$F_{p\_v} = (0.2)W_p \quad (8)$$

$F_{p\_h}$  and  $F_{p\_v}$  shall be applied at the center of gravity of the equipment.

### 6.6.8 Foundations supporting inherently acceptable equipment

Foundations supporting inherently acceptable equipment may be designed using loads that are less than the foundation loads determined from the qualification of the equipment and support.

Foundation may be analyzed to the following:

For high qualification areas (horizontal):

$$F_{p\_h} = (0.75) \times I_p \times W_p \quad (9)$$

For high qualification areas (vertical):

$$F_{p\_v} = (0.6) \times W_p \quad (10)$$

For moderate qualification areas (horizontal):

$$F_{p\_h} = (0.375) \times I_p \times W_p \quad (11)$$

For moderate qualification areas (vertical):

$$F_{p\_v} = (0.3) \times W_p \quad (12)$$

$F_{p\_h}$  and  $F_{p\_v}$  shall be applied at the center of gravity of the equipment.

### **6.6.9 Low seismic qualification level**

All foundations supporting equipment and structures for the low seismic qualification level may be designed for the following forces.

$$F_{p\_h} = (0.2) \times I_p \times W_p \quad (13)$$

$$F_{p\_v} = (0.16) \times W_p \quad (14)$$

### **6.6.10 Load combinations**

Load combinations given in ASCE 113 should be used for foundation design.

### **6.6.11 Site-specific design forces**

As an option to 6.6.6 through 6.6.10, the user may design the foundation for site-specific forces as determined by appropriate codes, such as IBC.

## **6.7 Seismic protective systems**

Seismic protective systems make use of technologies such as base isolation or supplemental damping in order to lessen the severity of earthquake-induced accelerations. The design of seismic protective systems should consider the following:

- a) The damping or frequency characteristics of the system may change over time due to change in material properties, exposure to weather, 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, creating the need for greater slack in electrical connectors.

The use of seismic protective systems shall be approved by the user. The seismic qualification of equipment using seismic protective systems shall be performed in accordance with the requirements of Annex W.

## **6.8 Suspended equipment**

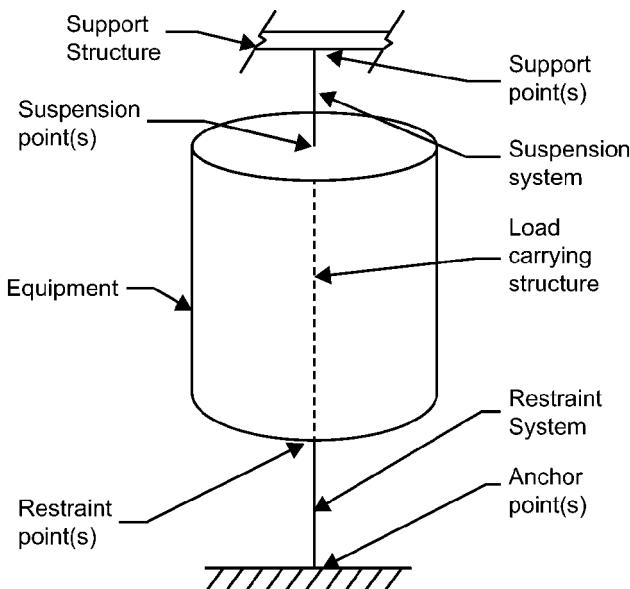
In general, suspended equipment will have dynamic characteristics similar to base-isolated equipment so that it may not be subject to the peak values of horizontal acceleration. However, just as with base-isolated equipment, it may experience significant horizontal displacement and/or vertical acceleration. Suspended equipment may also be subject to large loads associated with the snubbing action of restraints due to inadequate displacement capacity. Displacements of over one meter (3.28 ft) have been observed in 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 equipment response and loads on the support and restraint points. These interactions can cause large connection point loads. Examples of suspended equipment include 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.

The basic components to a suspended mounting configuration are as follows:

- a) Equipment.
- b) Suspension system.
- c) Restraint system.
- d) 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) (see I.1.5). 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.1.5.2) to the anchorage point(s), which are normally below the equipment. The following should be considered in the design of the restraint system:

- 1) The restraint system must be designed such that it maintains the required electrical clearances of the suspended equipment. It is recommended that the suspension and restraint system not have slack either initially or as the system moves in an earthquake. Experience has shown that designs with initial slack or systems that become slack in an earthquake have suffered impact.
  - 2) 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 along, any horizontal axis. The connection of the restraint system to the anchorage point(s) must allow rotational freedom about any horizontal axis.
  - 3) 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.
  - 4) For restraint systems that incorporate damping devices, care shall be taken not to over-damp the restraint system, thereby increasing the acceleration of the equipment.
- 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:

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

## 6.9 Interaction between substation equipment

### 6.9.1 General introduction

The seismic response of substation equipment interconnected by conductors may be significantly different from the same equipment that is unconnected (termed hereafter as standalone). The connection (conductor and terminal hardware) which has non-negligible mass and stiffness, forms a mechanical link between the equipment items.

Conductor interaction effects may be partially mitigated by providing sufficient slack in flexible bus work to prevent the conductor from becoming taut during an earthquake, and thus generating unwanted coupling and possibly large forces. Flexible connectors in rigid bus work serve a similar function. It has been shown that even when sufficient slack is provided, the presence of the connection may lead to an amplification or attenuation of equipment response when compared to its standalone behavior. The amplified seismic response is primarily exhibited as increased demand loads (usually bending moment) on equipment insulators.

The effects of interaction may vary widely in practice, depending upon the characteristics of the connection and the connected equipment, earthquake motions, and other factors. In general, the equipment manufacturer that performs the standalone seismic qualification of equipment will not be aware of the details of buswork design, nor the characteristics of the adjacent connected equipment such that those effects can be incorporated into the qualification. This is particularly true because of the wide variation in equipment arrangement, configuration, and design/installation practices of utilities and end-users that are responsible for designing the substation and buswork. Because of the complex nature of the interaction phenomena and the reasons noted, a simplified approach is employed in this recommended practice to provide for the potential increase of demand from the conductor interaction.

### **6.9.2 Basic seismic design guidelines for connections**

The basic guideline for properly designing a flexible connection is to provide sufficient slack (displacement capacity) to accommodate terminal displacements of the equipment items (displacement demand) while respecting necessary electrical clearances. The seismic analysis, design, and installation of connections should be performed in accordance with IEEE Std 1527, which provides recommended shapes of flexible connections and guidance on the use of flexible connectors for rigid bus applications. A companion reference Application Guide [B9] provides more detailed guidance.

### **6.9.3 Inclusion of interaction effects in the seismic qualification of equipment**

Effects of conductor interaction shall be included in the qualification of equipment in accordance with the requirements of this recommended practice. Interaction effects shall be considered by applying one of the following methods:

- a) Moment amplification factor method (MAF).
- b) Equivalent terminal force method (ETF).

The MAF and ETF methods are intended to account for the effects, on a generic basis, of equipment interconnection due to earthquake including conductor gravity loads. The application of MAF or ETF is intended to be a part of qualification, and does not guarantee the acceptable performance of all conductor designs.

Parameters for application of the MAF and ETF methods are provided in A.1.6. These methods shall be applied in accordance with A.1.2.4 and A.1.4.3 for the qualification of equipment. Depending on the situation, one of these methods might be more stringent than the other; the manufacturer may choose the one providing the lower increase in demand.

At present, interaction effects should be considered only for equipment items that are primarily interconnected horizontally. The conductor interaction effects for conditions listed below have not yet been studied and are not addressed by IEEE Std 1527 and this recommended practice:

- Vertical drops
- Disconnect switches mounted with switch base vertical

- Equipment where the terminal pad of the adjacent equipment/bus support is located more than 2:1 (vertical distance:horizontal distance) away from the equipment being qualified
- Suspended equipment
- Equipment installed with seismic protective devices
- Telescopic buses

For such geometries or equipment, MAF of ETF need not be applied; however, the manufacturer may wish to apply MAF or ETF as part of the qualification process to account for equipment that may be installed with different conductor orientations.

The user should provide sufficient conductor slack in the installation in accordance with the recommendations of IEEE Std 1527.

#### **6.9.4 Users' responsibilities**

The user or user's agent should assume responsibility for the following:

- a) Design buswork with sufficient slack in accordance with IEEE Std 1527.
- b) Install equipment and buswork in accordance with design documents. Installation of equipment and associated buswork that is depended upon for seismic performance should be subjected to inspection and other quality assurance activities.

The user may design the substation buswork to mitigate the effects of interaction and assess the acceptability of the installed equipment by using the following procedure:

- 1) Select seismic input. This may be a Design Level or Performance Level qualification (high, moderate, low) of this recommended practice, or site-specific input based upon seismological studies or seismic hazard maps. If site-specific input is used, the user should select the input ground motion based upon the level of risk it wishes to accept. It is recommended that the site-specific seismic input motion have a return period not less than 475 years.
- 2) Determine the ETF or MAF from A.1.6 Table A.1 or Table A.2. Adjust magnitude of terminal force as appropriate for seismic input motion selected in 1), and level of risk the user wishes to accept. In lieu of ETF or MAF methods, the user may perform a detailed analysis to assess interaction effects more precisely.
- 3) Demonstrate the adequacy of the equipment to accommodate interaction effects by comparing its capacity with the terminal force effect included in the qualification analysis or test by the ETF or MAF methods. If necessary, perform analysis of equipment by applying MAF or superimposing ETF from 2) with maximum load from standalone seismic qualification. For equipment qualified by time history shake-table test, the difference between the site-specific seismic input and the seismic test input also provides a measure of the available seismic margin that may be used to demonstrate its capability to accommodate interaction effects.

#### **6.10 Short-circuit loads**

Equipment need not be designed for concurrent earthquake and short-circuit loads.

Short-circuit loads do not seem to have been a significant cause of equipment failure during past earthquakes.

## **6.11 Wind loads**

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

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

## **6.12 Ice loads**

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

Ice loads do not seem to have been a significant cause of equipment failure during past earthquakes.

# **7. Operational considerations for seismic events**

## **7.1 General**

The satisfactory operation of a substation during and after an earthquake depends on the survival, without malfunction, of a diverse set 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 ground motion.

## **7.2 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 may 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, and Annex V.
- d) Verify that the support structures are rugged.
- e) Verify that there are no weak hinge points in the structures.
- 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.

### **7.3 Spare parts**

Substation equipment may fail electrically and in spite of best efforts, may be lost in earthquakes, so the need to replace equipment may arise from time to time. If equipment fails suddenly, due to earthquake or random failure, a replacement generally must be installed quickly. Because the lead time required to manufacture and deliver equipment may be lengthy, most utilities maintain an inventory of spare parts for substation equipment or whole assemblies. Although the performance objectives for spare and in-service equipment are similar, the concepts for anchoring and supporting them are quite different.

- a) *Loading allowables.* A good spare parts storage scheme will minimize internal loads on the equipment to the extent possible, at reasonable cost. Additional conservatism to keep equipment and component stresses well below specification or code minimums is desirable. The equipment/storage system should be evaluated to ensure acceptable performance.
- b) *Locations of facilities for spares storage.* Among the points to be considered when selecting locations of facilities for storage of spares are ease of supplying needed spares to a particular substation, risk of earthquake or other extreme environmental event, and availability of a transportation system. It may be beneficial to select the locations as part of a broader risk management strategy, in which various hypothetical scenarios are considered. Such a risk management strategy may help to determine the appropriate locations of facilities for spares storage, and what types and numbers of spare equipment and components are needed to respond to an equipment failure resulting from earthquake or other extreme event.
- c) *Storage rack precautions.* If spares are stored on racks, ensure that the racks are seismically qualified and that there is a restraint system to avoid either having the spare fall from the rack or having other stored items fall upon the spare. Refer to ASCE 7, Chapter 15 on steel storage racks for further information.

The above suggestions are intended for at-site storage. Should spare parts be stored off-site, the user should pay special attention to delivery of spares to the sites intended. Consider that roads and bridges may not be usable, so a delivery plan should be developed considering different delivery scenarios, including possible rail or air delivery plans.

### **7.4 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.

## 7.5 Emergency power systems

### 7.5.1 Station and other batteries

#### 7.5.1.1 Station batteries

Experience in moderate and large earthquakes 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. Station batteries that are installed in racks that are properly braced and anchored generally perform well in earthquakes. Annex J contains recommendations for design and installation. The capacity reserve of the battery (the number of hours the battery can supply emergency load) is typically designed for 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™ [B18] and IEEE Std 484™ [B19] for vented lead-acid batteries, IEEE Std 1106™ [B20] for vented nickel-cadmium batteries, and IEEE Std 1187™ [B22] for valve regulated lead-acid (VRLA) batteries).

#### 7.5.1.2 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.

#### 7.5.2 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.

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. 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.

## Annex A

(normative)

### Standard clauses

NOTE—Annex B through Annex P, and Annex V through Annex X provide the qualification requirements for electrical equipment, such as circuit breakers and transformers. Some qualification requirements are common to all equipment. To not repeat these requirements in each annex, those requirements are given once in Annex A, with Annex B through Annex P and Annex V through Annex X referring back to Annex A.

## A.1 Qualification procedures

### A.1.1 Overview of procedures

#### A.1.1.1 General

All equipment qualified under this recommended practice shall have a seismic qualification in accordance with this recommended practice. Any equipment not meeting the full requirements of this recommended practice shall not be supplied to the user as seismically qualified by IEEE Std 693.

#### A.1.1.2 Qualified under existing qualification

Two situations exist where equipment can be considered already qualified:

- a) Existing qualifications of equipment may be acceptable provided that the requirements of 4.5 are met.
- b) The equipment that can be shown to be less seismically vulnerable with respect to equipment previously qualified and meeting the requirements of qualification by group (refer to 4.7).

#### A.1.1.3 Qualification configuration

The equipment should be tested or analyzed in its equivalent in-service configuration<sup>16</sup>, including support structures. While it is preferable for the qualification to be in its exact in-service configuration, it is recognized that there are situations when the in-service configuration is either not practical or economical. In such circumstances, a modified input motion or dynamically equivalent structure, as defined in 5.10.5 may be used.

#### A.1.1.4 Normal operating loads

Normal operating loads are to be considered to act simultaneously with seismic and dead loads.

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<sup>16</sup> Guidelines on permissible variations between a qualification configuration and an intended installation configuration are given in 4.11 and 5.10.

#### A.1.1.5 Triaxial analysis and testing

Analysis and time history testing shall be triaxial with simulation of translational ground accelerations in three orthogonal directions. A test response spectrum that envelops the RRS shall be applied in the two perpendicular horizontal axes of the equipment together with a response spectrum in the vertical axis that shall have an acceleration of 80% of that in the horizontal axes. Techniques for earthquake component combination for analytical qualification shall be as given in A.1.4.4.

#### A.1.1.6 Damping

Damping can either be assumed at a conservative level (5.6) or determined by any of the following methods:

- a) *Measuring the decay rate.* The equivalent viscous damping can be calculated by recording the decay rate of the particular vibration mode. This procedure is often referred to as the logarithmic decrement method.
- b) *Measuring the half-power bandwidth.* The equipment should be excited with a slowly swept sinusoidal vibration. The response of any desired location in the equipment is measured and plotted as a function of frequency. From these response plots, the damping associated with each mode can be calculated by measurements of the width of the respective resonance peak at the half-power point.
- c) *Curve fitting to frequency response methods.* The equipment is excited by swept sine, random, or transient excitation, and a response transfer function is developed. The modal damping is obtained by fitting a mathematical model to the actual frequency response data (transfer function). This curve fitting will smooth out noise or small experimental errors.
- d) *Time domain curve fitting.* Use an impulse response of decayed response of the equipment to fit an exponentially damped sine wave. This method can identify nonlinearities in the response and identify the frequency and equivalent viscous damping.

$$h(t) = Ae^{-2\pi\zeta(t+\tau)} \sin(2\pi f(t+\tau))$$

where

- h(t) is impulse response of a linear, viscously damped, oscillator  
A is amplitude to fit the curve  
 $\zeta$  is fraction of critical damping  
 $\tau$  is time shift to fit the time history  
f is damped natural frequency of the system

#### A.1.1.7 High seismic qualification level

Qualifications to the high seismic qualification level shall meet the relevant requirements given in Annex A in conjunction with the spectrum depicted in Figure A.1. Relevant requirements shall be as stated in the applicable equipment-specific annex (Annex C through Annex P, Annex V, and Annex W) when the equipment being qualified can be so categorized. If the equipment being qualified cannot be categorized into an equipment-specific annex (as defined by operation and configuration), then the relevant requirements shall be as given in Annex B.

#### **A.1.1.8 Moderate seismic qualification level**

Qualifications to the moderate seismic qualification level shall meet the relevant requirements given in Annex A in conjunction with the spectrum depicted in Figure A.2. Relevant requirements shall be as stated in the applicable equipment-specific annex (Annex C through Annex P, Annex V, and Annex W) when the equipment being qualified can be categorized into an equipment specific annex (as defined by operation and configuration). If the equipment being qualified cannot be categorized into an equipment-specific annex (as defined by operation and configuration), then the relevant requirements shall be as given in Annex B.

#### **A.1.1.9 Low seismic qualification level**

A seismic report, seismic outline drawing, and a seismic identification plate are not required for equipment qualified to the low qualification level. However, the following shall be met:

- a) *Anchorage.* Calculations that demonstrate the following anchorage requirements shall be provided to the users or user's agent. The equipment anchorage for the low seismic level shall be capable of withstanding at least 0.2 times the equipment weight applied in one horizontal direction combined with 0.16 times the weight applied in the vertical direction at the center of gravity of the equipment and support. The resultant load shall be combined with the maximum normal operating load and dead load to develop the greatest stress on the anchorage. The anchorage shall be designed using the requirements of A.4.3.
- b) *Defined load path.* The equipment and its support structure shall have a well-defined load path. Documentation of the load path is not required. However, the manufacturer shall design the equipment such that it adheres to the characteristics described herein and provides a stable and adequately braced load path. The determination of the load path shall be established. The load path is the route the loads follow through the equipment to the foundations. The load path shall not include sacrificial collapse members, materials that undergo non-elastic deformations, unrestrained translation, or rotational degrees of freedom, solely friction-dependent restraint (engineered energy dissipating devices excepted).
- c) *Conductor interface.* Slack and/or a flexible connection should be provided between the conductor and equipment. Guidelines for providing conductor slack are given in IEEE Std 1527.

### **A.1.2 Time history shake-table test qualification**

#### **A.1.2.1 General**

Qualification of equipment by time history shake-table test shall be performed in accordance with the requirements of A.1.2.

Any equipment that has been shake-table tested shall not be provided to the user, unless the user has been notified in writing and has provided written acceptance of the tested equipment.

#### **A.1.2.2 Equipment with multiple open/closed positions**

Allowances described in this clause are permitted when testing equipment with multiple open/closed positions at the performance level. After completion of a performance level shake-table test of one equipment position or position combination (including functional testing), and before commencement of the next performance level time history shake-table test, the following actions are allowed:

- a) Adjust the test specimen to comply with the original manufacturer's specifications.

- b) To repair the test specimen to comply with the original manufacturer's specifications.
- c) To replace all or part of the test specimen with parts identical to those originally used in the previously completed time history shake-table test.

#### **A.1.2.3 Terminal masses**

Terminal attachments representing the in-service configuration of the equipment should be included in the equipment subjected to testing.

- a) Equipment that includes terminal pads as an integral part of the equipment need not have any additional terminal mass attached. Intended accessories such as corona shields shall also be attached at the time of testing.
- b) Equipment that does not include terminal pads as an integral part of the equipment shall have the following minimum weights added to the equipment conductor connection point(s) during the tests. These weights account for expected terminal fittings and corona protection:

500 kV and greater	11 kg (25 lbs)
Greater than 145 kV to less than 500 kV	7 kg (15 lbs)

The in-service installation of equipment shall restrict conductor connection masses to the appropriate mass listed above in order to meet the intent of this recommended practice.

#### **A.1.2.4 Conductor loading**

Equipment qualified by time history shake-table test may demonstrate adequacy for conductor interaction effects by one of the following in accordance with A.1.6:

- a) Demonstrate that insulating elements within the load path of the terminal load have strength capacity that is greater than the measured demand amplified by the MAF specified in A.1.6.2. The strength capacity shall be in accordance with the requirements of A.2.1 for a design level time history shake-table test and A.2.2 for a performance level time history shake-table test.
- b) Following time history test, perform static pull test on the insulator element in accordance with A.3. The applied static force shall be the calculated cantilever force corresponding to the maximum measured moment at the base of the insulator during the time history test plus the ETF specified in A.1.6.3. The static force shall be applied at the equipment/insulator terminal in the direction that produced the most critical forces/stresses on the insulator during the time history test. The equipment insulator shall satisfy the acceptance criteria of A.2.1 for a design level time history shake-table test and A.2.2 for a performance level time history shake-table test.

Terminal masses shall be attached to conductor connection points in accordance with A.1.2.3.

#### **A.1.2.5 Resonant frequency search test**

The resonant frequency search test is for determining the resonant frequencies and low response level damping of equipment. A sine sweep or random noise excitation test, as described below, shall be used for the frequency search test. A frequency search above 33 Hz is not required. No resonant frequency search in the vertical axis is required if it can be shown that no resonant frequencies exist below 33 Hz in the vertical direction. The data obtained from the test are an essential part of an equipment qualification; however, the test does not constitute a seismic test qualification by itself.

A sine sweep frequency search shall be conducted at a rate not greater than one octave per minute in the range for which the equipment has resonant frequencies, but at least from 1 Hz, in the two horizontal axes and the vertical axis to determine the resonant frequencies and the damping. The amplitude shall be no less than 0.05 g. It is suggested that amplitude of 0.1 g be used. Damping may be found using the half-power bandwidth method, see item b) in A.1.1.6.

A white noise test shall be performed with an input amplitude not less than 0.25 g and the test time in seconds is  $T = 8/(f_n \times z)$  or greater, where  $f_n$  is the lowest natural frequency and  $z$  is the fraction of critical damping expressed numerically (not in %). The modal damping may be obtained by fitting a mathematical model to the measured frequency response data (transfer function) using the least squares method (see Rinawi and Clough [B25]), or the half-power bandwidth method may be used with the analytical expression of the transfer function.

Many types of substation equipment have, for a given direction, a mode shape that significantly predominates movement when subjected to the RRS. Such equipment types may lend themselves to the determination of fundamental frequencies by either of the methods outlined here:

- a) *Snapback test.* In the axis of interest, the equipment (which is firmly restrained in its in-service configuration) is deflected by a load that is judged safe but significant. The load is then suddenly removed such that the equipment is free to oscillate. Measurements of the oscillation will give frequency information.
- b) *Man-shake test.* For some equipment, deflections can be noted (without instrumentation) at a level of loading that can be exerted by a human. In such cases, it is possible to manually input periodic loading such that significant deflections are achieved. When large deflections are attained, it is possible to cease inputs and measure the resulting oscillations to obtain frequency information.

In addition to obtaining frequency information, these tests can also give damping information through the method outlined in item a) of A.1.1.6.

Where design level testing is allowed, a resonant frequency search shall be conducted as the first and last test on the shake table. The first test is conducted to determine the natural frequencies of the test specimen. The last resonant frequency search test is used to determine whether there is a significant change. A change of more than 20% in the resonant frequencies as a result of qualification testing will be used only as one parameter to determine whether there are structural changes and the significance of the changes.

#### **A.1.2.6 Requirements for input motion for time history testing**

The input motion time history for all time history tests shall satisfy the requirements given below. This recommended practice principally uses response spectra to establish the characteristics of the time histories used to seismically qualify substation equipment. When taken alone, it is an imprecise method of specifying excitation motions. A time history may be such that its response spectrum envelops the RRS, but the energy content in certain frequency ranges will be low, so that equipment that has important natural frequencies in that range may not be adequately excited. This result can occur because of the design of the time history or the interaction of the equipment and the shake-table that is exciting it. There is a need to balance the concern that the equipment be adequately excited, with the desire to avoid over-testing equipment during its qualification. Although imposing a power spectral density requirement on the input time history can assure an acceptable distribution of energy over the frequency range of interest, this has proved problematic in attempting to address this issue (Kennedy [B23]). If the response spectrum of a time history is reasonably smooth, a reasonable distribution of the energy in the record is also assured (Kennedy [B23]). To avoid over-testing, the TRS is permitted to dip slightly below the RRS, per the criteria provided by this clause.

The lowest permissible resolution (i.e., maximum permissible spacing between frequency points) of the calculated response spectra is specified to provide consistency in the enveloping procedure between

different tests, and prevent deviations in the spectra that may be masked by the use of too coarse a resolution. When calculating response spectra, the 1.1 Hz frequency point shall be used in all cases, and additional frequency points are developed from this starting point, according to the stated resolution limits. The maximum permissible spacing of frequency points, which is specified in terms of a fraction of an octave (frequency interval between a frequency  $f$  and  $2f$ ), is defined by the following:

$$\frac{f_{i+1}}{f_i} = 2^{\frac{1}{n}}$$

where

$f_i$  is the  $i$ th frequency point

$n$  is the number of divisions per octave

In the following, a distinction is made between theoretical motions and table output motions. Theoretical motions refer to input motions developed by a variety of software packages and used as input to the shake table. Table output motions refer to motions that are measured from instruments mounted on the shake-table platform.

All theoretical and table output motions cited below refer to accelerations or signals that ultimately will be evaluated as accelerations.

The strong part ratio requirement provides some assurance that the energy contained in the input motion is distributed in a manner similar to large historic earthquakes:

- a) Spectral matching. The theoretical response spectrum developed for testing shall envelop the RRS according to the requirements of this sub-annex. When the high seismic level is specified, the performance level spectra with 5% damping as shown in Figure A.1 shall be used. When the moderate seismic level is specified, the performance level spectra with 5% damping as shown in Figure A.2 shall be used. Spectral acceleration shall be plotted on a linear scale, in all response spectra plots used for the purpose of demonstrating conformance to the spectral matching requirements.

The theoretical response spectrum for testing shall be computed at 5% damping, at the resolution stated, and shall include the lower corner point frequency of the RRS (1.1 Hz), for comparison with the RRS.

- b) Duration. The input motion shall have a duration of at least 20 s of strong motion. Acceleration ramp-up time and decay time shall not be included in the 20 s of strong motion. The duration of strong motion shall be defined as the time interval between when the plot of the time history reaches 25% of the maximum amplitude to the time when it falls for the last time to 25% of the maximum amplitude.
- c) Theoretical input motion. The spectrum matching procedure should be conducted at 24 divisions per octave resolution or higher and result in a theoretical response spectrum that is within  $\pm 10\%$  of the RRS at 5% damping.

The strong part ratio of the table input motion record shall be at least 30%. The strong part ratio of a given record is defined as the ratio of the time required to accumulate from 25% to 75% of the total cumulative energy of the record, to the time required to accumulate from 5% to 95% of the total cumulative energy of the record, where

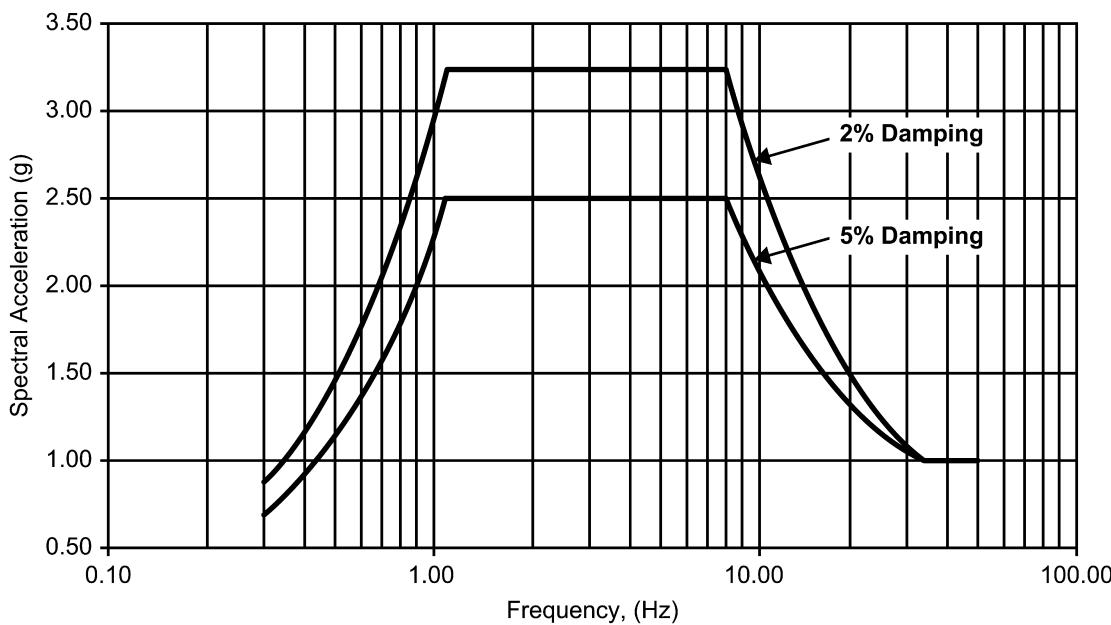
$$\text{Cumulative Energy} = \int a^2(\tau) d\tau$$

where

$a(\tau)$  is acceleration time history

See Q.5 for optional input motions for time history testing.

- d) Filtering limits. When required to satisfy the operating limits of the shake table, the theoretical input motion record used for testing may be high-pass filtered at frequencies less than or equal to 70% of the lowest frequency of the test article, but not higher than 2 Hz. The lowest frequency of the test article shall be established by test.
- e) Table output motion. The table output TRS shall envelop the RRS within a  $-10\% / +50\%$  tolerance band at 12 divisions per octave resolution or higher. A  $-10\%$  deviation is allowed, provided that the width of the deviation on the frequency scale, measured at the RRS, is not more than 12% of the center frequency of the deviation, and not more than five deviations occur at the stated resolution. For equipment when tested responds at a single dominant frequency in a given direction, such as instrument transformers, surge arresters, bushings, the TRS spectral acceleration at the equipment as-installed frequency shall not be less than the RRS. Over-testing that exceeds the  $+50\%$  limit is acceptable with concurrence of the equipment manufacturer. Exceedance of the stated upper tolerance limit at frequencies above 15 Hz is generally not of interest and should be accepted, unless resonant frequencies are identified in that range.



Spectral Accelerations,  $S_a$  (g), for Frequencies,  $f$  (Hz):

$$S_a = 2.288 \beta f \quad \text{for } 0.0 \leq f \leq 1.1$$

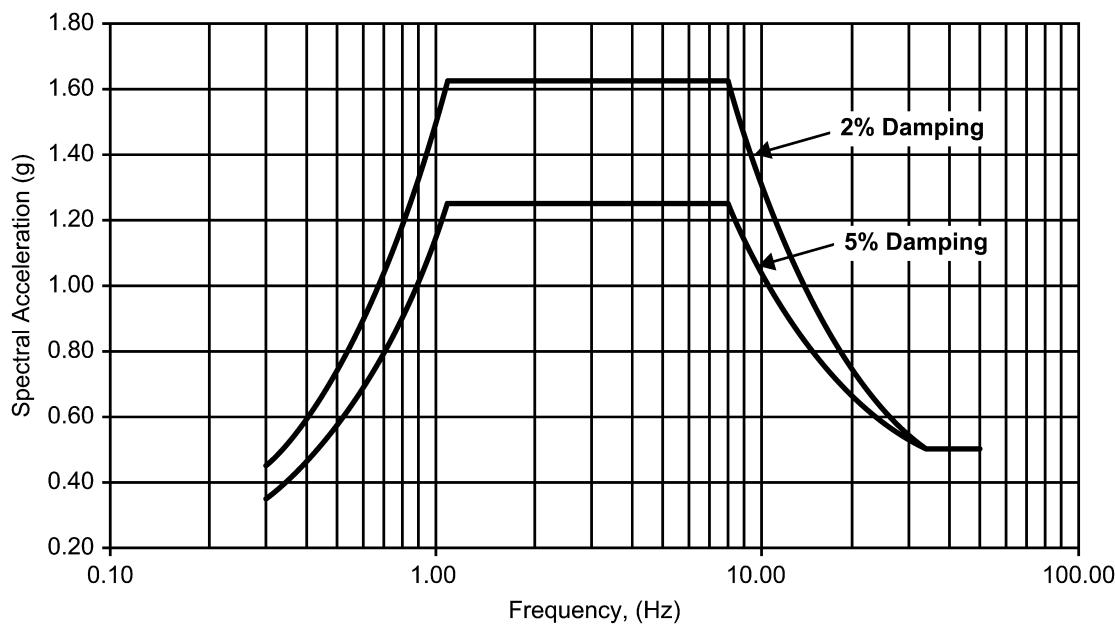
$$S_a = 2.50 \beta \quad \text{for } 1.1 < f \leq 8.0$$

$$S_a = (26.4 \beta - 10.56) / f - 0.8 \beta + 1.32 \quad \text{for } 8.0 < f \leq 33$$

$$S_a = 1.0 \quad \text{for } f > 33$$

$$\beta = (3.21 - 0.68 \ln(d)) / 2.1156 \text{ where } d \text{ is the percent damping (2, 5, 10, etc.) and } d \leq 20\%$$

**Figure A.1— High performance level required response spectrum, 1.0 g**



Spectral Accelerations,  $S_a$  (g), for Frequencies,  $f$  (Hz):

$$S_a = 1.144 \beta f \quad \text{for } 0.0 \leq f \leq 1.1$$

$$S_a = 1.25 \beta \quad \text{for } 1.1 < f \leq 8.0$$

$$S_a = (13.2 \beta - 5.28) / f - 0.4 \beta + 0.66 \quad \text{for } 8.0 < f \leq 33$$

$$S_a = 0.50 \quad \text{for } f > 33$$

$$\beta = (3.21 - 0.68 \ln(d)) / 2.1156 \text{ where } d \text{ is the percent damping (2, 5, 10, etc.) and } d \leq 20\%$$

**Figure A.2—Moderate performance level required response spectrum, 0.5 g**

### A.1.3 Static pull test qualification

#### A.1.3.1 Test procedure

Static pull test shall consist of pulling at the top of the equipment in the direction that provides the most severe structural action with a load that is two times the operating weight of the equipment. This load shall be applied for a minimum of 1 min. Oil or gas-filled equipment shall be pressurized to a minimum of 68.9 kPa gauge (10 psig). See acceptance criteria established in A.2.3.

#### A.1.3.2 Conductor loading

The static pull test force specified in A.1.3.1 includes the effects of conductor interaction for the purposes of qualification. No amplification or additional terminal force need be applied.

### A.1.4 Analytical qualification

#### A.1.4.1 Seismic loading

Analysis as required in this recommended practice shall be performed using the design level seismic loads corresponding to 50% of the performance level loading defined by the response spectra of Figure A.1 and Figure A.2 for the high and moderate performance levels.

#### **A.1.4.2 Terminal masses**

Terminal attachments representing the in-service configuration of the equipment should be included in the equipment subjected to analysis.

- a) Equipment that includes terminal pads as an integral part of the equipment need not have any additional terminal mass attached. Accessories such as corona shields shall also be attached in the analysis.
- b) Equipment that does not include terminal pads as an integral part of the equipment shall be analyzed with the following minimum weights added to the equipment conductor connection point(s). These weights account for expected terminal fittings and corona protection:

500 kV and greater	11 kg (25 lbs)
Greater than 145 kV to less than 500 kV	7 kg (15 lbs)

The in-service installation of equipment shall restrict conductor connection masses to the appropriate mass listed above in order to meet the intent of this recommended practice.

#### **A.1.4.3 Conductor loading**

The incremental increase in demand on the equipment insulator due to application of the MAF or ETF shall be applied for equipment qualified by analysis in accordance with A.1.6. The incremental increase in demand shall be applied in the direction producing the most critical forces/stresses on the equipment. The total seismic demand on the insulator element, including MAF or ETF shall be combined with seismic demands in the orthogonal directions using any approved method of combining earthquake components given in A.1.4.4. Terminal masses shall be included in analytical models in accordance with A.1.4.2.

#### **A.1.4.4 Analytical earthquake component combination techniques**

Analysis shall use an analytical orthogonal combination technique as defined in this clause to account for orthogonal acceleration effects. The SRSS method, as used in this recommended practice, combines seismic stresses at a particular location or combines local seismic forces acting on a particular element of a structure system. With this method, the stresses or local forces associated with each maximum required orthogonal seismic response are determined separately and then combined by squaring each value, adding them algebraically, and then taking the square root of that sum. The result of this calculation is the maximum seismic stress or force at the location or element in question, which shall then be applied in the direction that produces the most severe equipment stresses.

In lieu of the SRSS combination of three orthogonal earthquake components, a 100/40/40 (see ASCE 4) combination rule may be used. The 100/40/40 combination rule is applied by developing three sets of responses (forces or displacements) in which 100% of the effects of each earthquake component are taken in turn and combined absolutely with 40% of the effects of the remaining two earthquake components. The equipment and each structural element are designed for the most critical response resulting from one of the three sets of forces. The 100/40/40 combination rule is intended to account for the low likelihood that all three earthquake components will cause the maximum response of a given structural element at the same instant.

#### **A.1.4.5 Static analysis**

The forces on each component of the equipment shall be obtained by multiplying the values of the mass of the component by the acceleration specified in the principal directions. The resulting force shall be applied

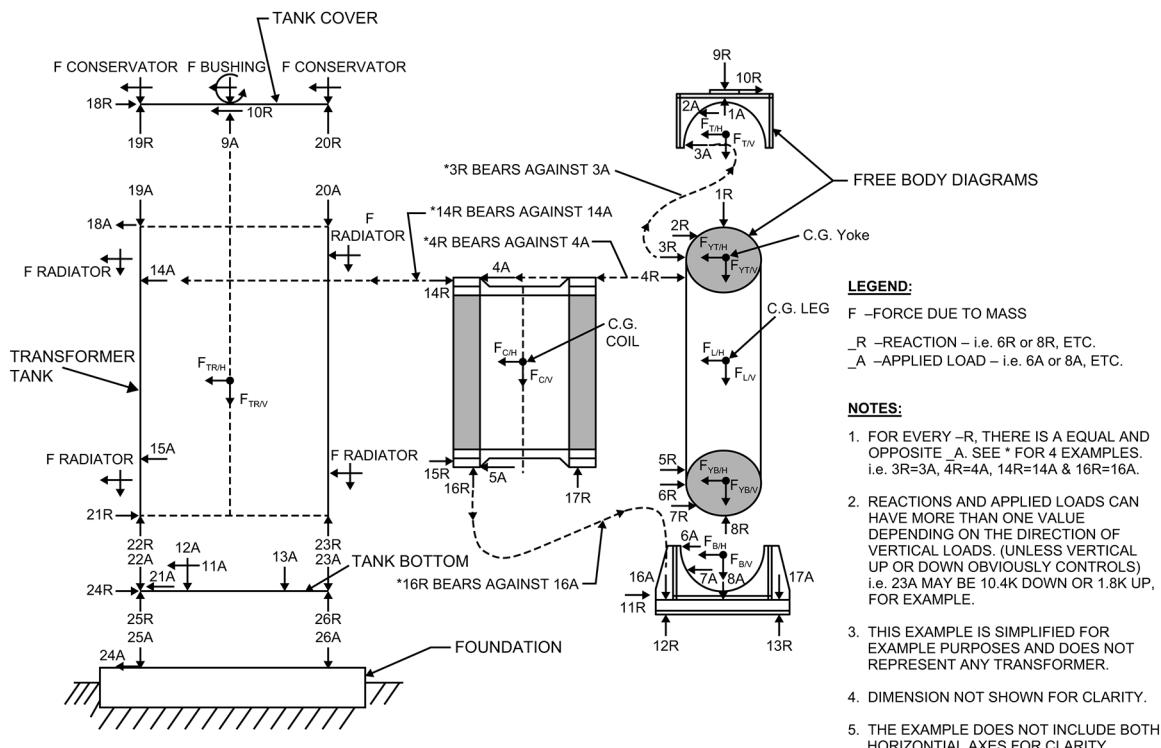
at the center-of-gravity of the component. A part may be subdivided into smaller components, to better represent the part's mass distribution.

The vertical seismic forces shall act simultaneously with both horizontal seismic forces. The horizontal forces are applied in the direction of the orthogonal axes. The three forces at each component's center-of-gravity shall be applied using one of the analytical earthquake component combination techniques in A.1.4.4, and then combined with dead load and any normal operating loads.

When the high seismic level is specified, the static analysis shall use a design level load consisting of 0.5 g in the two horizontal directions and 0.4 g in the vertical direction. When the moderate seismic level is specified, the static analysis shall use a design level load consisting of 0.25 g in the two horizontal directions and 0.2 g in the vertical direction.

The following is an acceptable process of performing the static analysis:

- a) Develop free-body diagrams.
  - 1) Divide the load path (i.e., the route the loads follow through the equipment to the foundations) for the equipment's principal axes into free-body diagrams.
  - 2) Label resultant forces and applied loads in each free-body diagram. Labels shall be consistent throughout all free-body diagrams (Figure A.3).
  - 3) Analyze each free-body diagram using principles of mechanics, starting with the free end mass and propagate the loads until they reach the foundation.
- b) Calculations or information needed for each free-body.
  - 1) Section properties of all structural members in the free-body.
  - 2) Provide all necessary dimensions.
  - 3) Provide all necessary loads/weights.
  - 4) Model the structure and loads.
  - 5) Determine stresses/loads/moment/deflections as necessary for all structural members.  
Combine the loads in the x, y, and z directions, as needed, for demands.
  - 6) Determine allowable/permissible values for all structural members.
- c) Compare demands to allowable strengths



**Figure A.3—Example of free body diagrams in load path**

#### A.1.4.6 Static coefficient analysis

The acceleration response of the equipment shall be determined using the maximum peak of the design level spectra at a damping value of 2%, unless a higher value for damping is justified by a test specified in A.1.1.6. The seismic forces on each component of the equipment are obtained by multiplying the values of the mass times the maximum peak of the design level spectra times the static coefficient. A static coefficient of 1.5 shall be used, unless otherwise noted herein, with 80% of the horizontal value being applied in the vertical axis. The resulting force shall be distributed over the components in a manner proportional to its mass distribution. The stress at any point in the equipment shall be determined by combining the three orthogonal directional stresses (at that particular point) by one of the analytical earthquake component combination techniques presented in A.1.4.4 at that point and combining all dead and normal operating stresses in such a manner to obtain the greatest stress at the point. The points of maximum stress shall be found.

When the high seismic level is specified, the design level spectrum equaling 50% of the performance level spectrum given in Figure A.1 shall be used. When the moderate seismic level is specified, the design level spectrum equaling 50% of the performance level spectrum given in Figure A.2 shall be used.

#### A.1.4.7 Dynamic response spectrum analysis

Using dynamic analysis, the equipment, its appendages and any support structure shall first be modeled as an assemblage of discrete structural elements interconnected at a finite number of points called nodes. The number, location, and properties of elements and nodes shall be such that an adequate representation of the modeled item(s) is obtained in the context of a seismic analysis. The resulting system is called a finite element model.

The finite element model shall be dynamically analyzed using a modal spectrum analysis, as described, for example, by Chopra [B8] and Gupta [B12]. In general, the modal responses of the finite element model to the dynamic analysis shall have three translational and three rotational components in and about the defined orthogonal axes system. Certain shell and solid elements may have inactive rotational degrees of freedom. The total response of all modes in any direction shall be determined by combining all modal response components acting in that direction using the SRSS technique, except if the mode frequencies differ by less than 10% of the lower mode, then these closely spaced modes are added directly and these added modes and the remaining modes are added using the SRSS method. Alternatively, the total response in any direction may be determined by applying the CQC technique to all modal response components acting in that direction.

Sufficient modes shall be included to ensure an adequate representation of the equipment's dynamic response. The acceptance criteria for establishing sufficiency in a particular direction shall be that the cumulative participating mass of the modes considered shall be at least 90% of the sum of effective masses of all modes. The acceptance criteria shall be applicable to the directions of orthogonal excitation and those response directions deemed significant, as determined by the specialist as defined in A.6 and the user, for the particular type of equipment being analyzed.

Should the finite element model have several resonant frequencies above 33 Hz such that the attainment of the acceptance criteria in an orthogonal excitation direction is impractical (as is often the case with vertically stiff equipment), then the effects of the orthogonal inputs can be simulated as follows:

- a) Determine the remaining effective mass in a given direction.
- b) For each component, apply a static force equal to the mass of the component times the percentage of mass missing times the design level ZPA.
- c) Calculate stresses, reactions, and other design parameters using these forces.
- d) For each direction, combine stresses, reactions, and other design parameters from the dynamic analysis with those from the analysis above using the SRSS.

Any of the earthquake component combination methods provided in A.1.4.4 may be used.

When the high seismic level is specified, the design level spectrum equaling 50% of the performance level spectrum given in Figure A.1 shall be used. When the moderate seismic level is specified, the design level spectrum equaling 50% of the performance level spectrum given in Figure A.2 shall be used.

A damping value of 2% or less shall be used for dynamic analysis, unless a higher damping value is justified by one of the tests specified in A.1.1.6.

### **A.1.4.8 Time history analysis**

#### **A.1.4.8.1 General**

The time history analysis method allows for evaluation of the structural response of the equipment on a step by step basis for a given earthquake record. Two methods for performing a time history analysis are provided. In both methods, it is assumed that the equipment itself remains elastic and any nonlinearity is confined to the support structure and or seismic protection devices. In both cases, the equipment and support shall first be modeled as prescribed in A.1.4.7 taking all measures necessary to adequately capture the structural dynamic behavior of the system.

#### **A.1.4.8.2 Linear and singularly non-linear systems**

Linear time history analysis is appropriate when it is anticipated that the equipment and its support are expected to respond as an elastic system. A singularly non-linear system is linear in nature and will be analyzed as elastic with the exception of singular change in stiffness that depends on distinct support elements experiencing tension or compression. Examples of systems that are singularly non-linear are systems with tension only members or systems where the foundation support (compression only) is modeled with gap elements.

For equipment and support systems that are inherently structurally linear or singularly non-linear, time history analysis shall be performed using a single triaxial earthquake record. The earthquake record used for the time history analysis shall satisfy the requirements for shake table testing input motions detailed in A.1.2.6. Filtering described in A.1.2.6.d shall not be applied to input motions used for analysis. In lieu of developing a set of input motions for the time history analysis, see Q.5 for optional input motions for time history analysis. In either case, it must be shown that the response spectra of the input motion in all three directions envelopes the design level spectra within the acceptable limitations for shake table output motions detailed in A.1.2.6.e). The instantaneous maximum (triaxial combination) loads, stresses, and displacements from the time history analysis shall be used to qualify the equipment according to the acceptance criteria of A.2.1.

#### **A.1.4.8.3 Non-linear systems**

Examples of nonlinear systems include equipment types that utilize seismic protective devices of Annex W or HVDC pendulum-type supports of Annex V. For these systems, the equipment itself will remain in its elastic range. However, the response of seismic protection device and/or support exhibit nonlinearity that cannot be accurately captured using linear analysis. Analysis at the performance level is required for such systems because the result at the design level input cannot be extrapolated to the performance level. For such cases, the acceptance criteria used for the analytical qualification shall be consistent with standard practice and agreed upon by the end user prior to proceeding with the analysis.

For equipment systems that fall in this category, time history analysis shall be performed using a minimum of three sets of triaxial earthquake records. The earthquake records developed for the time history analysis shall be scaled such that the average value of the response spectra of each of the three records in each direction envelopes the performance level spectra as detailed in item e) of A.1.2.6. Filtering described in A.1.2.6.d shall not be applied to input motions used for analysis.

When analyzed using three sets of triaxial earthquake records, the maximum value of the three instantaneous maximum (triaxial combination) loads, stresses, and displacements from each non-linear time history analysis shall be used to qualify the equipment as agreed upon with the end user for performance level analysis. If seven or more earthquake records are used to analyze the equipment, the average value of the seven (or more) instantaneous maximum (triaxial combination) loads, stresses, and deflections from each non-linear time history analysis shall be used to qualify the equipment as agreed upon with the end user for performance level analysis.

### **A.1.5 Inherently acceptable**

Certain substation equipment, particularly those of lower voltage classes, have historically demonstrated that they are intrinsically robust to seismic events when they are properly anchored. Annex C through Annex P, and Annex V identify equipment voltage classification that may be considered inherently acceptable. Such types of equipment are deemed to be inherently acceptable and do not require a seismic qualification report, seismic qualification identification tag, or seismic outline drawing. However, calculations that demonstrate the adequacy of the foundation anchorage to withstand seismic loads shall be provided to the user or user's agent.

The requirements are based on the possibility that the installed equipment has a fundamental frequency between 1.1 Hz and 8.0 Hz (in all directions of excitation) and a damping ratio of at least 2%. The equipment anchorage shall be capable of withstanding the following design level accelerations<sup>17</sup> applied at the center of gravity of the equipment:

Moderate qualification level:      0.81 g in each horizontal axis  
     0.65 g in the vertical axis

High qualification level:      1.62 g in each horizontal axis  
     1.30 g in the vertical axis

The resultant seismic loads shall be combined with any of the analytical earthquake component combination techniques given in A.1.4.4 and then summed with the maximum normal operating load and the dead load to develop the greatest stress on the anchorage. The application of the seismic accelerations shall be done in the most onerous directions of the equipment to result in the largest anchorage stress. The anchorage shall be designed according to the requirements of A.4.3.

The robustness of the equipment should be maintained by following the recommendations and design principles given in this document. Particular emphasis is made to the design requirements of A.4.

## **A.1.6 Conductor loading effects**

### **A.1.6.1 Methods**

Conductor interaction effects shall be considered in the qualification of equipment by using either the moment amplification factor (MAF) or equivalent terminal force (ETF) methods. Depending on the situation, one of these methods might be more stringent than the other; the manufacturer may choose the one providing the lower increase in demand.

### **A.1.6.2 Moment amplification factor (MAF) method**

In this method, the effect of conductor interaction is taken into account by multiplying the maximum net resulting moment found in the standalone qualification on the equipment insulator, by the moment amplification factor (MAF).

Table A.1 specifies the required MAF for equipment qualification. The MAF considered in the qualification shall be stated in the seismic qualification report.

**Table A.1—Moment amplification factor for seismic qualification from IEEE Std 1527**

Voltage class	MAF
< 110 kV	1.0
< 90 kV DCV for surge arresters	
110 kV to < 230 kV	1.35
90 to < 180 kV DCV for surge arresters	
≥ 230 kV	1.10
≥ 180 kV DCV for surge arresters	

### **A.1.6.3 Equivalent terminal force (ETF) method**

In this method, the effect of conductor interaction is accounted by applying an equivalent terminal force (ETF) in the direction corresponding to the horizontal axis of the terminal. The standalone seismic demand

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<sup>17</sup> These accelerations correspond to those obtained by a static coefficient analysis methodology with a static coefficient of 1.

is then summed absolutely with the effects of the ETF. Only one ETF need be applied to equipment undergoing qualification. For equipment with multiple terminals, the ETF shall be applied to the terminal that creates the most critical effects.

Table A.2 specifies the required ETF for equipment qualification at the performance level; for qualification at the design level, the specified forces shall be divided by 2. The ETF considered in the qualification shall be stated in the seismic qualification report.

**Table A.2—Equivalent terminal forces for seismic qualification at performance level from IEEE Std 1527**

Voltage class	Direction	ETF	
		Moderate performance level (0.5 g)	High performance level (1.0 g)
< 110 kV < 90 kV DCV for surge arresters	Horizontal	None	None
110 kV to < 230 kV 90 to < 180 kV DCV for surge arresters		750 N	1500 N
≥ 230 kV ≥ 180 kV DCV for surge arresters		600 N	1200 N
All	Vertical	None	None

## A.2 Acceptance criteria

### A.2.1 Acceptance criteria for design level qualifications

#### A.2.1.1 Design level load combinations

Where appropriate this recommended practice recognizes both ASD and LRFD design methodologies. The load combinations to be used for ASD and LRFD methods shall be as follows:

$$ASD = 1.0D + 1.0E_{DL} + 1.0OP$$

$$ASD = 0.6D + 1.0E_{DL} + 1.0OP$$

$$LFRD = 1.2D + 1.4E_{DL} + 1.0OP$$

$$LFRD = 0.9D + 1.4E_{DL} + 1.0OP$$

Use the more critical of the two equations ASD or LFRD, where:

$D$  is the dead load

$E_{DL}$  is the earthquake load demand from the design level spectra

$OP$  is the normal operating load

#### A.2.1.2 Design level allowable strength/stress

The total loads/stresses found shall not exceed the allowable load/stresses. Allowable load/stress shall be as follows, except as modified in A.2.2.

- a) *Porcelain.* Porcelain insulators and insulating components of bushings shall meet the applicable requirements given in Annex X.
- b) *Composite.* The composite insulators and insulating components of bushings shall meet the applicable requirements given in Annex X. All other composite materials shall meet the requirements of f) or g).

The user is cautioned that composite insulators can yield extreme displacements. The user should verify that the actual equipment deflections can be accommodated by bus work design (see IEEE Std 1527).
- c) *Steel.* Latest edition of the AISC Manual of Steel Construction.
- d) *Aluminum.* Latest edition of the Aluminum Association's Aluminum Design Manual.
  - 1) *ASD:* Substation structures shall be designed with the safety factors specified for bridge-type structures.
  - 2) *LRFD:* The LRFD capacities given in the Aluminum Design Manual have resistance factors calibrated for building-type structures only. Consequently, the specifics of the design methodology are inconsistent with the objectives of this recommended practice and should therefore not be used.
- e) *Unreferenced steel and aluminum.* Structural steel or aluminum not specified in the references given in item c) or item d) may be used providing all of the following conditions are met:
  - 1) The material is not used in a bolted fastener.
  - 2) The physical properties of the material are documented to the extent that all data required for the application of the relevant formulae of the references exist.
  - 3) The material meets the acceptance criteria of the appropriate references given in either item c) or item d).
- f) *Other materials covered by code.* Recognized applicable codes that are appropriate for use with this recommended practice may be used for materials not covered in item a) through item d) of this subclause.
- g) *Other materials.* Any structural material other than those mentioned in item a) through item d) of this subclause and not covered by an existing acceptable code shall only be used when the following ASD criteria are met:
  - 1) When the complete material and structural properties of the material are documented to the satisfaction of the user and seismic specialist in writing.
  - 2) When the material is classified as being brittle, then the material stress must be compared with one of the following and shown to not exceed that value:
    - i) 50% of the yield strength when the yield strength is determined from 0.2% offset.
    - ii) 50% of the force or strength factor determined from a static test of non-ductile components (refer to A.3).
  - 3) When a material is classified as ductile, then the ASD stress must not exceed 50% of the yield stress and must have a factor of safety against buckling of 1.7.
- h) *Oil-filled bushings.* In addition to the criteria specified in item a) through item f), the tested design level stress/load shall not exceed 50% of the leakage stress/load. The leakage stress/load shall be taken as the maximum stress/load on a component before the onset of leakage.
- i) *Components with strength determined by static testing.* The allowable component loading shall be one half the applied static component load when qualifying by static testing of the component (see A.3.2.f).

### **A.2.1.3 Design level analysis**

Equipment qualification by design level analysis will be acceptable if the requirements of A.2.1.1 and A.2.1.2 are met.

### **A.2.1.4 Design time history shake-table test(s)**

Equipment qualification by design level time history test will be acceptable if the requirements of A.2.1.1, A.2.1.2, and applicable requirements in A.2.4 are met.

## **A.2.2 Acceptance criteria for performance level time history test qualifications**

Equipment qualification by performance level time history test will be acceptable if the following acceptance requirements are met:

- a) Insulating components that are in the direct load path of an expected conductor load shall be monitored for loads and stresses by strain gauges or strain bolts during the performance level time history test. The measured loads and stresses must then be utilized as detailed in A.1.2.4 to meet the performance level acceptance criteria detailed in Annex X with the inclusion of conductor load effects.
- b) Insulating components, including porcelain and their end fittings or composite polymers and their end fittings, shall not crack, slip, leak, or otherwise fail. The permanent deformation of composite polymers must be less than 5% of peak deflection from the time history test.
- c) Oil-filled or gas-filled bushings shall not leak.
- d) Ductile metal parts including support structures, and composite parts may elongate or bend slightly provided the damage does not affect the function of the equipment.
- e) Brittle metal parts shall not crack or fail.
- f) The equipment shall satisfy the applicable requirements of A.2.4.

In lieu of monitoring requirements specified in A.2.4.5 and Annex B through Annex P, Annex V, and Annex W, monitoring of stresses on ductile components may be omitted, except monitoring requirements for accelerations and displacements shall remain unchanged.

See 5.4.1 for additional information regarding testing at the performance level.

### **A.2.3 Acceptance criteria for qualification by static pull test**

The static pull test will be acceptable if the equipment and support do not fail, crack, slip, buckle, or show any other permanent distress. For oil- or gas-filled equipment, there shall be no oil or gas leakage before or after the pull test.

## **A.2.4 Additional requirements and acceptance criteria for qualification by time history test**

### **A.2.4.1 General**

Equipment and support shall not fail, crack, buckle, or show any other permanent distress during or after the design level time history test. Equipment and support shall not fail, crack, or sustain significant damage as described in 5.2.2.

#### **A.2.4.2 Functionality test**

The specified functions of the equipment shall be checked before and after the shake-table testing. The test will be acceptable if, after the test, the equipment continues to perform its intended functions as defined in the applicable annex or as agreed upon by the user. If demonstration of correct functions during the shake-table test has been specified, then the test will be considered acceptable if the equipment has performed the functions successfully within the accepted limits set down for these functions.

#### **A.2.4.3 Porcelain insulators and bushings**

When stresses on porcelain insulators or insulating components of bushings are used to assess their acceptability (see X.8.5), such stresses shall be determined from strain gauge measurements computed by using the mean modulus of elasticity ( $E$ ) of porcelain for the type of component being qualified or by calibration factor with pull tests of a measured demand and corresponding measured strain.

#### **A.2.4.4 Gasketed assemblies**

Equipment with gaskets shall not suffer from leakage, obvious permanent movement of the gasket, or permanent movement relative to the gasket.

#### **A.2.4.5 Monitoring of shake-table testing**

The following monitoring requirements shall be met:

- a) Strain gauges on insulators: Strain gauges are used to measure the moments at the base of porcelain and composite insulators, from which the equivalent cantilever load at the top of insulators can be determined during shake-table testing, and to assess conductor load effects. This is used for insulators such as, but not limited to station posts, instrument transformers, surge arresters, and bushings. Horizontal insulators supported at both ends shall have strain gauges applied at both ends of the insulator. Horizontal insulators acting as cantilevers need only have strain gauges applied at the supported end of the insulator. Four gauges are required to measure the axial strain around the insulator and should be positioned at 90° intervals. Locating strain gauges near stiffener plates, gussets, and welds should be avoided in order to obtain large representative strains at the section. Gauges can be positioned on the barrel of the lower flange or for porcelain at the root diameter, low on the porcelain. For composite insulators, gauges can be positioned on the lower barrel of the flange housing. Strain gauges for composite insulators may alternatively be positioned on the lower end of the insulator tube, about 30 mm (1.2 in) above the top of the lower end fitting after removing the sheath material to expose the core tube at the gauge locations, provided that electrical function tests are not affected, and the equipment is not offered to the end-user (A.1.2.1). The gauges shall be calibrated from cantilever pull tests, using a pull force that is large enough to obtain reliable calibration data.
- b) Strain gauges on equipment and support structure: Strain gauges are used to ensure that strains on the equipment and its support structure satisfy the requirements of the recommended practice. They should be placed at locations where largest strains are anticipated. These are critical variables associated with the test.
- c) Components with complex geometry: In order to evaluate the adequacy of components with complex geometry (A.3), a critical variable that can be measured during the shake-table test shall be identified. The critical variable shall be representative of the dominant force or action applied to the component under evaluation, and may be strains, displacements, or other responses. A.3 describes a static pull test to help ensure acceptable performance of the complex assembly and establishes the limit of the critical variable that can be experienced during the shake-table test.

- d) Displacements: Measure the horizontal displacements at the top of the support structure and at the conductor attachment points. Displacements derived by double integration of accelerations have historically yielded poor results and should not be used unless their accuracy can be validated.
- e) Strain bolts: Strain bolts are recommended to measure the anchorage loads of the equipment to its support structures and of the support structure to the shake table, but they are not required.
- f) Accelerometers: As a minimum, triaxial accelerometers shall be located on the table, at or close to the center of gravity of the equipment, if possible, at conductor attachment points, at the top of the equipment, and the top of the support, and as specified in an equipment-specific annex.
- g) Other measurements as specified in an equipment-specific annex.

## A.3 Static testing of components

### A.3.1 Scope of applicability

Static testing of components is a method to determine acceptable loading in lieu of either the stress monitoring, as given in A.2.4.5, or the stress calculations. The static testing of components is appropriate in the following circumstances:

- a) Test qualifications:
  - 1) Strain gauge/bolt application is not possible due to the inaccessibility of the component in the test configuration.
  - 2) The component material is incompatible with strain gauge technology.
  - 3) No appropriate holes for the use of strain bolts.
  - 4) The presence of complex geometry (e.g., gussets, cutouts, curves, tapered geometry, fastening interfaces, etc.) such that the location of maximum stress is not intuitive.
- b) Analytical qualifications:
  - 1) The presence of complex geometry (e.g., gussets, cutouts, curves, tapered geometry, fastening interfaces, etc.) such that the employed engineering theory cannot accurately determine the maximum stress.
  - 2) The material properties data of the component are limited or nonexistent (e.g., unique materials, the use of processes that alter material characteristics to an unknown extent).

### A.3.2 Test procedure

The test of the component shall consist of the application of static loads as follows:

- a) The component shall be restrained in its in-service configuration (refer to A.1.1.3).
- b) Loads shall be simultaneously and statically applied to the component in the directions of interest. Although the simulation of seismic loads is a triaxial load state, often an axis contributes minimal stress and can be dismissed.
- c) If testing is conducted in only one axis at a time, then the load magnitude should be increased 40% unless substantiated by an analysis dictating an alternative factor.
- d) The magnitude of loading shall be the level of loading at the performance level and the provisions in item b).
- e) Where practical, it is preferable to test to destruction or permanent yield of the component so that a definitive margin can be established.

- f) The level of loading required by item c) and item d) such that the component remains in a state that is in keeping with the aims of the seismic qualification objective (refer to 5.2) shall be called the static component load.
- g) It is preferable to conduct multiple tests of the component so that statistical variations can be established for the static component load.

## A.4 Design requirements

### A.4.1 General

Equipment, support structures, connections, and anchorages shall satisfy the requirements of A.2, and A.4.2 through A.4.7.

### A.4.2 Support structures

#### A.4.2.1 Acceptance criteria

The design of support structures shall satisfy the acceptance criteria specified in A.2.

#### A.4.2.2 Construction details

The details of design such as the materials used, fabrication details, and workmanship shall be as specified for the following materials:

- a) Rolled steel: AISC Manual of Steel Construction.
- b) Cold-formed steel: AISI North American Specification for the Design of Cold-formed Steel Structural Members.
- c) Aluminum: Aluminum Association ADM

#### A.4.2.3 External supply

If the support structure is designed by the manufacturer and is to be fabricated by the user, then the appropriate details shall be supplied to the user (fabrication drawings, bills of materials, weld details, etc.).

### A.4.3 Anchorage to concrete

#### A.4.3.1 General

All anchorage to concrete assemblies, including welds and anchor rods, shall be designed for loads resulting from the design level analysis or from the performance level test. Both the equipment manufacturer and the user must each do their part to ensure an adequate fastening system (that is, the design of the equipment interface above the concrete, the fastener, or weld itself and the interface within the concrete).

#### **A.4.3.2 Manufacturers requirements for anchor rods**

When anchor rods are specified, the manufacturer shall provide a design that conforms to the following:

- a) Size the anchorage assuming that the anchor rod material conforms to ASTM F1554 Grade 36 using the requirements of AISC, except that the interaction ratio shall not exceed 1.1.
- b) The anchor rods shall not be less than 19 mm (0.75 in) in diameter, unless it can be shown that the allowable stresses exceed the applied stresses by not less than a factor of two.
- c) The use of leveling nuts, if recommended, shall be in accordance with design methodologies outlined in ASCE 113.
- d) The minimum center-to-center spacing of anchors shall be as follows, where  $d$  is the anchor diameter:  $4d$  for cast in anchors that will not be torqued,  $6d$  for cast in anchors that will be torqued, and  $6d$  for post-installed anchors that will not be torqued. Spacing limits for torqued post-installed anchors and other exceptions to spacing shall be as determined in accordance with ASCE 113.
- e) Indicate on the seismic outline drawing restrictions, if any, for field-welding of attachments such as welded plate washers for anchor rods.

#### **A.4.3.3 Manufacturers requirements for welded anchorage**

When welded anchorage is specified, the manufacturer shall size the weld in accordance to the requirements of AISC.

#### **A.4.3.4 Users requirements for anchor rods**

When anchor rods are specified by the manufacturer, the user shall:

- a) Design the anchorage interface within the concrete in accordance to the provisions of ASCE Manual 113.
- b) The user may use a different grade or size of anchor rods provided that the capacity of such anchors is equal to or greater than the demand loading given by the qualification.
- c) Resizing anchors may require the use of field welded washers to enable better distribution of the equipment base shear to the anchor bolts. The user shall conform to manufacturer's restrictions related to welded washers.

#### **A.4.3.5 Users requirements for welded anchorage**

When welded anchorage is specified by the manufacturer, the user shall:

- a) Design the embedded interface within the concrete in accordance to the provisions of ASCE Manual 113 and ACI 318.
- b) Ensure that the welds conform to the requirements specified by the manufacturer.

#### **A.4.4 Structural bolts**

Structural bolts, including equipment and support bolts, with an ultimate tensile (minimum) strength greater than 1040 MPa (151 ksi) shall not be used. Structural bolts 10 mm (0.41 in) and smaller shall not be used unless it can be shown that the allowable stresses exceed the applied stresses by not less than a factor of 1.2. These requirements do not apply to non-structural bolts (i.e., material not in the load path).

#### **A.4.5 Structural steel**

Structural steel with a yield strength greater than 650 MPa (94.3 ksi) or an ultimate tensile strength of 965 MPa (140 ksi) shall not be used, unless approved in writing by the user. These requirements do not apply to non-structural materials (i.e., material not in the load path).

#### **A.4.6 Composite insulators**

Composite insulators shall satisfy the shed seal tests as described in X.9.5.

#### **A.4.7 Seismic protective systems**

Seismic protective systems including devices that modify the frequency or damping of a system shall not be used unless permitted in writing by the user or user's agent. Manufacturers who pre-qualify equipment with seismic protective devices should be aware that such equipment requires design by the end-user to accommodate large displacements and other checks for suitability of the use of such devices for the installation site, and may not be acceptable. The use of such devices shall conform to Annex W.

### **A.5 Seismic test qualification report**

#### **A.5.1 Preparation of the test qualification report**

A seismic qualification report, including a corrected (as-tested) test plan, shall be prepared and supplied to the user for moderate and high qualification levels. The report shall contain the information and data applicable to the type of test conducted, and should be formatted as described in Annex T. The report is to be supplied in two parts. Part 1 should contain the key information listed in the applicable annexes, including Annex T. Part 2 should contain the detailed data and charts that support the key information. The Test Laboratory Report meets the requirements for the second part. The report, test(s), test plan, and all test results, calculations, seismic outline drawing, charts, and records that show compliance with the seismic requirements of this recommended practice shall be approved before issuance to the user by a qualified seismic specialist (A.5.2) competent in seismic testing and qualification of electrical equipment. The seismic specialist shall sign the report, test plan, and seismic outline drawing.

The documentation demonstrating compliance with the requirements of A.5 shall be provided to the user or the user's agent upon request.

The report shall be supplied to the user or the user's agent in English and in the units required by the initial user, if there is one. Should corrections or additions be needed to the initial report, only those pages needing revisions need be corrected and submitted for acceptance. Once agreement of corrections and omissions has been reached, then the entire report shall be resubmitted to the user with the corrections and omissions incorporated in their proper location in the report and the errors removed.

#### **A.5.2 Seismic specialist-testing**

The seismic specialist shall meet the following requirements:

- a) Understands and complies with the applicable requirements of this recommended practice.
- b) Provides a report acceptable to the user. An acceptable report provides the data and results required herein, in sufficient detail, which is easily understood, with labeled sketches and charts, organized as described in Annex T, with calculations that meet industry standards of competency.

- c) Has had an appropriate and adequate education in seismic testing. (The education may be on-the-job training.)
- d) Has had appropriate and adequate experience in preparing electrical equipment seismic testing-qualification reports.

If any of the requirements of A.5.2.a) though A.5.2.d) are not met, the person will not be considered qualified to sign the seismic qualification report and documents described in A.5.1.

The following criteria will be considered, but they are not mandatory:

- Holds a valid Civil, Structural, or Mechanical Professional Engineering license.
- Has taught or written papers concerning seismic testing.
- Has directed and signed seismic testing-qualification reports.

### **A.5.3 Equipment description and test plan**

In this subclause, the equipment to be tested is identified and an instrumentation plan, test methods, and test sequence are established. A test plan shall be prepared and approved by the seismic specialist before the test, except in the case of a static pull test. This plan, as a minimum, shall contain the following:

- a) *Description of equipment to be tested.* This should include the general description (such as disconnect switch, capacitor voltage transformer), its rated operating voltage, rated operating current, short circuit current, and rated BIL voltage. Applicable drawings or part numbers such as outline drawings, assembly drawings, insulator drawings, and frame drawings that define the equipment to be tested should be listed.
- b) *Monitoring requirements.* An outline drawing of the equipment showing the proposed locations of the monitoring devices, such as accelerometers and strain gauges using the same transducer numbering system as contained in the shake-table laboratory test report. Add to the bottom of the list other instruments not mounted on the shake table, such as those items used for the pull test needed for composite insulators or polymer arresters.
- c) *Functional test.* Description of functional tests and where test will be performed.
- d) *Qualification level.* The plan shall state the qualification level (moderate/high, design/performance level).
- e) *Listing of tests.* The plan shall include a sequence listing of all tests to be performed at the test facility.

See Annex T for an example of a test plan.

The test plan shall be submitted to the potential user(s) for review a minimum of three months before the scheduled shake-table test. If the potential users are to witness the test, 4.10 should be followed.

Static load testing does not require a test plan.

### **A.5.4 Data (shake-table test)**

The report shall include the following:

- a) Tabulated summary of maximum controlling (where applicable) stresses, loads, and/or deflections (f), allowable capacities (F), and their margins, starting in order with the equipment component's smallest (F/f) factor, for the support structure and equipment. The part 2 source page number of the

data shall be referenced (see the “Example of the Shake-Table Test—Summary of Maximum Stresses, Loads, etc.” in Annex T).

- b) Location, telephone number of test laboratory, and date of test.
- c) Test engineer’s name and title.
- d) Description of testing equipment, test method(s), and instrumentation.
- e) Photographs showing the test setup and instrumentation location.
- f) Sketch showing location of strain gauges and accelerometers.
- g) Anchorage of the equipment calculation, details, and material strength.
- h) Serial number of the equipment and equipment components being tested.
- i) Resonant frequencies and damping, including resonant frequency search records for pre- and post-test, and supporting calculations.
- j) Comparison of the RRS and the TRS.
- k) Tabulated list of maximum accelerations, stresses, and displacements at measurement points of all tests, including resonant frequency searches (see “Example of Data Measurement Points” in Annex T).
- l) Reactions (report dead and seismic loads separately) at base support points and associated calculations.
- m) Indicate whether MAF or ETF was utilized for terminal loads and the magnitude used.
- n) List any anomalies observed, and document any areas of distress or damage.
- o) Modifications required to pass the test.
- p) List of utility (user) representative(s), if any, who witnessed the testing and which part(s) of the testing was witnessed.
- q) Tabulated list of acceptance criteria allowable values and performance values as required.
- r) A picture or graphical reproduction of the identification plate (see A.7).
- s) Document justifying the insulator strength.
- t) A calibration list of test laboratory equipment that lists the equipment to be used during the test and the last calibration date.
- u) Describe supplemental work if any (refer to A.5.6).
- v) Test results for any static testing of components (refer to A.3).
- w) Shed seal test for composites (refer to Annex K for polymer surge arresters and Annex X for composite insulators and/or composite bushings).

A video recording of the tests shall be provided with the test report. The video shall be labeled with the following information: equipment type, report number, and date of testing.

#### **A.5.5 Seismic outline drawing (shake-table test)**

The supplier shall also include in the report a one page, 280 mm x 432 mm (11 in x 17 in), A3, 216 mm x 280 mm (8½ in x 11 in), or A4 seismic outline drawing of the equipment and any support. The seismic outline drawing should be as shown in accordance with Figure T.1 or Figure T.2 in Annex T. All of the following shall be shown on one drawing:

- a) Include in drawing block:

- 1) Type of equipment.
  - 2) Equipment voltage.
  - 3) Approved by.
  - 4) Report or contract number.
  - 5) Statement referencing this recommended practice/version (year) and qualification level (high or moderate).
  - 6) Drawing number block.
- b) Total weight.
  - c) Dimension and weight of support (if applicable) and major components of the equipment.
  - d) Location of the center of gravity of the equipment, with support (if applicable) and location of the center of gravity of the equipment only.
  - e) Anchoring details showing bolt and weld sizes, their type and grade, and their locations.
  - f) Resonant frequencies and damping ratio of the equipment.
  - g) The test(s) performed to qualify the equipment.
  - h) Maximum deflection(s) at conductor attachment point(s).
  - i) Controlling reactions at the base of the supporting structure for seismic loads and for seismic plus normal operating loads. Report dead and seismic loads separately.
  - j) Date of test.
  - k) Outline view(s) of the equipment and support, giving the x, y, and z axes used in the report. Note the equipment outline must be kept recognizable, but simple with minimal detail (see Annex T for an example).

Only that information listed in A.5.5 should be shown on the seismic outline drawing. Additional information not listed in A.5.5 should be shown on separate drawings or sheets.

#### **A.5.6 Supplemental work and options**

A Supplemental Work and Options section shall be included in the report. It shall include a listing of supplemental work and options, such as the following:

- a) Anything requiring written approval by the user.
- b) The manufacturer used materials not covered in item a) through item d) of A.2.1.2, such as structural plastics, which are not directly provided for in this recommended practice, but were approved by the original user (note that the use of such materials must be approved by all subsequent users also).
- c) The original user required the seismic specialist to also be a licensed Engineer.
- d) The manufacturer chooses to exercise one of the options of 4.6.
- e) Or the section shall state that there was no supplemental work or options performed.

## A.6 Seismic analysis-qualification report

### A.6.1 Preparation of the analysis-qualification report

A seismic report shall be prepared and supplied to the user for moderate and high design level qualifications. The report should be as described in Annex S. The report, calculations, seismic outline drawing, charts, and records that show compliance with the seismic requirements of this recommended practice shall be approved and signed before issuance to the user by a qualified seismic specialist (A.6.2) competent in seismic analysis and qualification of electrical equipment. Test reports and plans used to justify any part of the analysis shall also be approved and signed before issuance to the user by the seismic specialist.

The report should include a general description of the equipment (such as disconnect switch, capacitor voltage transformer), its rated operating voltage, rated operating current, short circuit current, and rated BIL voltage. Applicable drawings or part numbers such as outline drawings, assembly drawings, insulator drawings, and frame drawings that define the equipment analyzed should be listed.

The documentation demonstrating compliance with the requirements of A.6 shall be provided to the user or the user's agent upon request.

The report shall be supplied to the user or the user's agent in English and in the units required by the initial user, if there is one. Should corrections or additions be needed to the initial report, the entire final report shall be resubmitted to the user with the corrections and omissions included, once agreement of corrections and omissions have been reached.

### A.6.2 Seismic specialist analysis

The seismic specialist shall meet the following requirements:

- a) Understands and complies with all requirements of this recommended practice.
- b) Provides a report acceptable to the user. An acceptable report provides the data and results required herein, in sufficient detail, which is easily understood, with labeled sketches and charts, organized as recommended in Annex S, with calculations that meet industry standards of competency.
- c) Uses assumptions generally acceptable to experienced seismic specialists.
- d) Has had an appropriate and adequate education in seismic analysis.
- e) Has had appropriate and adequate experience in preparing electrical equipment seismic analysis-qualification reports.

If any of the requirements of A.6.2.a) through A.6.2.e) are not met, the person will not be considered qualified to sign the seismic qualification report and documents described in A.6.1.

The following criteria will be considered, but are not mandatory:

- Holds a valid Civil, Structural, or Mechanical Professional Engineering license.
- Has taught or written papers concerning seismic analysis.
- Has directed and signed seismic analysis-qualification reports.

### A.6.3 Data (analysis)

The report shall include the following:

- a) Tabulated summary of maximum controlling stresses, loads, and/or deflections (f), allowable capacities (F), and their margins, starting in order with the equipment component's smallest (F/f) factor, for the support structure and equipment. (See the "Example of the Dynamic Analysis—Summary of Maximum Stresses, Loads, etc." in Annex S.)
- b) Tabulated list of the controlling load cases showing maximum accelerations, stresses or loads, and displacements at critical points, if by dynamic analysis.
- c) Tabulated list of equipment and structure reactions at foundation support points, including magnitude and direction, at each reaction point for each load case.
- d) Anchorage details, including size, location, and material strength for structural members, bolts, or plates.
- e) Maximum input (ground) accelerations.
- f) Describe supplemental work if any (refer to A.6.5).
- g) Method of analysis and computer program name, if computer program used.
- h) Assumptions made in modeling the equipment and supporting structure.
- i) Tabulated list of material types and strengths.
- j) Selected inputs and outputs from computer programs necessary to demonstrate the requirements of this recommended practice.
- k) Model<sup>18</sup> with labeled nodes, members, and dimensions, if by dynamic analysis.
- l) Member properties.
- m) Plot of all significant modes considered, if by dynamic analysis.
- n) Tabulated list of acceptance criteria allowable values and performance values.
- o) A picture or graphical reproduction of the identification plate (see A.7).
- p) Document justifying the insulator strength.
- q) Indicate whether MAF or ETF was utilized for terminal loads and the magnitude used.
- r) Shed seal test for composites (refer to Annex K for polymer surge arresters and Annex X for composite insulators and/or composite bushings).

#### A.6.4 Seismic outline drawing (analysis)

The supplier shall also include in the report a one page 280 mm x 432 mm (11 in x 17 in), A3, 216 mm x 280 mm (8½ in x 11 in), or A4 seismic outline drawing of the equipment and support, if any support. The seismic outline drawing should be as shown in accordance with Figure S.1 or Figure S.2 in Annex S. All of the following shall be shown on one drawing:

- a) Include in drawing block:
  - 1) Type of equipment.
  - 2) Equipment voltage.
  - 3) Approved by.
  - 4) Report or contract number.

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<sup>18</sup> If the model is complex, with many nodes and members, the model may be simplified provided all critical nodes and members are shown.

- 5) Statement referencing this recommended practice/version (year) and qualification level (high or moderate).
  - 6) Drawing number block.
  - 7) Total weight.
- b) Dimensions and weight of support (if applicable) and major components of the equipment.
  - c) Location of the center of gravity of the equipment, with support (if applicable) and location of the center of gravity of the equipment only.
  - d) Anchoring details showing bolt and weld sizes, their type and grade, and their locations.
  - e) Resonant frequencies and damping ratio of the equipment, if by dynamic analysis.
  - f) The analysis method used.
  - g) Any tests used to qualify the equipment, including the acceleration levels used.
  - h) Maximum deflection(s) at conductor attachment point(s).
  - i) Controlling reactions at the base of the supporting structure for seismic plus normal operating loads. Report dead and seismic loads separately.
  - j) Date prepared.
  - k) Outline view(s) of the equipment and support.

#### **A.6.5 Supplemental work and options**

A Supplemental Work and Options section shall be included in the report. It shall include a listing of supplemental work and options, such as:

- a) Anything requiring written approval by the user.
- b) The manufacturer used materials not covered in item a) through item d) of A.2.1.2, such as structural plastics, which are not directly provided for in this recommended practice, but were approved by the original user (note that the use of such materials must be approved by all subsequent users also).
- c) The original user required the seismic specialist to also be a licensed engineer.
- d) The manufacturer chooses to exercise one of the options of 4.6.
- e) Or the section shall state that there was no supplemental work or options performed.

#### **A.7 Seismic qualification identification plate**

##### **A.7.1 Qualifications using the current version of the recommended practice**

The seismic qualification identification plate shall be designed and attached to the equipment to last its service life. The plate shall use the following designation:

Seismic Qualification plate: XYZ Manufacturing Company  
IEEE 693-201X—[DATE REPORT SIGNED]—QUALIFICATION LEVEL—[REPORT NUMBER] —  
QUALIFICATION METHOD

An example plate is shown below for a 121 kV power circuit breaker:

Seismic Qualification plate: XYZ Manufacturing Company  
IEEE 693-201X—[12/2018]—Moderate PL—[56877 FL]—Time history shake-table test

IEEE 693-201X	This recommended practice and version used
[12/2018]	Date (Month/Year) testing or analysis report signed
Moderate PL	Seismic qualification level: High or moderate; design level (DL) or performance level (PL)
[56877-FL]	Seismic qualification report number
Time history shake-table test	Qualification method used: Time history shake table test, static pull test, dynamic analysis, static coefficient analysis, static analysis

This example illustrates a seismic identification plate for a 121 kV power circuit breaker that was qualified using performance level shake-table testing in lieu of the IEEE Std 693 specified dynamic analysis.

### A.7.2 Qualifications using a previous version of the recommended practice

Equipment that has been qualified using a previous version of this recommended practice shall use the following designation:

Seismic Qualification plate: XYZ Manufacturing Company  
IEEE 693-2005—[DATE ORIGINAL REPORT SIGNED]—QUALIFICATION LEVEL—[REPORT NUMBER]—QUALIFICATION METHOD  
IEEE 693-201X—[DATE SUPPLEMENTAL REPORT SIGNED]—SUPPLEMENTAL REPORT NUMBER

An example plate is shown below for a 245 kV power circuit breaker that was qualified to a previous version of IEEE Std 693 with a Supplemental Report to conform to the current recommended practice:

Seismic Qualification plate: XYZ Manufacturing Company  
IEEE 693-2005—[12/2007]—High DL—[QR 56877]—Time history shake-table test  
IEEE 693-201X—[6/2019]—Supplemental Report [SR 56877]

IEEE 693-2005	Recommended practice and version of original qualification
[12/2007]	Date (Month/Year) original testing or analysis report signed
High DL	Seismic qualification level: High or moderate, design level (DL) or performance level (PL)
Time history shake-table test	Qualification method used: Time history shake-table test, static pull test, dynamic analysis, static coefficient analysis, static analysis
[QR 56877]	Seismic qualification report number (original qualification)
IEEE 693-201X	Recommended practice and version used for Supplemental Report
[6/2019]	Date (Month/Year) testing or analysis Supplemental Report signed

This example illustrates the seismic identification plate for a 245 kV power circuit breaker that was originally qualified to a previous version of IEEE Std 693-2005 at the high design level (0.5 g ZPA RRS) by time history shake-table test. A Supplemental Report to the current version of the recommended practice provides the supporting documentation.

## Annex B

(normative)

### Non-categorized equipment

NOTE—Qualification requirements for specific equipment types are given in Annex C through Annex P, Annex V, and Annex W. This annex may be used, if applicable, to qualify equipment that is not specifically provided for in Annex C through Annex P, Annex V, and Annex W.

#### B.1 General

##### B.1.1 Scope of applicability

The requirements of this annex are applicable to equipment not specifically addressed in Annex C through Annex P, Annex V, and Annex W. Such equipment, within the context of this annex, will be termed “non-categorized” equipment.

##### B.1.2 Additional requirements from the user or the user’s agent

Unlike the equipment-specific annexes (Annex C through Annex P, Annex V, and Annex W), the non-categorized equipment qualification does not benefit from having specific qualification techniques associated with it (refer to Q.5). Accordingly, the user or the user’s agent must, in addition to the suggested information given in 4.3 and Annex A, provide the following:

- a) The qualification method. To ensure that the qualification method is conservative, the allowed qualification methods are restricted to time history shake-table test or dynamic analysis. No optional qualification techniques are permitted for non-categorized equipment.
- b) The qualification level for testing. The requirement of this recommended practice is to perform testing at the performance level unless it is explicitly allowed to test the equipment to the design level as discussed in 5.4. It is the user’s option to allow for design level testing of non-categorized equipment in lieu of performance level testing.
- c) Authorization to use other materials if required (refer to A.2.1).

##### B.1.3 High seismic qualification level

The requirements of Annex B, with the exception of B.1.4 and B.1.5, are applicable non-categorized equipment for qualification to the high seismic level.

##### B.1.4 Moderate seismic qualification level

The requirements of Annex B, with the exception of B.1.3 and B.1.5, are applicable non-categorized equipment for qualification to the moderate seismic level.

### **B.1.5 Low seismic qualification level**

The requirements of A.1.1.9 are applicable to all non-categorized equipment for qualification to the low seismic level.

## **B.2 Operational requirements**

The equipment and supporting structure shall be designed to meet the seismic qualification objective described in 5.2. In addition, equipment shall maintain the correct operational state during the seismic event.

## **B.3 Seismic qualification methods**

Seismic withstand capability shall be demonstrated as directed by the user or the user's agent (either time history shake-table testing or dynamic analysis).

## **B.4 Qualification procedures**

### **B.4.1 General**

The qualification procedure shall be according to the requirements of A.1.

### **B.4.2 Qualification procedure for time history shake-table testing**

The equipment and structure, if required, shall be tested according to the requirements of A.1.2. A resonant frequency search shall be performed according to the requirements of A.1.2.5.

### **B.4.3 Monitoring requirement for resonant frequency search and time history test**

Critical locations on the equipment and supporting structure shall be monitored for maximum displacement, maximum accelerations, and maximum loading or stresses on equipment/support elements. Monitoring requirements shall be in accordance with A.2.4.5 and the following:

- a) Maximum displacement: Conductor attachment points of insulators and bushings.
- b) Maximum accelerations (vertical and horizontal): Top of insulators and bushings.
- c) Maximum stresses: Base of supporting structure's leg(s).

### **B.4.4 Qualification procedure for dynamic analysis**

Non-categorized equipment to be qualified by dynamic analysis and shall meet the general requirements of A.1.4 and the specific requirements of A.1.4.7.

## **B.5 Acceptance criteria**

### **B.5.1 General**

The qualification will be considered acceptable if the requirements given in this annex, the applicable clauses, and the requirements given in B.5.1 and B.5.2 are met.

The general requirements are as follows:

- a) The general criteria specified in A.2.1 and A.2.2.
- b) If the time history test is required, the requirements of A.2.1 or A.2.2.
- c) If dynamic analysis is required, the requirements of A.2.1.

### **B.5.2 Functional requirements for shake-table tested equipment**

The specified functions of the equipment shall be checked before and after the shake-table testing. The test will be acceptable if, after the test, the equipment continues to perform its intended function as defined by the manufacturer. The test will be considered acceptable if the equipment has performed the functions successfully within the acceptance limits set by the manufacturer and as agreed with the user.

## **B.6 Design requirements**

The equipment, support, and anchorage shall be designed according to A.4.

## **B.7 Report**

### **B.7.1 Report for shake-table test**

A report shall be prepared and supplied. The report shall be in accordance with A.5.

### **B.7.2 Report for dynamic analysis**

A report shall be prepared and supplied. The report shall be in accordance with A.6.

### **B.7.3 Seismic identification plate**

A seismic identification plate shall be attached to each piece of equipment supplied. The plate shall be as specified in A.7.

## **Annex C**

(normative)

### **Circuit breakers**

#### **C.1 General**

##### **C.1.1 Voltage classes and other characteristics**

The voltage/voltage class, kV, as used in this annex, is the rated maximum voltage as defined in ANSI C37.06. In the case where the voltage to ground is greater than the rated voltage, e.g., a series capacitor bypass circuit breaker, the higher voltage shall apply.

##### **C.1.2 High seismic qualification level**

The requirements of Annex C, with the exception of C.1.3 and C.1.4, are applicable to all circuit breakers for qualification to the high seismic level.

##### **C.1.3 Moderate seismic qualification level**

The requirements of Annex C, with the exception of C.1.2 and C.1.4, are applicable to all circuit breakers for qualification to the moderate seismic level.

##### **C.1.4 Low seismic qualification level**

The requirements of A.1.1.9 are applicable to all circuit breakers for qualification to the low seismic level.

#### **C.2 Operational requirements**

The circuit breaker and supporting structure shall be designed to meet the seismic qualification objective described in 5.2. In addition, equipment shall maintain the correct operational state during the seismic event.

#### **C.3 Seismic qualification methods**

Seismic withstand capability shall be demonstrated as follows:

Greater than 550 kV	By design level shake-table testing	C.4.1
170 kV to 550 kV	By performance level shake-table testing	C.4.2
123 kV to < 170 kV	By dynamic analysis	C.4.3
38 kV to < 123 kV	By static coefficient method	C.4.4
Less than 38 kV	By inherently acceptable	C.4.5

## C.4 Qualification procedures

### C.4.1 Design level time history shake-table testing

#### C.4.1.1 General

The qualification procedures shall be according to the requirements of A.1.

For circuit breakers whose poles are dynamically independent, only one pole need be tested. The tested equipment shall include the control cabinet, including stored energy sources, and the associated current transformer, if applicable.

The qualification procedure shall be in five stages:

- a) Stage 1: Resonant frequency search. A resonant frequency search shall be conducted to determine resonant frequencies according to the requirements of A.1.2.5.
- b) Stage 2: Time history test. The equipment and support structure shall be tested according to the requirements of A.1.2. The circuit breaker shall be tested in both the closed and open positions. Pressurization is not required for this stage.
- c) Stage 3: Time history operational test. The circuit breaker and support structure shall be subjected to the same test described above in stage 2 with the addition of a breaker open-close-open (O-C-O) operation, during the strong motion. Breaker operation should be initiated at approximately the time at which the normalized Arias Intensity of 50% of maximum is achieved for one horizontal component of motion. During this test, the gas breakers shall be filled with gas at the rated operating pressure. Gas for pressurizing the breaker need not be SF<sub>6</sub>.
- d) Stage 4: Resonant frequency search. A resonant frequency search shall be conducted according to the requirements of A.1.2.5.

To prevent injury or damage from possible failure of pressurized components, test with protective barriers and other appropriate precautions, as needed. As a minimum, all precautions shall be in accordance with any laboratory and legal requirements.

#### C.4.1.2 Monitoring requirements

Critical locations on the circuit breaker and supporting structure shall be monitored during all stages required above and for each test run for maximum displacement, maximum accelerations, and maximum loading or stresses. Monitoring requirements shall be in accordance with A.2.4.5 and the following:

- a) Maximum displacement: Top of bushing or connection point of conductor to equipment.
- b) Maximum accelerations (vertical and horizontal): Top of bushing or insulator.
- c) Maximum stresses: Base of supporting structures leg.

To detect relay bounce and to verify that false operation will not occur, the following components shall be energized and monitored during stage 2 and stage 3 tests:

- The trip and close circuits and mechanism motor shall be energized.
- The X and Y relay contacts and SF<sub>6</sub> density switch contacts shall be monitored.

The timing characteristics of the circuit breaker and the measurement of the resistance of the current carrying parts shall be recorded before the testing begins and as a minimum after completion of the last shake-table test. Insulating gas pressure readings and leak tests, using a portable leak detector, shall be made directly after each pressurized shake-table test to detect possible leaks.

The equipment and supports shall be inspected for cracking, buckling, or other types of failure or distress. Gaskets associated with support columns and bushings shall be inspected for evidence of slippage.

#### **C.4.1.3 Production tests after shake-table testing**

The circuit breaker shall undergo standard production tests after the completion of the shake-table tests. Some tests may need to be performed at a high voltage laboratory separate from the shake table test facility.

#### **C.4.2 Performance level time history shake-table testing**

##### **C.4.2.1 General**

The qualification procedures shall be according to the requirements of A.1.

For circuit breakers whose poles are dynamically independent, only one pole need be tested. The tested equipment shall include the control cabinet, including stored energy sources, and the associated current transformer, if applicable.

The qualification procedure shall be in four stages:

- a) Stage 1: Resonant frequency search. A resonant frequency search shall be conducted to determine resonant frequencies according to the requirements of A.1.2.5.
- b) Stage 2: Time history test. The equipment and support structure shall be tested according to the requirements of A.1.2. The circuit breaker shall be tested in both the open and closed positions. Pressurization is not required for this stage.
- c) Stage 3: Time history operational test. The circuit breaker and support structure shall be subjected to the same test described above in stage 2 with the addition of a breaker open-close-open (O-C-O) operation, during the strong motion. Breaker operation should be initiated at approximately the time at which the normalized Arias Intensity of 50% of maximum is achieved for one horizontal component of motion. During this test, gas breakers shall be filled with gas at the rated operating pressure. Gas for pressurizing the breaker need not be SF<sub>6</sub>.

To prevent injury or damage from possible failure of pressurized components, test with protective barriers and other appropriate precautions, as needed. As a minimum, all precautions shall be in accordance with any laboratory and legal requirements.

##### **C.4.2.2 Monitoring requirements**

Monitoring requirements for performance level testing are the same as those required for design level testing as detailed in C.4.1.2 with the following exception: monitoring stresses on the base of the supporting structure legs can be excluded from the performance level test.

#### **C.4.2.3 Production tests after shake-table testing**

The circuit breaker shall undergo standard production tests after the completion of the shake-table tests. Some tests may need to be performed at a high voltage laboratory separate from the shake-table test facility.

#### **C.4.3 Dynamic analysis**

The qualification procedure shall be according to the general requirements of A.1.4 and the specific requirements of A.1.4.7.

The analyzed equipment shall include the control cabinet, including stored energy sources, and associated current transformer, if applicable.

#### **C.4.4 Static coefficient analysis**

The qualification procedure shall be according to the general requirements of A.1.4 and the specific requirements of A.1.4.6. The static coefficient may be taken as 1.0.

#### **C.4.5 Inherently acceptable**

The qualification procedure shall be according to the requirements of A.1.5.

### **C.5 Acceptance criteria**

#### **C.5.1 General**

The qualification will be considered acceptable if the requirements given in this annex, the applicable clauses and the requirements given in C.5.1 and C.5.2 are met.

The general requirements are as follows:

- a) The general criteria of A.2.1 for design level qualifications and A.2.2 for performance level qualification. Also, there shall be no evidence of support column or bushing gasket slippage.
- b) For the design level time history test, the requirements of A.2.1.4.
- c) For the performance level time history test, the requirements of A.2.2.
- d) For the dynamic and static coefficient analysis, the requirements of A.2.1.3.

#### **C.5.2 Functional requirements for shake-table tested equipment**

The equipment shall meet the requirements of A.2.4.2.

The circuit breaker shall maintain the correct operational state; its trip coils shall perform their desired function, and contact bounce of circuits shall not occur to the extent that malfunction or mis-operation will occur during testing.

No leaks are found using a portable leak detector.

There shall not be a significant change in resistance readings between the terminals of each pole of the circuit breaker when measured in accordance with the manufacturer's procedures. If changes in readings do occur, they shall be within the tolerances in the manufacturer's specifications.

Changes in the opening and closing timing parameters, which shall include, as a minimum, open (contact part) time and opening velocity, and close (contact make) time and closing velocity, shall not exceed normal operation-to-operation variations, which are typically within a time of milliseconds.

Passage of the 1-min high-voltage withstand tests as specified by 5.16 of IEEE Std C37.09 is required. These tests will have to be performed in a high voltage laboratory. The tests should be performed in accordance with the manufacturer's production test procedures.

## **C.6 Design requirements**

The equipment and support shall be designed according to A.4.

## **C.7 Report**

### **C.7.1 Report for shake-table test**

#### **C.7.1.1 General**

The report shall be in accordance with A.5.

#### **C.7.1.2 Timing and resistance**

The circuit breaker's pre-test and post-test opening and closing-timing characteristics and the resistance measurements of its current carrying parts shall be included in the report. Pre-test characteristics and measurements shall be provided before the beginning of shake-table tests.

#### **C.7.1.3 Circuits monitoring**

A list of circuits that were monitored along with any indication of a change in status during the tests shall be included in the report.

### **C.7.2 Report for dynamic or static analysis**

The report shall be in accordance with A.6.

## **C.8 Seismic identification plate**

A seismic identification plate shall be attached to each piece of equipment supplied. The plate shall be as specified in A.7.

## Annex D

(normative)

### Transformers and liquid-filled reactors

#### D.1 General

##### D.1.1 Voltage classes and other characteristics

For transformers and liquid-filled reactors, the voltage/voltage class, kV, as used in this annex is the highest voltage for the tank internals and attachments exclusive of bushings and surge arresters. The voltage/voltage class for bushings and arresters is the nominal system voltage as defined in IEEE Std C57.12.00.

##### D.1.2 High seismic qualification level

The requirements of Annex D, with the exception of D.1.3 and D.1.4, are applicable to transformers and liquid-filled reactors for qualification to the high seismic level.

##### D.1.3 Moderate seismic qualification level

The requirements of Annex D, with the exception of D.1.2 and D.1.4, are applicable to all transformers and liquid-filled reactors for qualification to the moderate seismic level.

##### D.1.4 Low seismic qualification level

The requirements of A.1.1.9 are applicable to all transformers and liquid-filled reactors for qualification to the low seismic level.

#### D.2 Operational requirements

Transformers and liquid-filled reactors shall be designed so there will be neither structural damage nor loss of function during and after an earthquake when subjected to design seismic loads occurring simultaneously with dead and normal operation loads.

#### D.3 Seismic qualification methods for tank internals and attachments

Seismic withstand capability shall be demonstrated as follows:

Transformers and liquid-filled reactors (kV referenced is the high side of the transformer and liquid-filled reactors), except bushings and surge arresters:

Greater than 34.5 kV	By static analysis	D.4.1, D.4.2
Less than or equal to 34.5 kV	By inherently acceptable	D.4.3

## **D.4 Qualification procedures for transformers tanks**

### **D.4.1 Qualification of tank components (excluding bushings and appendages)**

The qualification procedure shall be in accordance with A.1.1. The transformer tank, core, coils, anchorage, and other components other than appendages, bushings, and surge arresters shall be qualified using static analysis according to the requirements of A.1.4.5.

The static analysis calculations shall include verification of the load path from the core, coils, tank, and base to the anchorage for all three orthogonal axes. All components of the load path shall have sufficient rigidity to restrain the core and coil from shifting. Sketches shall be provided with the analysis that clearly show a complete load path(s) to the anchorage, see Figure A.3. Load path parts and members shall be clearly labeled and dimensioned. Section properties, calculated stresses, and allowable stresses of all load path parts and members shall be provided.

### **D.4.2 Qualification of appendages, such as radiators, conservators, and control cabinets**

The qualification procedure shall be in accordance with A.1.1. Appendages such as radiators and conservators shall be qualified by static analysis according to the requirements of A.1.4.5, where the acceleration values are multiplied by 3. Control cabinets shall be qualified by static analysis according to the requirements of A.1.4.5, where the acceleration values are multiplied by 1.5.

### **D.4.3 Transformers qualified as inherently acceptable**

The qualification procedure shall be in accordance with the requirements of A.1.5.

## **D.5 Qualification procedures for bushings**

### **D.5.1 Voltage classes and qualification methods for bushings**

The qualification procedure shall be according to the requirements of A.1.1.

The seismic qualification method for bushings:

Greater than 138 kV class	By performance level time history shake table test	D.5.2
Greater than 34.5 kV to 138 kV class	By static pull test	D.5.3
Less than or equal to 34.5 kV class	By inherently acceptable	D.5.4

### **D.5.2 Time history shake-table tests**

#### **D.5.2.1 Test procedure-time history test**

Bushings above 138 kV class shall be qualified by time-history test in accordance with the requirements of A.1.2, except as described herein.

Projection of bushing performance beyond the actual tested level is difficult due to the typical non-linear behavior of bushings. Because bushings are not mounted directly to the ground or on simple support structures, the ground accelerations can be amplified through the transformer tank, and the as-mounted frequency may be lowered, thus possibly increasing spectral accelerations to which the bushing is subjected. For these reasons, the following additional requirements/adjustments shall be applied:

- a) Each bushing shall be tested at no less than its in-service slope (the slope angle measured from vertical). It is recommended that the bushing be tested at 20 degrees measured from vertical. Hence, the bushing qualification will be acceptable for use on all transformers with angles from vertical to 20 degrees. In service mounting of bushings at an angle greater than that which it was tested will negate the qualification.
- b) The bushing shall be mounted on a rigid frame. The rigid frame shall have its lowest horizontal frequency not less than 24 Hz demonstrated by analysis with the weight of the bushing and its mounting plate attached to the top of the frame.
- c) A resonant frequency search shall be conducted according to A.1.2.5.
- d) A modified Performance-Level Required Response Spectrum as described below shall be developed for the bushing time history test.
  - 1) The accelerations of the Performance-Level spectrum of the applicable level shall be multiplied by 2 to account for potential amplification of the transformer that supports the bushing.
  - 2) The spectral acceleration of the plateau of the modified Performance-Level Required Response Spectrum shall be extended from 8 Hz to the lesser of 1.05 times the stiff-mounted bushing frequency or 22 Hz. At frequencies beyond the lesser of 1.05 times the stiff-mounted bushing frequency or 22 Hz, the spectral accelerations shall not be less than twice the Performance-Level Spectrum.
- e) Bushings shall be subjected to a time history test in accordance with the requirements of this recommended practice except that the required response spectrum as described in d) shall be used to develop the input motion. The peak moment derived or measured at the insulator/flange interface is the bushing shake-table-rated moment. It is recommended that the bushing shake-table rated moment be determined and reported in the seismic qualification report.
- f) Following the time history shake-table test, a resonant frequency search shall be conducted according to A.1.2.5.

#### **D.5.2.2 Preparation of center-clamped bushing test article**

Center clamped bushings shall have a reduction of pre-stressing force due to thermal expansion, relaxation, or material creep effects anticipated at operating temperatures accounted for in qualification tests. As a minimum, specimens used for seismic qualification tests shall be assembled with core clamping forces adjusted for both ambient and operating temperatures above the temperature at assembly.

Rise due to ambient temperature in excess of temperature at assembly shall be based on an operating ambient of +30 °C. Operating temperature rise may be conservatively based on the thermal basis of rating requirements given in IEEE Std C57.19.00. Thermal analysis or test data applicable to the specific bushing model may be used in lieu of values given in IEEE Std C57.19.00. Temperature differentials for the bushing shell, core tube, flange, and other affected parts shall be determined from tests, analysis, or other rational methods.

A suggested method for adjustment of the core clamping force due to elevated temperatures is given as follows:

- a) Identify and compute the stiffness (force required to cause a unit displacement) of elements that carry loads due to the core clamping force. Typically these components include the porcelain

sections, flange, spacers, spring assemblies, and core tube. The elements having the lowest stiffness will have the greatest effect on loss of core clamping force. Particular caution should be used in developing the stiffnesses of nonlinear elements such as gaskets. The stiffness of spring assemblies should account for their arrangement (e.g., whether individual springs or their sub-assemblies are placed to act in parallel, or stacked in series). In general, the predicted loss of core clamping force will be overestimated by the use of higher stiffnesses of the individual components. Because ignoring the contribution of any element is equivalent to setting its stiffness to infinity, omission of any element from the stiffness calculation will overestimate the predicted loss of core clamping force, and it is acceptable.

- b) Compute the effective stiffness of the bushing (the components described above may be considered to be springs connected in series, because they all carry the same magnitude of force, although some are loaded in tension, whereas others are loaded in compression). Note that overestimating the stiffness of the bushing or its individual components will result in an increased predicted loss of clamping force, which is conservative.

$$K_{\text{eff}} = \frac{1}{\sum(1/K_i)} \quad (\text{D.1})$$

where

$K_i$  is the stiffness of the  $i$ th component that carries forces due to core clamping

$K_{\text{eff}}$  is the effective stiffness of bushing

- c) Determine temperature differentials ( $\Delta T$ ) for each component that carries clamping force, and compute extension due to  $\Delta T$ . Compute net extension ( $\Delta_{\text{exp}}$ ) of the assembly by summing the change in length of the individual components.

$$\Delta_{\text{exp}} = \sum(\Delta T_i C_i L_i) \quad (\text{D.2})$$

where

$\Delta T_i$  is the temperature differential for the  $i$ th component

$C_i$  is the coefficient of thermal expansion for the  $i$ th component

$L_i$  is the length of the  $i$ th component in the direction parallel to the core tube

NOTE—The quantity ( $\Delta T_i C_i L_i$ ) is taken as negative if the component is loaded in compression (e.g., porcelain and flange) and positive if loaded in tension (e.g., core tube).

- d) Determine the adjusted clamping force simulating in-service conditions as follows:

$$P_f = P_o - K_{\text{eff}} \Delta_{\text{exp}} \quad (\text{D.3})$$

where

$P_f$  is the adjusted clamping force simulating an in-service condition

$P_o$  is the initial clamping force applied during assembly

$\Delta_{\text{exp}}$  is the net expansion of assembled bushing components

The adjusted clamping force  $P_f$  should be used during assembly of the seismic qualification test specimen.

### **D.5.2.3 Monitoring requirements for porcelain bushings**

Monitoring requirements shall be in accordance with A.2.4.5 and the following:

- a) Maximum vertical and horizontal accelerations at the top of the bushing, at the end of the bottom of the bushing, at the bushing flange, transverse accelerations at the center of gravity of the portion of the bushing above the porcelain/flange interface, and at the top of the shake table.
- b) Maximum stresses in the flange attachment bolts. The maximum stresses in the bolts may be found by calculations. However, the use of strain bolts is recommended.
- c) Slippage of bushing porcelain relative to the flange.

### **D.5.2.4 Monitoring requirements for composite polymer bushings**

Monitoring requirements shall be in accordance with A.2.4.5 and the following:

- a) Maximum vertical and horizontal accelerations at the top of the bushing, at the end of the bottom of the bushing, at the bushing flange, and at the top of the shake table.
- b) Maximum stresses in the flange attachment bolts. The maximum stresses in the bolts may be found by calculations. However, the use of strain bolts is recommended.

## **D.5.3 Bushing static pull test**

Bushings greater than 34.5 kV class to 138 kV class shall be qualified by static pull test, as specified in A.1.3.

## **D.5.4 Bushings qualified as inherently acceptable**

The qualification procedure shall be in accordance with the requirements of A.1.5.

## **D.5.5 Acceptance of previously qualified bushings**

### **D.5.5.1 General**

Bushings qualified to IEEE Std 693-1997 and later will be deemed in conformance with the current version of this recommended practice if the requirements of 4.5.2, and D.5.5.2 through D.5.5.4 are satisfied.

### **D.5.5.2 Bushings previously qualified as inherently acceptable**

Bushings qualified as inherently acceptable are not subject to conductor load requirements of A.1.6. Such bushings have no seismic qualification identification plate and a supplemental report is not required. These bushings are considered to be qualified to the current recommended practice.

### **D.5.5.3 Bushings previously qualified by static pull test**

Bushings previously qualified by static pull test are considered to have conductor load effects included in the applied static pull force. Such bushings are considered to be qualified to the current recommended

practice. The seismic qualification identification plate may state that these bushings are qualified to the current recommended practice.

#### **D.5.5.4 Bushings previously qualified by time history shake-table test**

Bushings that were required to be qualified by time history shake-table test under previous versions of this recommended practice shall be demonstrated to satisfy the following adequacy of input spectrum and conductor load effects requirements.

- a) *Adequacy of input spectrum.* The previous shake-table test is demonstrated to be equivalent to or more severe than the provisions in the current recommended practice if the spectral acceleration of the old TRS at 0.95 to 1.05 times the stiff-mounted frequency of the bushing exceeds the value of the plateau of the required response spectrum specified in D.5.2.1.d).
- b) *Capability to accommodate conductor load effects.* The bushing is demonstrated to have sufficient capacity to withstand conductor load effects of the current recommended practice by meeting one of the following conditions:
  - 1) If the bushing was over tested, that is, the spectral acceleration of the TRS at the stiff-mounted frequency exceeds the plateau of the required response spectrum, a margin in the equivalent dynamic cantilever load exists over the equivalent dynamic cantilever load at the plateau spectral acceleration. If this margin can accommodate the conductor load effects of either the MAF or ETF, the bushing is qualified.
  - 2) If the bushing was not over tested, or if requirements in 1) above are not satisfied, the bushing can be subjected to a cantilever pull test equal to or greater than the equivalent dynamic cantilever load plus the conductor load effect of either the MAF or ETF.

If a) and b) are satisfied, the seismic qualification identification plate can state that the bushing meets the requirements of the current recommended practice. A supplemental report shall be prepared that clearly explains and documents how these requirements have been satisfied.

The determination of the equivalent dynamic cantilever load shall be based on measurements from strain gauges on the bushing (A.2.4.5).

#### **D.6 Qualification of surge arresters**

Surge arresters of all voltage classes shall be qualified in accordance with the requirements of D.6.

Surge arresters are preferred to be mounted on dedicated supports, and not mounted on transformers in order to improve seismic performance of the surge arrester.

Surge arresters shall be independently qualified in accordance with the requirements of Annex K. If a surge arrester is mounted on a transformer, the transformer manufacturer shall provide bracing or other means of support for the arrester such that the base of the arrester will be sufficiently restrained to prevent movement relative to the transformer body in both horizontal and vertical directions during a seismic event. Bracing need not be applied for surge arresters with DCV < 90 kV. Arrester supports and their bracing shall not be attached to the transformer radiator or bushing turret.

Surge arresters mounted on transformers shall be qualified using an input motion that is amplified by a factor of 2.5 to account for flexibility of the transformer and arrester support.

## D.7 Acceptance criteria

### D.7.1 Transformers

The qualification will be considered acceptable if the requirements given in this annex, the applicable clauses, and the requirements given in D.7.1 are met.

- a) *General criteria.* The stresses in parts, members, tank components, appendages, including connection elements such as welds and bolts, shall meet the requirements of A.2.1.
- b) *Requirements for radiators.* For radiators of transformers and liquid-filled reactors having a high side of 115 kV and above, horizontal and vertical seismic bracing for the radiator shall be connected directly to the body of the transformer. Bending, shear, and axial loads across the gasket connection of the radiators or radiator manifolds to the main body of the transformer shall be limited by assuring that stiffness of the radiator bracing system is much larger than that of the gasket connection. Radiator piping shall not be counted upon to provide structural support of the radiator unless the piping, flanged joints, welds, and other connections are subjected to structural evaluation. As an alternative, the radiator can be supported independent of the transformer and connected to the transformer by flexible connections. Support of the radiator by both the transformer and an independent support to the foundation is not permitted, unless the following conditions are met:
  - 1) The radiator is supported on the same continuous pad as the tank.
  - 2) The horizontal seismic bracing for the radiator is connected directly to the body of the transformer. Vertical dead weight and seismic loads only may be transmitted directly to the foundation from the radiator.
  - 3) Bending, shear, and axial loads across the gasket connection of the radiators or radiator manifolds to the main body of the transformer shall be limited by assuring that stiffness of the radiator bracing system is much larger than that of the gasket connection.

### D.7.2 Bushings

#### D.7.2.1 General

The qualification will be considered acceptable if the requirements given in this annex, the applicable clauses, and the requirements given in D.7.2 are met.

- a) *General criteria.* For components that are shake-table tested, there shall be no evidence of damage, such as broken, shifted, or dislodged insulators; or broken support flanges.
- b) *Time history shake-table test.* Bushings subjected to Performance Level time history test (D.5.2.1) shall satisfy the acceptance criteria of A.2.2.
- c) *Leakage criteria for bushings.* Bushings shall not leak, and porcelain bushings shall not slip at the porcelain-flange interface.
- d) *Static pull test.* Bushings qualified by the static pull test shall meet the requirements of A.2.3. Items a) and b) of D.7.2.1 do not apply to bushings qualified by static pull test.

#### D.7.2.2 Functional requirements for shake-table tested equipment

The equipment shall meet the requirements of A.2.4.2.

After shake-table testing of bushings, they shall be subjected to and pass all routine tests as specified in the latest revision of IEEE Std C57.19.00.

### **D.7.3 Surge arresters**

The qualification will be considered acceptable if the requirements given in K.5, and the applicable clauses are met.

Surge arresters qualified by the time history shake-table test shall be subjected to and pass all standard production electrical and mechanical tests as defined by IEEE Std C62.11 following the time history test.

## **D.8 Design requirements**

### **D.8.1 Design and construction**

The transformer or liquid-filled reactor tank shall be fabricated from steel. The transformer or liquid-filled reactor and supports for appendages shall be designed in accordance with A.4.

### **D.8.2 Anchorage**

Transformers and liquid-filled reactors may be designed to be field welded to embedded plates or beams. The manufacturer shall indicate, on the seismic outline drawing, locations, size, and length of field welds, and if applicable, locations where welding is not allowed.

If the equipment is designed for anchorage with anchor rods, the manufacturer shall provide brackets or fittings of sufficient stiffness and strength to transfer the required forces, including prying effects. The manufacturer shall indicate on the seismic outline drawing, locations, and sizes of the required anchors.

The user shall be responsible for adequacy of anchorage elements embedded in concrete.

## **D.9 Report**

Portions of the transformer or liquid-filled reactor are qualified by analysis, whereas other portions are qualified by testing (bushing and surge arresters).

For portions qualified by analysis, an analysis report shall be prepared and supplied in accordance with A.6.

For components qualified by testing, a test report shall be prepared and supplied in accordance with A.5. The report for center-clamped bushings that are tested shall document the proper pre-load in the core and the pre-load used for qualification testing.

## **D.10 Seismic identification plate**

A seismic identification plate shall be attached to each piece of equipment supplied. The plate shall be as specified in A.7.

## **Annex E**

(normative)

### **Disconnect and grounding switches**

#### **E.1 General**

##### **E.1.1 Voltage classes and other characteristics**

The voltage/voltage class, kV, as used in this annex, is the rated maximum voltage as defined in IEEE Std C37.30.1.

All qualifications of disconnect and grounding switches shall include the operating mechanism and other associated equipment required for a field installation.

##### **E.1.2 High seismic qualification level**

The requirements of E.1, with the exception of E.1.3 and E.1.4, are applicable to all disconnect and grounding switches, for qualification to the high seismic level.

##### **E.1.3 Moderate seismic qualification level**

The requirements of E.1, with the exception of E.1.2 and E.1.4, are applicable to all disconnect and grounding switches for qualification to the moderate seismic level.

##### **E.1.4 Low seismic qualification level**

The requirements of A.1.1.9 are applicable to all disconnect and grounding switches for qualification to the low seismic level.

#### **E.2 Operational requirements**

The disconnect switches, grounding switches, and support structures shall be designed to meet the seismic qualification objectives described in 5.2. The operational state shall remain correct during the seismic event.

#### **E.3 Seismic qualification methods**

Seismic withstand capability shall be demonstrated as follows:

170 kV and above	By performance level time history shake-table testing	E.4.1
123 kV to < 170 kV	By dynamic analysis	E.4.2
38 kV to < 123 kV	By static coefficient analysis	E.4.3
Less than 38 kV	By inherently acceptable	E.4.4

## **E.4 Qualification procedures**

### **E.4.1 Performance level time history shake-table testing**

#### **E.4.1.1 General**

The qualification procedures shall be according to the requirements of A.1.

The tests shall be performed with the disconnect switch open and closed. If a ground switch is included, the tests shall be performed with the disconnect switch open and the ground switch closed, with the disconnect switch open and the ground switch open, and with the disconnect switch closed and the ground switch open.

The switch, structure, operating mechanism, and other associated equipment shall be set up (on the shake table) and adjusted. Correct operating (full opening and full closing) is to be verified before any testing. After the equipment is set up and adjusted, the testing is to proceed as follows:

The equipment and structure shall be tested according to the requirements of A.1.2.

A resonant frequency search shall be performed according to the requirements of A.1.2.5.

#### **E.4.1.2 Monitoring requirements**

Critical locations on the disconnect switch and grounding switch shall be monitored for maximum displacements, maximum accelerations, and maximum loading on insulators. Monitoring requirements shall be in accordance with A.2.4.5 and the following:

- a) Maximum displacement at the top of the insulator.
- b) Maximum accelerations, vertically and horizontally, at the top of the insulator, the end of the blade, and the top of the shake table.
- c) Maximum stresses at the base of the porcelain insulator.
- d) Any electrical equipment, such as a motor operator, shall be energized during testing and monitored to detect relay bounce and the potential for misoperation.

All data shall be time dependent, so values can be compared.

## **E.4.2 Dynamic analysis**

The qualification procedures shall be according to the requirements of A.1.

The analysis shall be performed with the disconnect switch open and closed. If a ground switch is included, the analysis shall be performed with the disconnect switch open and the ground switch closed, with the disconnect switch open and the ground switch open, and with the disconnect switch closed and the ground switch open.

The qualification procedure shall be according to the requirements of A.1.4.7.

#### **E.4.3 Static coefficient analysis**

The qualification procedures shall be according to the requirements of A.1.

The analysis shall be performed with the disconnect switch open and closed. If a ground switch is included, the analysis shall be performed with the disconnect switch open and the ground switch closed, with the disconnect switch open and the ground switch open, and with the disconnect switch closed and the ground switch open.

The qualification procedure shall be according to the requirements of A.1.4.6. A static coefficient of 1.0 may be used.

#### **E.4.4 Inherently acceptable**

The qualification procedure shall be according to the requirements of A.1.5.

### **E.5 Acceptance criteria**

#### **E.5.1 General**

The qualification will be considered acceptable if the requirements given in this annex, the applicable clauses, and the requirements given in E.5.1 and E.5.2 are met. The general requirements are as follows:

- a) The criteria of A.2.1 for design level qualifications and A.2.2 for performance level qualifications.
- b) During the testing, the disconnect switch and grounding switch shall maintain the correct operational state. When tested in the “closed position,” it shall stay closed throughout the duration of testing, and when tested in the “open position,” it shall stay open throughout the duration of testing.
- c) For the performance level time history test, the requirements of A.2.2.
- d) For the dynamic and static coefficient analysis, the requirements of A.2.1.

#### **E.5.2 Functional requirements for shake-table tested equipment**

The equipment shall meet the requirements of A.2.4.2.

The shake-table tested switch shall pass the following tests to ensure its functionality:

- a) *Millivolt drop test.* Circuit resistance shall be tested before and after the shake-table test as specified in IEC 62271-102.
- b) *Continuity.* Electrical continuity shall be monitored across the main disconnect switch or ground circuit when the switch or ground is closed during shake-table testing.
- c) *Mechanical operating test.* The disconnect switch and the ground switch, if applicable, shall be operated (closed to opened, and opened to closed). Correct operation, full opening, and full closing shall be verified. The correct operation and function of all associated equipment shall be verified. Insulator support plates, shafts, and mechanical linkage should be evaluated or monitored for deformation or failure.

The post shake-table millivolt drop test and the mechanical operating test shall be performed while the disconnect switch is on the shake table.

## **E.6 Design requirements**

The equipment and support shall be designed according to A.4.

All linkage connections that operate the main and grounding blades shall have positive mechanical connections such that resistance is not dependent solely on friction.

## **E.7 Report**

### **E.7.1 Report for shake-table test**

The report shall be prepared in accordance with A.5.

The values of critical variables shall be tabulated for the blade open and blade closed switch configurations.

### **E.7.2 Report for dynamic or static coefficient analysis**

The report shall be prepared in accordance with A.6.

## **E.8 Seismic identification plate**

A seismic identification plate shall be attached to each piece of equipment supplied. The plate shall be as specified in A.7.

## **Annex F**

(normative)

### **Instrument transformers**

#### **F.1 General**

##### **F.1.1 Voltage classes and other characteristics**

The requirements of F.1 are applicable to all instrument transformers (IT), including the following:

- a) Capacitor voltage transformers (CVTs)
- b) Coupling capacitor voltage transformers (CCVTs)
- c) Voltage transformers (VTs)
- d) Current transformers (CTs)
- e) Station service voltage transformers (SSVTs)

The voltage/voltage class, kV, as used in this annex, is the nominal system voltage (kV) per IEEE Std C57.13 for CT, VT, and SSVT, and per ANSI C93.1 for CVT and CCVT.

##### **F.1.2 High seismic qualification level**

The requirements of F.1, with the exception of F.1.3 and F.1.4 are applicable to all instrument transformers for qualification to the high seismic level.

##### **F.1.3 Moderate seismic qualification level**

The requirements of F.1, with the exception of F.1.2 and F.1.4 are applicable to all instrument transformers for qualification to the moderate seismic level.

##### **F.1.4 Low seismic qualification level**

The requirements of A.1.1.9 are applicable to all instrument transformers for qualification to the low seismic level.

## **F.2 Operational requirements**

The equipment and supporting structure shall be designed to meet the seismic qualification objectives described in 5.2. In addition, equipment shall maintain the correct operational state during the seismic event.

### **F.3 Seismic qualification methods**

Seismic withstand capability of the equipment shall be demonstrated by:

230 kV and greater, or having a total equipment height equal to or greater than 6.1 m (20 ft)	By performance level time history shake-table testing	F.4.1
69 kV to < 230 kV	By dynamic analysis	F.4.2
35 kV to < 69 kV	By static coefficient analysis	F.4.3
Less than 35 kV	By inherently acceptable	F.4.4

### **F.4 Qualification procedures**

#### **F.4.1 Performance level time history shake-table testing**

##### **F.4.1.1 General**

The qualification procedures shall be according to the requirements of A.1.

The equipment to be shake-table tested shall be tested according to the requirements of A.1.2. Devices that are pressurized should be shake-table tested in a pressurized condition.

A resonant frequency search shall be performed according to the requirements of A.1.2.5.

##### **F.4.1.2 Monitoring requirements**

Critical locations on the equipment shall be monitored for maximum displacement, maximum accelerations, and maximum loading on insulating components. Monitoring requirements shall be in accordance with A.2.4.5 and the following:

- a) Maximum displacement: Top of equipment
- b) Maximum accelerations (vertical and horizontal): Top of equipment

##### **F.4.1.3 Post-shake-table testing**

The equipment shall undergo routine production electrical and mechanical tests after the completion of the shake-table tests. In addition, devices that are pressurized or sealed against atmospheric contamination shall be tested to ensure seal integrity. Oil-filled units shall be checked for leaks.

### **F.4.2 Dynamic analysis**

The qualification procedures shall be according to the requirements of A.1. The equipment shall be dynamically analyzed according to the requirements of A.1.4.7.

#### **F.4.3 Static coefficient analysis**

The qualification procedures shall be according to the requirements of A.1. The equipment shall be analyzed according to the requirements of A.1.4.6. The static coefficient may be taken as 1.0.

#### **F.4.4 Inherently acceptable**

The qualification procedure shall be according to the requirements of A.1.5.

### **F.5 Acceptance criteria**

#### **F.5.1 General**

The qualification will be considered acceptable if the requirements given in this annex, the applicable clauses, and the requirements given in F.5.1 and F.5.2 are met. The general requirements are as follows:

- a) The general criteria of A.2.1 for design level qualifications and A.2.2 for performance level qualifications.
- b) For the performance level time history shake-table test, the requirements of A.2.2.
- c) For dynamic and static coefficient analysis, the acceptance requirements of A.2.1.3.

#### **F.5.2 Functional requirements for shake-table tested equipment**

The equipment shall meet the requirements of A.2.4.2.

Functional requirements for post-shake-table testing include passage of routine production electrical and mechanical tests. In addition, devices that are pressurized and sealed against atmospheric contamination shall be tested to ensure seal integrity. Oil-filled units shall not leak.

### **F.6 Design requirements**

The equipment and support shall be designed according to A.4.

### **F.7 Report**

#### **F.7.1 Report for shake-table test**

The report shall be in accordance with A.5.

#### **F.7.2 Report for dynamic or static coefficient analysis**

The report shall be in accordance with A.6.

### **F.8 Seismic identification plate**

A seismic identification plate shall be attached to each piece of equipment supplied. The plate shall be as specified in A.7.

## Annex G

(normative)

### Air core reactors

#### G.1 General

##### G.1.1 Voltage classes and other characteristics

Liquid-filled reactors shall meet the requirements specified in Annex D.

The voltage/voltage class, kV, as used in this annex, is the nominal system voltage as defined in IEEE Std C57.16 and IEEE Std C57.21.

The seismic qualification procedure for suspended air core reactors shall be according to 6.8 and Annex I.

Devices used to provide air core reactors with the necessary clearance to the foundation for convection cooling, voltage clearance, and magnetic field effects are deemed to be an inherent component of an air core reactor.

##### G.1.2 High seismic qualification level

The requirements of Annex G, with the exception of G.1.3 and C.1.4, are applicable to all air core reactors for qualification to the high seismic level.

##### G.1.3 Moderate seismic qualification level

The requirements of Annex G, with the exception of G.1.2 and G.1.4, are applicable to all air core reactors for qualification to the moderate seismic level.

##### G.1.4 Low seismic qualification level

The requirements of A.1.1.9 are applicable to all air core reactors for qualification to the low seismic level.

#### G.2 Operational requirements

Reactors and their supporting structures shall be designed to meet the seismic qualification objectives described in 5.2.

#### G.3 Seismic qualification methods

Seismic withstand capability shall be demonstrated as follows:

115 kV and above	By dynamic analysis	G.4.1
35 kV to < 115 kV	By static coefficient analysis	G.4.2
Less than 35 kV	By inherently acceptable	G.4.3

## **G.4 Qualification procedures**

### **G.4.1 Dynamic analysis**

The qualification procedures shall be according to the requirements of A.1. The qualification procedure shall be according to the requirements of A.1.4.7.

### **G.4.2 Static coefficient analysis**

The qualification procedures shall be according to the requirements of A.1. The qualification procedure shall be according to the requirements of A.1.4.6. The static coefficient shall be taken as 1.5 for stacked reactors. For single reactors, a static coefficient of 1.0 may be used.

### **G.4.3 Inherently acceptable**

The qualification procedure shall be according to the requirements of A.1.5.

## **G.5 Acceptance criteria**

The qualification will be considered acceptable if the requirements given in this annex, the applicable clauses, and the requirements of A.2.1 are met.

## **G.6 Design requirements**

The equipment and supports shall be designed according to A.4.

## **G.7 Report**

A report shall be prepared in accordance with A.6.

## **G.8 Seismic identification plate**

A seismic identification plate shall be attached to each piece of equipment supplied. The plate shall be as specified in A.7.

## **Annex H**

(normative)

### **Circuit switchers**

#### **H.1 General**

##### **H.1.1 Voltage classes and other characteristics**

The voltage/voltage class, kV, as used in this annex, is the rated maximum voltage, as defined in IEEE Std C37.016 for voltage/voltage classes at 245 kV or less, and IEEE Std C37.100.1 for voltage/voltage classes above 245 kV, the highest root-mean-square voltage, above nominal system voltage, for which the circuit switcher is designed.

##### **H.1.2 High seismic qualification level**

The requirements of Annex H, with the exception of H.1.3 and H.1.4, are applicable to all circuit switchers for qualification to the high seismic level.

##### **H.1.3 Moderate seismic qualification level**

The requirements of Annex H, with the exception of H.1.2 and H.1.4, are applicable to all circuit switchers for qualification to the moderate seismic level.

##### **H.1.4 Low seismic qualification level**

The requirements of A.1.1.9 are applicable to all circuit switchers for qualification to the low seismic level.

### **H.2 Operational requirements**

The circuit switcher consisting of interrupter, optional disconnecting switch, operating mechanism, control cabinet, and supporting structure shall be designed to meet the seismic qualification objectives described in 5.2. The circuit switcher shall not mis-operate during the seismic event.

### **H.3 Seismic qualification methods**

Seismic withstand capability shall be demonstrated as follows:

Greater than 550 kV	By design level time history shake-table testing	H.4.1
170 kV to 550 kV	By performance level time history shake-table testing	H.4.2
123 to < 170 kV	By dynamic analysis	H.4.3
38 kV to < 123 kV	By static coefficient analysis	H.4.4
Less than 38 kV	By inherently acceptable	H.4.5

## H.4 Qualification procedures

### H.4.1 Design level time history shake-table testing

#### H.4.1.1 General

The qualification procedures shall be according to the requirements of A.1.

The tests shall be performed with the circuit switch open and closed. If a ground switch is included, the tests shall be performed with the circuit switch open and the ground switch closed, with the circuit switch open and the ground switch open, and with the circuit switch closed and the ground switch open.

The switch, structure, operating mechanism, and other associated equipment shall be set up (on the shake table) and adjusted. Correct operating (full opening and full closing) is to be verified before any testing. After the equipment is set up and adjusted, the testing is to proceed as follows:

The qualification procedure shall be in five stages:

- a) Stage 1: Resonant frequency search. A resonant frequency search shall be conducted according to the requirements of A.1.2.5.
- b) Stage 2: Time history shake-table test. The circuit switcher and structure shall be tested according to the requirements of A.1.2. The circuit switcher shall be tested in both closed and opened positions. Pressurization is not required for this stage.
- c) Stage 3: Time history shake-table operational test. The circuit switcher shall be tested again according to the requirements of A.1.2. But this time, the circuit switcher shall be operated open from a closed position during the strong motion period. Circuit switcher operation should be initiated at approximately the time at which the normalized Arias Intensity of 50% of maximum is achieved for one of the horizontal components of motion. During this test, gas circuit switchers shall be filled with gas at rated operating pressure. Gas for pressurizing the breaker need not be SF<sub>6</sub>.

NOTE—Test with protective barriers to prevent injury or damage from failure of pressurized components.

- d) Stage 4: Resonant frequency search. A resonant frequency search shall be conducted according to the requirements of A.1.2.5.

#### H.4.1.2 Monitoring requirements

Critical locations on the circuit switcher, grounding switch, and supporting structure shall be monitored to determine the maximum displacements, maximum accelerations, and maximum loading or stresses on equipment/support elements. Monitoring requirements shall be in accordance with A.2.4.5 and the following:

- a) Horizontal displacements of circuit switcher terminals.
- b) Accelerations, vertical and horizontal, of the top ends of vertical insulating components.
- c) Stresses at the base of the supporting structures.

The main power contact circuits and auxiliary contact stack shall be monitored to verify that the circuit switcher does not misoperate during the seismic event.

Timing and resistance measurements shall be taken before the testing begins and after the shake-table tests are completed.

The circuit switcher shall be monitored for leaks before and after each time history test. Pressure readings shall be made after each pressurized time history test for comparison with pretest readings to detect leaks.

#### **H.4.1.3 Production tests following shake-table testing**

The circuit switcher shall undergo standard production tests after the completion of the shake-table tests.

### **H.4.2 Performance level time history shake-table testing**

#### **H.4.2.1 General**

The qualification procedures shall be according to the requirements of A.1.

The tests shall be performed with the circuit switch open and closed. If a ground switch is included, the tests shall be performed with the circuit switch open and the ground switch closed, with the circuit switch open and the ground switch open, and with the circuit switch closed and the ground switch open.

The switch, structure, operating mechanism, and other associated equipment shall be set up (on the shake table) and adjusted. Correct operating (full opening and full closing) is to be verified before any testing. After the equipment is set up and adjusted, the testing is to proceed as follows:

The qualification procedure shall be in three stages:

- a) Stage 1: Resonant frequency search. A resonant frequency search shall be conducted according to the requirements of A.1.2.5.
- b) Stage 2: Time history shake-table test. The circuit switcher and structure shall be tested according to the requirements of A.1.2. The circuit switcher shall be tested in both closed and opened positions. Pressurization is not required for this stage.
- c) Stage 3: Time history shake-table operational test. The circuit switcher shall be tested again according to the requirements of A.1.2. But this time, the circuit switcher shall be operated open from a closed position during the strong motion period. Circuit switcher operation should be initiated at approximately the time at which the normalized Arias Intensity of 50% of maximum is achieved for one of the horizontal components of motion. During this test, gas circuit switchers shall be filled with gas at rated operating pressure. Gas for pressurizing the breaker need not be SF<sub>6</sub>.

NOTE—Test with protective barriers to prevent injury or damage from failure of pressurized components.

#### **H.4.2.2 Monitoring requirements**

Monitoring requirements for performance level testing are the same as those required for design level testing as detailed in H.4.1.2 with the following exception: monitoring stresses on the base of the supporting structure legs can be excluded from the performance level test.

#### **H.4.2.3 Production tests following shake-table testing**

The circuit switcher (all tested switches) shall undergo standard production tests after the completion of the shake-table tests.

#### **H.4.3 Dynamic analysis**

The qualification procedures shall be according to the requirements of A.1.

The analysis shall be performed with the circuit switch open and closed. If a ground switch is included, the analysis shall be performed with the circuit switch open and the ground switch closed, with the circuit switch open and the ground switch open, and with the circuit switch closed and the ground switch open.

The dynamic analysis procedure shall be according to the general requirements of A.1.4 and the specific requirements of A.1.4.7.

#### **H.4.4 Static coefficient analysis**

The qualification procedures shall be according to the requirements of A.1.

The analysis shall be performed with the circuit switch open and closed. If a ground switch is included, the analysis shall be performed with the circuit switch open and the ground switch closed, with the circuit switch open and the ground switch open, and with the circuit switch closed and the ground switch open.

The qualification procedure shall be according to the general requirements of A.1.4 and the specific requirements of A.1.4.6. The static coefficient may be taken as 1.0.

#### **H.4.5 Inherently acceptable**

The qualification procedure shall be according to the requirements of A.1.5.

### **H.5 Acceptance criteria**

#### **H.5.1 General**

The qualification will be considered acceptable if the requirements given in this annex, the applicable clauses, and the criteria given in H.5.1 and H.5.2 are met. The general requirements are as follows:

- a) The general criteria of A.2.1 for design level qualifications and A.2.2 for performance level qualifications.
- b) During the testing, the circuit switch and grounding switch shall maintain the correct operational state. When tested in the “closed position,” it shall stay closed throughout the duration of testing, and when tested in the “open position,” it shall stay open throughout the duration of testing.
- c) For the design level time history shake-table test, the requirements of A.2.1.4.
- d) For the performance level time history shake-table test, the requirements of A.2.2.
- e) For the dynamic and static coefficient analysis, the requirements of A.2.1.3.

## **H.5.2 Functional requirements for shake-table tested equipment**

The equipment shall meet the requirements of A.2.4.2.

The circuit switcher shall maintain the correct operational state during the time history test. The circuit switcher shall properly open during the time history operational shake-table test. Control logic components, trip and close coils, and mechanical systems shall operate properly. Pressurized modules shall not leak. Resistance readings between the terminals shall be within manufacturing limits for a new device after shake-table testing. Disconnect blades shall operate without binding or requiring physical adjustment.

The circuit switcher (all tested switches) shall pass all standard production tests after completion of the shake-table tests.

## **H.6 Design requirements**

The circuit switcher and support shall be designed according to A.4.

## **H.7 Report**

### **H.7.1 Report for shake-table test**

The report shall be in accordance with A.5.

Pretest circuit switcher open and close timing characteristics and resistance readings shall be included. A list of circuits, which were monitored during the tests, shall also be included.

### **H.7.2 Report for dynamic or static coefficient analysis**

The report shall be in accordance with A.6.

## **H.8 Seismic identification plate**

A seismic identification plate shall be attached to each piece of equipment supplied. The plate shall be as specified in A.7.

## **Annex I**

(normative)

### **Suspended equipment**

#### **I.1 General**

##### **I.1.1 Characteristics**

Equipment shall only be considered suspended if:

- a) It is provided with suspension points and restraint points.
- b) There are provisions to control the movement of the equipment horizontally and vertically.
- c) The system complies with 6.8.

Thyristor valves are often suspended. However, thyristor valves are out of the scope of this annex. Seismic qualification levels are given in I.1.2 through I.1.4.

##### **I.1.2 High seismic qualification level**

The requirements of Annex I, with the exception of I.1.3 and I.1.4, are applicable to all suspended equipment for qualification to the high seismic level.

##### **I.1.3 Moderate seismic qualification level**

The requirements of Annex I, with the exception of I.1.2 and I.1.4, are applicable to all suspended equipment for qualification to the moderate seismic level.

##### **I.1.4 Low seismic qualification level**

The requirements of A.1.1.9 are applicable to suspended equipment for qualification to the low seismic level.

#### **I.1.5 Load carrying components**

##### **I.1.5.1 Suspension point(s)**

Suspension point(s) are attachment point(s) from which the equipment is suspended. There may be more than one suspension point. The equipment manufacturer shall supply suspension point(s). The user will supply suspension systems beyond the suspension point(s).

### **I.1.5.2 Restraint point(s)**

Restraint point(s) are attachment point(s) from which lateral restraint is provided. An external component, such as a cable, will limit the deflection of the equipment under the action of lateral loads, such as winds or earthquakes, and will be attached to the restraint point(s). There shall be at least one restraint point. A restraint point may be coincident with a suspension point. The manufacturer shall supply restraint point(s). The user will supply restraint systems beyond the restraint point(s).

### **I.1.5.3 Load-carrying structure**

The load-carrying structure is the equipment's component or components through which the suspension points and restraint points are transmitted. The load-carrying structure may include the components, which provide the function of the equipment, such as the insulator units or electrical component housings, or may be structural components, such as rods or other members, whose only function is to transmit these loads.

## **I.2 Operational requirements**

The equipment, including the suspension point(s), load-carrying structure, and restraint point(s), shall be designed so that there will be neither damage nor loss of function during and after a seismic event. In addition, equipment shall maintain the correct operational status during the seismic event.

## **I.3 Seismic qualification methods**

The seismic withstand capability shall be demonstrated by static analysis in accordance with the methods described in I.4.

## **I.4 Qualification procedures—static analysis**

### **I.4.1 Configuration requirements**

The equipment will be installed in a suspended configuration. The entire weight will be carried from one or more suspension points of the equipment. The equipment will be restrained laterally at one or more restraint points on the equipment.

Suspension point(s), restraint point(s), and the load-carrying structure shall be capable of supporting the loads described in I.4.2 through I.4.3. All loads given herein are design level loads.

### **I.4.2 Suspension point(s)**

Each suspension point shall be capable of supporting and transmitting the following combined vertical and horizontal loads from where the suspension point attaches to the load-carrying structure to where the suspension point attaches to the cable or other external supporting component:

- a) Vertical positive (upward) load equal to the following values times the weight of the equipment appropriately distributed to the suspension points, if more than one point, plus any positive vertical normal operating load carried by the suspension point.
  - 1) 5 for the high seismic qualification level
  - 2) 3.5 for the moderate seismic qualification level

- b) Horizontal load equal to the following values times the weight of the equipment appropriately distributed to the suspension points, if more than one point, applied in both principal horizontal axes, plus any horizontal normal operating load carried by the suspension point.
  - 1) 0.5 for the high seismic qualification level
  - 2) 0.25 for the moderate seismic qualification level

#### **I.4.3 Restraint point(s)**

Restraint point(s) shall be positioned such that they can restrain horizontal movement. Restraint point(s) may induce additional vertical and horizontal load. Restraint point(s) shall not induce torsion or other unbalanced loads [i.e., the restraint point(s) shall be “balanced” with the suspension point(s)]. Each restraint point shall be capable of resisting and transmitting the following combined vertical and horizontal loads from where the restraint point attaches to the load-carrying structure to where the restraint point attaches to the cable or another external restraining component:

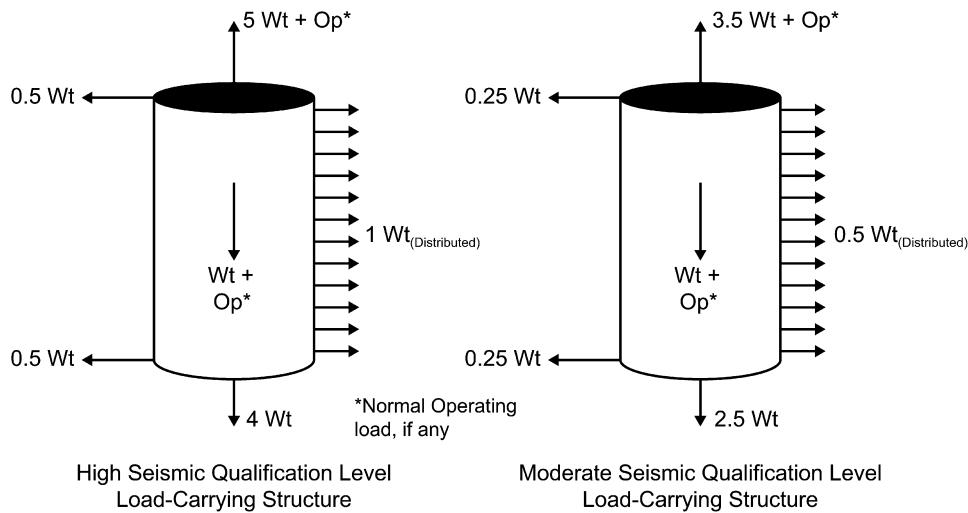
- a) Vertical negative (downward) load equal to the following values times the weight of the equipment distributed according to the laws of static's to the restraint point(s), plus any vertical normal operating load carried by the restraint point(s). (The vertical load includes dynamic loads and preloads.)
  - 1) 4 for the high seismic qualification level
  - 2) 2.5 for the moderate seismic qualification level
- b) Horizontal load equal to the following values times the weight of the equipment applied in both principal horizontal axes and distributed according to the laws of statics to the restraint point(s), plus any horizontal normal operating load carried by the restraint point(s).
  - 1) 0.5 for the high seismic qualification level
  - 2) 0.25 for the moderate qualification level

The manufacturer shall notify the user of any restrictions in preload.

#### **I.4.4 Load-carrying structure**

The load-carrying structure, which can be an equipment structure or an independent structure, shall be capable of transmitting the combined vertical and horizontal loads from the suspension point(s) to the restraint point(s).

For the analysis, the load-carrying structure shall be treated as a free-body with the boundary suspension point(s) and the boundary restraint point(s) assumed to be supported and the loads required by I.4.2 and I.4.3 applied horizontally and vertically through the load-carrying structure, as illustrated in Figure I.1.



**Figure I.1—Illustration of loads on suspended equipment**

The load-carrying structure shall be analyzed using the following values times the equipment's weight distributed according to its actual weight distribution, applied simultaneously in both principal horizontal axes, simultaneously with the vertical loads required in I.4.2 and I.4.3.

- 1.0 for the high seismic qualification level
- 0.5 for the moderate seismic qualification level

## I.5 Acceptance criteria

The qualification will be considered acceptable if the requirements given in this annex, the applicable clauses, and the acceptance criteria of A.2.1 are met.

## I.6 Design requirements

The connections shall be designed according to A.2.1 and A.4.

## I.7 Report

A report shall be prepared and supplied in accordance with A.6, except that the seismic outline drawing requirements given below shall be used in lieu of the requirements of A.6.4.

- The supplier shall supply one 289 mm x 432 mm (11 in x 17 in), A3, 216 mm x 280 mm (8.5 in x 11 in), or A4 seismic outline drawing of the equipment.
- An outline drawing of the equipment, including overall dimensions, weights, and location of the center of gravity of the equipment.
- Connection details showing bolt and weld sizes, if applicable, and their corresponding locations.
- Suspension and restraint point locations.
- The method used to qualify the equipment, including the acceleration levels used (e.g., 0.5 g).

## I.8 Seismic identification plate

A seismic identification plate shall be attached to each piece of equipment supplied. The plate shall be as specified in A.7.

## **Annex J**

(normative)

### **Station batteries and battery racks**

#### **J.1 General**

##### **J.1.1 Characteristics**

Battery racks, as used in this annex, refers to the load-carrying structure, which may consist of stacked, steel-encased cell modules, or open-frame multi-tier or multi-step racks.

##### **J.1.2 High seismic qualification level**

The requirements of Annex J, with exception of J.1.3 and J.1.4, are applicable to all station batteries and battery racks for qualification to the high seismic level.

##### **J.1.3 Moderate seismic qualification level**

The requirements of Annex J, with exception of J.1.2 and J.1.4, are applicable to all station batteries and battery racks for qualification to the moderate seismic level.

##### **J.1.4 Low seismic qualification level**

The requirements of A.1.1.9 are applicable to all station batteries and battery racks for qualification to the low seismic level.

#### **J.2 Operational requirements**

The station battery rack shall be designed so that there will be neither battery damage nor loss of battery function during and after the seismic event.

#### **J.3 Seismic qualification methods**

##### **J.3.1 Station batteries**

Station batteries are qualified if they meet the requirements given in J.6.2.

##### **J.3.2 Other batteries**

Non-station batteries are qualified if they meet the requirements given in J.6.3.

### **J.3.3 Battery racks**

The seismic withstand capability of battery racks shall be demonstrated as follows:

Non-rigid racks of three or more stacks	By performance level time history shake-table testing	J.4.1
Non-rigid racks of two stacks	By dynamic analysis	J.4.2
Rigid racks and all racks of one stack	By static analysis	J.4.3

## **J.4 Qualification procedure**

### **J.4.1 Performance level time history shake table test**

#### **J.4.1.1 General**

The qualification shall be conducted according to the requirements of A.1. Battery racks shall be qualified in accordance with the requirements of A.1.2. The rack that is tested shall have a full complement of batteries, interconnected in their *in situ* configuration. Cells shall be mounted in the battery rack or a representative section of the battery rack, if approved by the user.

A resonant frequency search shall be performed according to the requirements of A.1.2.5.

#### **J.4.1.2 Monitoring requirements**

During time history shake-table testing, critical locations on the battery rack assembly shall be monitored for maximum displacements and maximum accelerations. Monitoring requirements shall be in accordance with the following:

- a) Maximum displacements: Top of battery rack assembly and connection points.
- b) Maximum accelerations: Vertical and horizontal at the top of the rack.

### **J.4.2 Dynamic analysis**

Battery racks shall be qualified in accordance with A.1 and A.1.4.7.

### **J.4.3 Static analysis**

Battery racks shall be qualified according to the requirements of A.1 and A.1.4.5.

## **J.5 Acceptance criteria**

### **J.5.1 General**

The qualification will be considered acceptable if the requirements given in this annex, the applicable clauses, and the criteria given in J.5.1 and J.5.2 are met. The general criteria of A.2 or as applicable to the qualification method shall be met.

## **J.5.2 Functional requirements for shake-table tested equipment**

The equipment shall meet the requirements of A.2.4.2. The battery rack shall effectively restrain the battery cells without impacting rack restraints.

## **J.6 Design requirements**

### **J.6.1 General**

Batteries are considered inherently acceptable; however, they must be properly installed.

### **J.6.2 Station batteries**

When station batteries are mounted in a seismically qualified battery rack, the battery cells, or multi-cell modules, will be seismically qualified when the following criteria are met:

- a) All connections between cells and multi-cell modules shall be of the bolted type.
- b) Batteries shall employ spacers to maintain the correct separation between cells or multi-cell units.
- c) Horizontal restraints on the battery rack shall be designed to prevent the cells from impacting the restraints. The restraints shall be positioned to prevent the cells from falling or toppling from the rack.
- d) Terminal cable connectors and cable connections between different levels or rows of cells shall have adequate slack to accommodate movement of the rack and conductor anchor points.
- e) Long cable runs, for example, from the battery's main terminal to the load or between racks on the opposite side of the battery room, shall be supported close to the battery connection to reduce stress on the battery terminal.

### **J.6.3 Other batteries**

When non-station batteries are mounted in a seismically qualified battery rack, the battery cells, or multi-cell modules, will be seismically qualified when the batteries are restrained to their support structure and are prevented from impacting their restraints. Battery terminal connections similar to those used on automobile batteries are acceptable.

### **J.6.4 Battery racks**

The battery rack shall be mounted to a structural floor with sufficient strength to resist lateral and overturning loads according to A.4. If the mounting surface is not at grade, the dynamic amplification of the battery rack support must be used to modify the RRS. The structure's materials must withstand dead and seismic stress imposed by the mass of the battery.

## **J.7 Report**

A report shall be prepared and supplied in accordance with A.5 or A.6 as applicable.

## **J.8 Frequency or damping modifying devices or attachment**

The requirements of A.4.7 shall be met.

## **J.9 Seismic identification plate**

A seismic identification plate shall be supplied with each battery rack. The plate shall be as specified in A.7.

## **Annex K**

(normative)

### **Surge arresters**

#### **K.1 General**

##### **K.1.1 Voltage classes and other characteristics**

The voltage/voltage class, kV, as used in this annex, is the duty cycle voltage rating as defined in IEEE Std C62.11. Duty cycle voltage rating (DCV) is defined as the designated maximum permissible root-mean-square (rms) value of power-frequency voltage between its line and ground terminals at which it is designed to perform its duty cycle.

##### **K.1.2 High seismic qualification level**

The requirements of Annex K, with the exception of K.1.3 and K.1.4, are applicable to all surge arresters for qualification to the high seismic level.

##### **K.1.3 Moderate seismic qualification level**

The requirements of Annex K, with the exception of K.1.2 and K.1.4, are applicable to all surge arresters for qualification to the moderate seismic level.

##### **K.1.4 Low seismic qualification level**

The requirements of A.1.1.9 are applicable to all surge arresters for qualification to the low seismic level.

#### **K.2 Operational requirements**

The equipment and supporting structure shall be designed to meet the seismic qualification objectives described in 5.2. Additionally, equipment shall maintain correct operational states during the seismic event.

#### **K.3 Seismic qualification methods**

The seismic withstand capability, where the kV rating is a measure of the duty cycle voltage rating, shall be demonstrated by:

90 kV DCV and above	By performance level time history shake-table testing	K.4.1
54 kV DCV to < 90 kV DCV	By dynamic analysis	K.4.2
35 kV DCV to < 54 kV DCV	By static coefficient analysis	K.4.3
Less than 35 kV DCV	By inherently acceptable	K.4.4

## K.4 Qualification procedures

### K.4.1 Performance level time history shake-table testing

#### K.4.1.1 General

The qualification procedures shall be in accordance with the requirements of A.1. Surge arresters to be shake-table tested shall be tested according to the requirements of A.1.2.

A resonant frequency search shall be performed according to the requirements of A.1.2.5.

Requirements particular to surge arresters regarding pre- and post-seismic testing and monitoring during the seismic testing are given in K.4.1.1 through K.4.1.3.

#### K.4.1.2 Monitoring requirements for porcelain arresters

Critical locations on the surge arrester shall be monitored for maximum displacements, maximum accelerations, and maximum loading. Monitoring requirements shall be in accordance with A.2.4.5 and the following:

- a) Maximum relative displacement at the top of the arrester to the base shall be measured during the test.
- b) Maximum vertical and horizontal accelerations at the top of the arrester, at the bottom of the arrester, at the unit center of gravity, and at the top of the shake table.
- c) Strain shall be measured at the base of the supporting structure (if applicable). The use of strain bolts is not required but recommended.

#### K.4.1.3 Monitoring requirements for polymer arresters

Critical locations on the surge arrester shall be monitored for maximum displacements, maximum accelerations, and maximum loading. Monitoring requirements shall be in accordance with A.2.4.5 and the following:

- a) Maximum relative displacement at the top of the arrester to the base shall be measured during the test.
- b) Maximum vertical and horizontal accelerations at the top of the arrester, at the bottom of the arrester, at the unit center of gravity, and at the top of the shake table.
- c) Strain shall be measured at the base of the supporting structure (if applicable). The use of strain bolts is not required but recommended.

## K.4.2 Dynamic analysis

The qualification procedures shall be in accordance with the requirements of A.1. The surge arrester to be dynamically analyzed shall be analyzed according to the requirements of A.1.4.7.

#### **K.4.3 Static coefficient analysis**

The qualification procedures shall be in accordance with the requirements of A.1. The qualification procedure shall be according to the requirements of A.1.4.6. The static coefficient may be taken as 1.0.

#### **K.4.4 Inherently acceptable**

The qualification procedure shall be according to the requirements of A.1.5.

#### **K.4.5 Qualification for transformer mounting**

Surge arresters shall be independently qualified based on the requirements within Annex K. Surge arresters mounted on transformers shall be qualified using a ground spectrum amplification factor of 2.5. When surge arresters are mounted on transformers, the transformer manufacturer shall provide bracing or other means of support for the arrester such that the base of the arrester will be sufficiently restrained to prevent movement relative to the transformer body in both horizontal and vertical directions during a seismic event. Bracing need only be applied for surge arresters 90 kV DCV and above. Surge arrester supports shall not be attached to the transformer radiator or bushing turret.

#### **K.4.6 Shed-seal test for polymer arresters**

The following test procedure shall apply to polymer surge arresters in lieu of the requirements of X.9.5.

Polymer housed surge arresters require an additional shed-seal test be performed as follows. This is a test of the ability of the sheath-shed seal to the metal-end fitting to prevent the entrance of moisture into the core and internal components. This test need not be performed on the seismically tested unit. Only one test needs to be performed for each seal design method. The test applies to all arresters using the sealing method and need not be repeated for different types when the same sealing method is used.

A tension line shall be connected to one end of the polymer arrester with the other end of the arrester anchored rigidly to produce a moment connection, as shown in Figure K.1. The tension line shall be pulled to produce the specified long-term load (SLL) in the arrester. The tension shall be held for at least two minutes, and then the interface of the metal end fittings and the shed at the moment end of the arrester shall be heavily coated or flooded with dye penetrant. The load shall be removed and the metal end fittings shall be cut longitudinally and transversely at the highest stressed areas to determine whether any dye penetrant penetrated beyond the external surface.

This test will be considered acceptable if both of the following are satisfied:

- No dye has penetrated to within 2 mm of the outer surface of the fiberglass core via any leak path other than through the thickness of the sheath.
- No dye has penetrated through the thickness of the sheath to within 2 mm of the outer surface of the fiberglass core. For sheath thicknesses of 4 mm or less, dye shall not penetrate more than 50% of the sheath thickness.

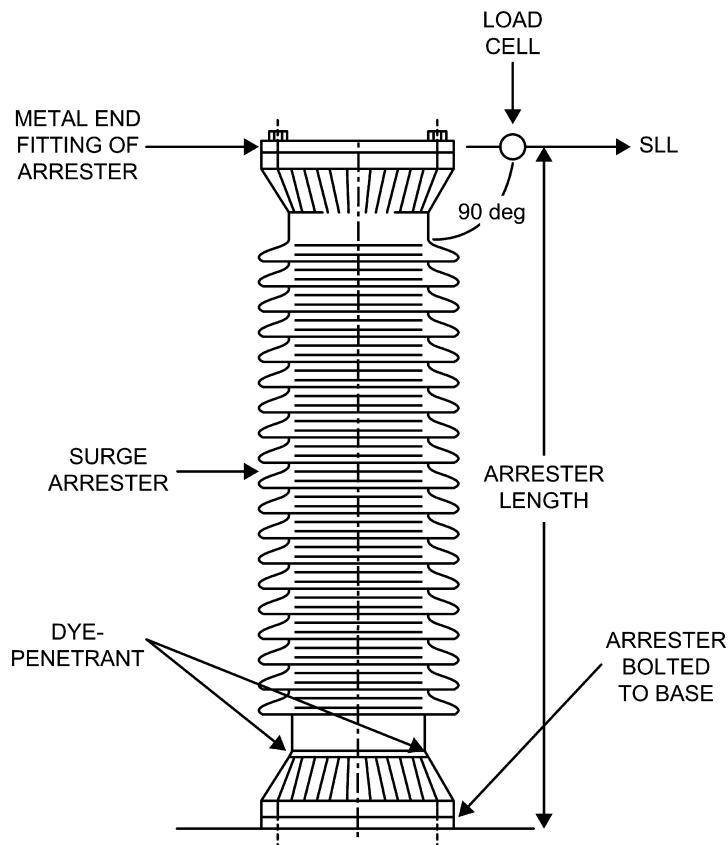


Figure K.1—Polymer arrester shed seal test setup

## K.5 Acceptance criteria

### K.5.1 General

The qualification will be considered acceptable if the requirements given in this annex, the applicable clauses and the requirements given in K.5.1 through K.5.4 are met. The general requirements are as follows:

- a) The general criteria of A.2.1 and A.2.2
- b) For the shake-table test, the time history test requirements of A.2.2
- c) For the dynamic analysis, the requirements of A.2.1.3
- d) For static coefficient analysis, the requirements of A.2.1.3

### K.5.2 Acceptance criteria for shake-table tested arresters

#### K.5.2.1 Acceptance criteria for shake-table tested porcelain arresters

Porcelain arresters shall meet the following criteria:

- a) Meet the applicable requirements of A.2.2.

- b) The ultimate cantilever load experienced during shake-table testing shall not exceed the ultimate cantilever capability as defined in X.8.5.2.

#### **K.5.2.2 Acceptance criteria for shake-table tested polymer arresters**

Polymer arresters shall meet the following criteria:

- a) Meet the applicable requirements of A.2.2.
- b) Meet the applicable requirements of either of the following:
  - 1) The ultimate cantilever load experienced during shake-table testing shall not exceed the SML as defined in X.9.2 for hollow-core polymer arresters,
  - 2) The ultimate cantilever load experienced during shake-table testing shall not exceed 100% of a manufacturer-defined SML for solid-core polymer arresters.

#### **K.5.3 Functional requirements for shake-table tested equipment**

The equipment shall meet the requirements of A.2.4.2.

For shake-table tested surge arresters, the equipment shall maintain the correct operational state during the seismic event. Confirmation of this requirement shall entail passage of standard production electrical and mechanical tests as defined by IEEE Std C62.11 after completion of any shake-table tests.

#### **K.5.4 Polymer arrester shed seal test**

All polymer arresters must meet the requirements of the Polymer Arrester Shed Seal Test (K.4.6). This test need not be performed on the seismically tested unit.

### **K.6 Design requirements**

The equipment and supports shall be designed according to A.4.

### **K.7 Report**

A report shall be prepared and supplied in accordance with A.5 or A.6 as applicable.

The qualification report for shake-table-tested equipment shall clearly state whether the test was performed with, or without, a support structure and any amplification factors applied to the input motion.

A signed copy of the shed seal test shall be included with the seismic report. The following information shall be provided: the equipment type tested, images of the cut pieces (including evidence of the dye), and a description of how the cut pieces fit into the end fitting.

### **K.8 Seismic identification plate**

A seismic identification plate shall be attached to each piece of equipment supplied. The plate shall be as specified in A.7.

## Annex L

(normative)

### **Substation electronic devices, distribution panels and switchboards, and solid-state rectifiers**

#### **L.1 General**

##### **L.1.1 Scope of applicability**

These requirements are applicable to the following substation electronic devices (SEDs):

- a) Remote terminal units (RTUs)
- b) Digital fault recorders (DFRs)
- c) Sequence of events recorders (SERs)
- d) Intelligent electronic devices (IEDs)

These requirements are also applicable to distribution panels and switchboards for ac and dc power and solid-state rectifiers for battery charging.

Seismic qualification levels are given in L.1.2 through L.1.4.

##### **L.1.2 High seismic qualification level**

The requirements of L.1, with the exception of L.1.3 and L.1.4, are applicable to all equipment listed in L.1 for qualification to the high seismic level.

##### **L.1.3 Moderate seismic qualification level**

The requirements of L.1, with the exception of L.1.2 and L.1.4, are applicable to all equipment listed in L.1 in moderate seismic qualification level areas.

##### **L.1.4 Low seismic qualification level**

The requirements of A.1.1.9 are applicable to all equipment listed in L.1 for qualification to the low seismic level.

#### **L.2 Operational requirements**

The equipment and supporting structure shall be designed to meet the seismic qualification objectives described in 5.2.

### **L.3 Seismic qualification methods**

The seismic withstand capability shall be demonstrated by performance level time history shake-table testing for the RTUs and IEDs. The seismic withstand capability of all other equipment listed in L.1 shall be demonstrated as follows:

- a) The internal components may be qualified by experience-based qualification (see Q.9).
- b) The panels or cubicles and their hold down fittings shall be qualified by static analysis.

### **L.4 Qualification procedures**

#### **L.4.1 RTU and IED qualification procedures**

The qualification procedures shall be according to the requirements of A.1. The RTUs and IEDs shall be tested according to the requirements of A.1.2.

A resonant frequency search shall be performed according to the requirements of A.1.2.5.

#### **L.4.2 Equipment listed in L.1, except RTUs and IEDs, qualification procedures**

The qualification procedures shall be according to the requirements of A.1. All equipment listed in L.1, except RTUs and IEDs, shall be analyzed according to the requirements of A.1.4.6. The static coefficient shall be taken as 1.0.

### **L.5 Acceptance criteria**

#### **L.5.1 General**

The qualification will be considered acceptable if the requirements given in this annex, the applicable clauses, and the requirements in L.5.1 through L.5.2 are met. The general requirements are as follows:

- a) The general criteria of A.2.1 for design level qualifications and A.2.2 for performance level qualifications.
- b) For the RTUs and IEDs, the performance level testing requirement of A.2.2.
- c) For all equipment listed in L.1, except RTUs and IEDs, the requirements of A.2.1.

#### **L.5.2 Functional requirements for shake-table tested equipment**

The equipment shall meet the requirements of A.2.4.2.

The following shall be carried out in sequence:

- a) Before the shake-table tests, the RTU or IED shall be tested by simulating all of its functions. Appropriate signals shall be injected to inputs, and all outputs shall be monitored for correct operation. Also, noise testing shall be conducted with the latest revisions to the applicable standard as follows:
  - 1) Surge withstands capability and fast transient tests in accordance with IEEE Std C37.90.1.
  - 2) Radiated radio frequency wave test in accordance with IEEE Std C37.90.2.

- 3) Radiated transient voltage tests in accordance with IEEE Std 518.
- b) Only monitoring of critical circuits for relay bounce shall be carried out during the shake-table tests. Any failures shall be noted.
- c) After the shake-table tests, the functional and noise tests in item a) shall be repeated. Also, all components shall be inspected to ensure that no components have shaken loose or broken off, and that they are securely in their sockets. The integrity of the wiring shall also be checked. Any failures shall be noted.

Inspection per item c) may also be carried out before the testing per item a), but only to ensure the correct state of components within the device. However, no attempt shall be made to press down components within their sockets.

## **L.6 Design requirements**

All equipment listed in L.1 shall be designed according to A.4.

## **L.7 Report**

The following reports shall be prepared and supplied:

- a) For RTU and IED, a report in accordance with A.5.
- b) For all equipment listed in L.1, except RTUs and IEDs, a report in accordance with A.6.

## **L.8 Seismic identification plate**

A seismic identification plate shall be attached to each piece of equipment supplied. The plate shall be as specified in A.7.

## **Annex M**

(normative)

### **Metalclad switchgear**

#### **M.1 General**

##### **M.1.1 Voltage classes and other characteristics**

The voltage/voltage class, kV, as used in this annex, is the rated maximum voltage, as defined in IEEE Std C37.20.2.

##### **M.1.2 High seismic qualification level**

The requirements of Annex M, with the exception of M.1.3 and M.1.4, are applicable to all voltage levels of indoor and outdoor metalclad switchgear for qualification to the high seismic level.

##### **M.1.3 Moderate seismic qualification level**

The requirements of Annex M, with the exception of M.1.2 and M.1.4, are applicable to all voltage levels of indoor and outdoor metalclad switchgear for qualification to the moderate seismic level.

##### **M.1.4 Low seismic qualification level**

The requirements of A.1.1.9 are applicable to all metalclad switchgear for qualification to the low seismic level.

#### **M.2 Operational requirements**

The completely assembled and installed equipment shall be designed so that there will be neither damage nor loss of function during and after a seismic event. In addition, metalclad switchgear and equipment installed in the switchgear shall maintain the correct operational state during a seismic event.

#### **M.3 Seismic qualification methods**

Metalclad switchgear installations design shall be demonstrated by the following:

38 kV and above	By dynamic analysis	M.4.1
Less than 38 kV	By inherently acceptable	M.4.2

## **M.4 Qualification procedures**

### **M.4.1 Dynamic response spectrum analysis**

The qualification procedures shall be in accordance with the requirements of A.1.

Dynamic response spectrum analysis shall be according to the requirements of A.1.4.7.

### **M.4.2 Inherently acceptable**

The qualification procedure shall be according to the requirements of A.1.5.

## **M.5 Acceptance criteria**

The qualification will be considered acceptable if the requirements given in this annex, the applicable clauses, and the requirements given in M.5.

The general criteria requirements of A.2.1 for design level qualifications are applicable.

## **M.6 Design requirements**

The complete components installation shall be designed in accordance with A.4. Other subclauses of this recommended practice may apply to individual devices or equipment of this installation.

## **M.7 Report**

An analysis report shall be prepared and supplied in accordance with A.6, including subclauses pertaining to data and the seismic outline drawing.

## **M.8 Seismic identification plate**

A seismic identification plate shall be attached to each piece of equipment supplied. The plate shall be as specified in A.7.

## **Annex N**

(normative)

### **Cable terminators (potheads)**

#### **N.1 General**

##### **N.1.1 Voltage classes**

The voltage/voltage class, kV, as used in this annex, is the insulation class, as defined in IEEE Std 48.

##### **N.1.2 High seismic qualification level**

The requirements of Annex N, with the exception of N.1.3 and N.1.4, are applicable to all cable terminators for qualification to the high seismic level.

##### **N.1.3 Moderate seismic qualification level**

The requirements of Annex N, with the exception of N.1.2 and N.1.4, are applicable to all cable terminators for qualification to the moderate seismic level.

##### **N.1.4 Low seismic qualification level**

The requirements of A.1.1.9 are applicable to all cable terminators for qualification to the low seismic level.

#### **N.2 Operational requirements**

The cable terminators and supporting structures shall be designed to meet the seismic qualification objectives described in 5.2. Cable terminators shall include any cantilever loads acting on terminator porcelains due to seismic disturbance.

#### **N.3 Seismic qualification methods**

Seismic withstand capability shall be demonstrated by the following:

Greater than 500 kV	By design level time history shake-table testing	N.4.1
230 kV to 500 kV	By performance level time history shake-table testing	N.4.2
Greater than 35 kV to < 230 kV	By static pull test	N.4.3
Less than or equal to 35 kV	By inherently acceptable	N.4.4

## **N.4 Qualification procedures**

### **N.4.1 Design level time history shake-table testing**

The qualification procedure shall be according to the requirements of A.1 and A.1.2 using the design level required response spectra.

A resonant frequency search shall be performed according to the requirements of A.1.2.5.

### **N.4.2 Performance level time history shake-table testing**

The qualification procedure shall be according to the requirements of A.1 and A.1.2 using the performance level required response spectra.

A resonant frequency search shall be performed according to the requirements of A.1.2.5.

### **N.4.3 Static pull test**

The qualification procedure shall be as defined in A.1 and A.1.3.

### **N.4.4 Inherently acceptable**

The qualification procedure shall be according to the requirements of A.1.5.

### **N.4.5 Monitoring requirements**

Critical locations on the potheads shall be monitored for maximum displacement, maximum accelerations, and maximum loading on insulators. Monitoring requirements shall be in accordance with A.2.4.5 and the following:

- a) Maximum displacement: Top of the terminator.
- b) Maximum accelerations (vertical and horizontal): Top of the terminator.
- c) Maximum stresses: Base of the supporting structure (may be omitted for performance level time history test).

### **N.4.6 Post-shake-table testing**

The terminator shall undergo standard electrical production tests after the completion of the shake-table tests. In addition, terminators that are sealed against atmospheric contamination shall not leak during or after the shake-table tests.

## **N.5 Acceptance criteria**

### **N.5.1 General**

The qualification will be considered acceptable if the requirements given in this annex, the applicable clauses, and the requirements given in N.5.1 and N.5.2 are met.

The general requirements are as follows:

- a) The general requirements of A.2.1 for design level qualifications and A.2.2 for performance level qualifications.
- b) For the design level time history test, the requirements of A.2.1.4.
- c) For the performance level time history test, the requirements of A.2.2.
- d) For the static pull test, the requirements of A.2.3.
- e) All cable terminators requiring shake-table testing for qualification shall be subjected to a routine or production pull test. Note that the insulator shell of the terminator could be tested rather than the assembled terminator. For composite cable terminators the test shall conform to the requirements for routine mechanical tests in Section 10.4 of IEC 61462. For porcelain cable terminators the test shall conform to the requirements for post insulators.

### **N.5.2 Functional requirements for shake-table tested equipment**

The equipment shall meet the requirements of A.2.4.2.

The shake-table tested cable terminators shall pass the following electrical requirements as defined in IEEE Std 48:

- a) Visual inspection. There shall be no damage or cracks in any part, including the porcelain, and no oil leakage before or after the shake-table test.
- b) Mechanical efficiency of seal temperature rise.
- c) Power frequency withstands voltage.
- d) Power frequency flash over.
- e) Impulse withstands voltage.
- f) Capacitance measurements.
- g) Ionization measurements.
- h) Radio influence.
- i) Pressure (leak).

## **N.6 Design requirements**

The terminator and support shall be designed to the requirements given in A.4.

## **N.7 Report**

A report shall be prepared and supplied in accordance with A.5.

## **N.8 Seismic identification plate**

Supplier shall attach a seismic identification plate to each cable terminator. The plate shall be as specified in A.7.

## **Annex O**

(normative)

### **Series capacitors and shunt capacitors**

#### **O.1 General**

##### **O.1.1 Voltage classes**

The voltage/voltage class, kV, as used for shunt capacitors and for series capacitors in this annex, is the system nominal voltage as defined in IEEE Std 1036 and IEEE Std 824, respectively.

##### **O.1.2 High seismic qualification level**

The requirements of Annex O, with the exception of O.1.3 and O.1.4, are applicable to all series and shunt capacitors in high seismic qualification level areas.

##### **O.1.3 Moderate seismic qualification level**

The requirements of Annex O, with the exception of O.1.2 and O.1.4, are applicable to all series and shunt capacitors for qualification to the moderate seismic level.

##### **O.1.4 Low seismic qualification level**

The requirements of A.1.1.9 are applicable to all series capacitors and shunt capacitors for qualification to the low seismic level.

#### **O.2 Operational requirements**

Series and shunt capacitors installations shall be designed to meet the seismic qualification objectives of 5.2.

#### **O.3 Seismic qualification methods**

Seismic withstand capability shall be demonstrated as follows:

230 kV and above	By dynamic analysis	O.4.1
38 kV to < 230 kV	By static coefficient analysis	O.4.2
Less than 38 kV	By inherently acceptable	O.4.3

#### **O.4 Qualification procedures**

The qualification procedure shall be according to the requirements of A.1.

#### **O.4.1 Dynamic analysis**

Series and shunt capacitors to be dynamically analyzed shall be analyzed in accordance with the requirements of A.1.4.7.

#### **O.4.2 Static coefficient analysis**

The qualification procedure shall be in accordance with A.1.4.6. The static coefficient may be taken as 1.0.

#### **O.4.3 Inherently acceptable**

The qualification procedure shall be in accordance with A.1.5.

### **O.5 Acceptance criteria**

The qualification will be considered acceptable if the requirements given in this annex, the applicable clauses, and the requirements of A.2.1 are met.

### **O.6 Design requirements**

The complete shunt capacitor or series capacitor shall be designed in accordance with A.4.

### **O.7 Report**

A report shall be prepared in accordance with A.6.

### **O.8 Seismic identification plate**

A seismic identification plate shall be attached to each shunt capacitor or series capacitor supplied. The plate shall be as specified in A.7.

## Annex P

(normative)

### Gas-insulated switchgear

#### P.1 General

##### P.1.1 Voltage classes

The voltage/voltage class, kV, as used in this annex, is the rated maximum voltage, phase-to-phase, kV rms voltage rating as defined in IEEE Std C37.122. Seismic qualification levels are given in P.1.2 through P.1.4.

##### P.1.2 High seismic qualification level

The requirements of Annex P, with the exception of P.1.3 and P.1.4, are applicable to all gas-insulated equipment for qualification to the high seismic level.

##### P.1.3 Moderate seismic qualification level

The requirements of Annex P, with the exception of P.1.2 and P.1.4, are applicable to all gas-insulated equipment for qualification to the moderate seismic level.

##### P.1.4 Low seismic qualification level

The requirements of A.1.1.9 are applicable to all gas-insulated equipment for qualification to the low seismic level.

#### P.2 Operational requirements

The equipment and supporting structure shall be designed to meet the seismic qualification objectives described in 5.2. Additionally, equipment shall maintain the correct operational states during the seismic event.

#### P.3 Seismic qualification methods

The seismic withstand capability, where the kV rating is a measure of the system voltage rating, as defined in Table 1 of IEEE Std C37.122 shall be demonstrated by:

170 kV and above	By performance level time history shake-table testing	P.4.1
123 kV to < 170 kV	By dynamic analysis	P.4.2
38 kV to < 123 kV	By static coefficient analysis	P.4.3
Less than 38 kV	By inherently acceptable	P.4.4

## P.4 Qualification procedures

### P.4.1 Performance level time history shake-table testing

#### P.4.1.1 General

The qualification procedures shall be in accordance with the requirements of A.1.

The qualification procedure shall be in three stages:

- a) Stage 1: Resonant frequency search. A resonant frequency search shall be conducted to determine resonant frequencies according to the requirements of A.1.2.5.
- b) Stage 2: Time history shake-table testing. The equipment and support structure shall be tested according to the requirements of A.1.2.
- c) Stage 3: Time history shake-table operational testing. The circuit breaker and support structure shall be subjected to the same test described above in stage 2 with the addition of a breaker open–close–open (O–C–O) operation, during the strong motion. Breaker operation should be initiated at approximately the time at which the normalized Arias Intensity of 50% of maximum is achieved for one of the horizontal components of motion. During this test, the breaker shall be filled with gas at the rated operating pressure.

To prevent injury or damage from possible failure of pressurized components, test with protective barriers and other appropriate precautions, as needed. As a minimum, all precautions shall be in accordance with applicable laboratory and legal requirements.

Equipment too large to fit on the shake table may be modified as detailed in 4.11.

#### P.4.1.2 Monitoring requirements

Critical locations on the switchgear and supporting structure shall be monitored during all stages required above and for each test run for maximum displacement, maximum accelerations, and maximum loading on air insulators. Monitoring requirements shall be in accordance with A.2.4.5 and the following:

- a) Maximum displacement: Top of bushing.
- b) Maximum accelerations: (vertical and horizontal) Top of bushing and center of gravity of each sub-equipment component (i.e., disconnect switch, surge arrester, etc.).

To detect relay bounce and to verify that false operation will not occur, the following components shall be energized and monitored during stage 2 and stage 3 tests:

- The trip and close circuits and mechanism motor shall be energized.
- The X and Y relay contacts and SF<sub>6</sub> density switch contacts shall be monitored.

The timing characteristics of the circuit breaker and the measurement of the resistance of the current carrying parts shall be taken before the testing begins and as a minimum after completion of the last shake-table test. Pressure readings and sniff tests shall be made directly after each pressurized time history test to detect possible leaks.

The equipment and supports shall be inspected for cracking, buckling, or other types of failure or distress. Gaskets associated with support columns and bushings shall be inspected for evidence of slippage.

#### **P.4.1.3 Production tests following shake-table testing**

The switchgear shall undergo standard production tests after the completion of the shake-table tests.

#### **P.4.2 Dynamic analysis**

The qualification procedure shall be according to the requirements of A.1 and A.1.4.7.

#### **P.4.3 Static coefficient analysis**

The qualification procedure shall be according to the requirements of A.1 and A.1.4.6. The static coefficient may be taken as 1.0.

#### **P.4.4 Inherently acceptable**

The qualification procedure shall be in accordance with A.1.5.

### **P.5 Acceptance criteria**

#### **P.5.1 General**

The qualification will be considered acceptable if the requirements given in this annex, the applicable clauses, and the requirements in P.5.1 and P.5.2 are met. The general requirements are as follows:

- a) The general criteria of A.2.1 and A.2.2. Also, there shall be no evidence of support column or bushing gasket slippage (refer to A.2.4.4).
- b) For the Performance Level time history test, the requirements of A.2.2.
- c) For the dynamic and static coefficient analysis, the requirements of A.2.1.4.

#### **P.5.2 Functional requirements for shake-table tested equipment**

The equipment shall meet the requirements of A.2.4.2, C.5.2, E.5.2, F.5.2, K.5.3, and N.5.2 as applicable.

### **P.6 Design requirements**

The equipment and support shall be designed according to A.4.

## **P.7 Report**

### **P.7.1 Report for shake-table test**

#### **P.7.1.1 General**

The report shall be in accordance with A.5.

#### **P.7.1.2 Timing and resistance**

The circuit breaker's pre-test and post-test opening and closing-timing characteristics and resistance measurements of its current carrying parts shall be included in the report. Pre-test characteristics and measurements shall be provided before the beginning of the shake-table tests.

#### **P.7.1.3 Circuits monitoring**

A list of circuits that were monitored along with any indication of a change in status during the tests shall be included in the report.

### **P.7.2 Report for dynamic or static analysis**

The report shall be in accordance with A.6.

## **P.8 Seismic identification plate**

A seismic identification plate shall be attached to each piece of equipment supplied. The plate shall be as specified in A.7.

## Annex Q

(informative)

### Qualification methods: An overview

#### Q.1 General

Static analysis, static coefficient analysis, dynamic response spectrum analysis, time history dynamic analysis, time history testing, and static pull testing are methods used in this recommended practice to qualify electrical equipment. This annex briefly explains these methods, as well as some of the fundamental seismic qualification concepts. This annex does not provide qualification requirements. The requirements for the qualification methods are given in Annex A.

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

- a) *The expected magnitude of the excitation.* The geographical region, local site and soil conditions, seismic hazard, 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, and higher voltage equipment has lower natural frequencies and is more susceptible to seismic excitations. Therefore, simpler calculation methods are generally acceptable for more rigid, or lower-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 5.2 for more detailed information. Review of previous seismic performance or testing of similar equipment is recommended.

#### Q.2 Fundamental concepts

##### Q.2.1 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 [B8]. 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 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 depict the RRS for high and moderate qualification levels, respectively.

The response spectra used in this recommended practice are intended to reasonably envelop anticipated earthquakes for most sites (refer to 5.8.3). 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.

### **Q.2.2 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 recommended 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 in this recommended practice. Claims of any damping beyond 2% must be substantiated by testing (A.1.1.6). 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 allowed in this recommended practice.

## **Q.3 Analysis methods**

### **Q.3.1 Static analysis**

For rigid equipment, 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.1.4.5 for further requirements.

### **Q.3.2 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 spectral acceleration 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 multi-mode effects. Refer to A.1.4.6 for more details.

### **Q.3.3 Response spectrum dynamic analysis**

For structures with many modes in the seismic range, a detailed finite element model is needed. The response spectrum dynamic analysis method is used with damping ratio determined in accordance with A.1.1.6 or a conservatively low value (e.g., 2%, refer to 5.6.2) is used. The lower frequencies of the mathematical model should, if possible, also be verified by simple-bump or other specified test methods.

Response spectra are used as load inputs in a dynamic analysis of the finite element model to calculate responses (strain, velocity, displacement, acceleration) for each natural frequency or mode shape. After the maximum response for each mode is determined, the combined total response can be calculated. The combined total response is not obtained by adding the response variable of each mode shape, because different modes will attain 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.<sup>19</sup> The loads and modal stresses are combined using the SRSS method, or closely spaced modes (within 10% of lower modes) are added absolutely and then the remaining modes are combined using the SRSS method. A commonly used alternative method for combining modes is the CQC technique. Residual mass effects at the center of mass should be included (refer to A.1.4.7).

#### **Q.3.4 Time history dynamic analysis**

This method is a powerful tool when evaluating multiple, interconnected equipment or when studying equipment too large to test. 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. Refer to A.1.4.8 for more details.

### **Q.4 Testing methods**

#### **Q.4.1 Test methods used in this recommended practice**

Testing has historically been conducted using a variety of test methods, but the following methods are used in this recommended practice:

- a) Time history shake-table test
- b) Static pull test

#### **Q.4.2 Time history shake-table test qualification**

For time history shake-table testing, a displacement time history can be fed to actuators or hydraulic rams that shake the table and thereby simulate the effects of earthquake on the equipment. 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.

An important consideration 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.

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<sup>19</sup> *Dynamics of Structures, A Primer*, Earthquake Engineering Research Institute, Anil K. Chopra, Text modified by committee.

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.

Historically, the direction categories for testing include biaxial and triaxial. However, in this recommended practice, only triaxial testing is recognized.

Instrumentation to measure accelerations at the overall center of gravity (CG) is recommended. 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.

#### **Q.4.3 Static pull test**

The static pull test is a simplified test prescribed for specific types of lower voltage equipment. The test is accomplished by applying a specified load, for a specified duration, in the most onerous direction, at the top of the equipment.

### **Q.5 Optional input motion time histories for testing and analysis**

In lieu of developing a set of input motions for time history testing and analysis as described in A.1.2.6, the time history test and analysis may be conducted with one of the three-component acceleration time histories available at the following link: [standards.ieee.org/downloads/693-2018\\_downloads.zip](https://standards.ieee.org/downloads/693-2018_downloads.zip). Both empirically-based and numerically-synthesized time histories are available. These input motion time histories are provided for the convenience of the user or user's agent. The user or user's agent is free to develop acceptable input motion time histories of their own if they believe the IEEE website time histories are too conservative or inappropriate in some circumstances. Two reports in the public domain are available which describe the development of the time histories: "Development of Time Histories for IEEE 693 Testing and Analysis (Including Seismically Isolated Equipment)," PEER Report No. 2017/10, Pacific Earthquake Engineering Research Center, University of California, Berkeley, December 2017 [B26], and "Time Histories for IEEE 693 Testing and Analysis: A Summary of Unfiltered and Filtered Versions," Structures Laboratory Report 2017/01, Department of Civil and Environmental Engineering, University of California, Berkeley, December 2017 (link: [standards.ieee.org/downloads/693-2018\\_downloads.zip](https://standards.ieee.org/downloads/693-2018_downloads.zip)) [B27].

### **Q.6 Special test cases**

Generic testing beyond specified requirements (over testing) 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 over testing 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).

## **Q.7 Qualification method for specific equipment**

The table of contents of this recommended practice lists annexes for most 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.

## **Q.8 Functionality of equipment**

The functional aspects of specific equipment are defined in the “Operational requirements” 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 the performance level of a particular seismic event and performing the required functions before, during, and after the test. Switches, linkages, relays, and other components 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 allowable provided failure modes are known and stresses at appropriate locations are measured.

## **Q.9 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 [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 EPRI/SQUG standard [B11]. Qualification by experience data requires appreciable expertise; it is suggested that the standards developed by the nuclear industry be used whenever possible.

## Annex R

(informative)

### Composite and porcelain insulators

#### R.1 Composite insulators

Composite insulators, as used in this recommended practice, are composed of a fiber-reinforced core, elastomer sheath-sheds, and metal end fittings.

##### R.1.1 Definitions

The following terms are used in this annex:

- a) Elastomer: A synthetic rubber.
- b) Hydrophobicity: Lacking affinity for water, water repellent, causing water to bead.
- c) Mandrel: Tube or rod device onto which the fiber and resin is placed to form a hollow fiberglass tube.
- d) Pultrusion: Continuous fiber, which has been soaked in resin, is formed into either a solid rod or a hollow tube by pulling the fiber through a die. The finished shape is then oven cured. The fiber runs axially.
- e) Vulcanization: The cross-linking of long molecular chains of the polymer materials resulting in keeping elastic properties and removing the plasticity of the original rubber.

##### R.1.2 Core

The core usually consists of glass fibers in a resin matrix. The core provides the load-bearing nonconductive structure for the insulator.

###### R.1.2.1 Core types

Cores can be categorized into two general types: solid core (rod) and hollow tube core. It is important to recognize that the method of manufacture, the mechanical behavior, and the application are often different. The two different core types are as follows:

- a) *Solid core rod.* The glass fibers are pultruded axially. Solid core rods are used in all tension load applications. Because solid core rods are currently only made to a maximum of 76 mm to 89 mm (3 in to 3.5 in) in diameter, they are generally used in bending only when service loads are low to moderate. Applications include transmission line insulators, dead-end insulators, and line post and station post insulators. (For high bending load applications, hollow core composite insulators are generally used due to its greater rigidity and, depending on its design, its greater strength.)
- b) *Hollow tube core.* The glass fibers can be axial (pultruded) or a crisscrossing weave (mandrel wrapped). Hollow tube crisscrossing weave-type fiberglass cores are the recommended type for seismic applications. In the weave core type, the glass fibers are wound onto a mandrel at a specific angle, crisscrossing in both directions. Hollow core composite insulators are generally used for

apparatus such as bushings, current and voltage transformers, surge arresters and other equipment parts where bending and pressure are major considerations.

### R.1.2.2 Materials of core

The fiberglass structure is generally made of epoxy resin or polyester resin reinforced by glass fiber, or fiberglass-reinforced polymer (FRP). The fiberglass core generally contains more than 50% by weight of glass type fiber.

### R.1.2.3 Core properties

The strength properties of fiber-reinforced hollow and solid core vary depending on many factors, such as the winding pitch of the fiber, the choice of reinforcing material and resin, the volume of the fibers, the number of fiber layers, and the method of winding. FRP strength and property values can vary greatly. Table R.1 and Table R.2 offer a general material property comparison of FRPs (these values should not be used for design) with other materials such as porcelain, steel, and aluminum.

Table R.1 shows typical FRP properties.

**Table R.1—Typical FRP properties**

Properties	Data	
Ultimate stress (rod)	550–750 MPa	80–109 ksi
Damage limit (rod)	450–550 MPa	65–80 ksi
Poisson's ratio	0.25–0.28	

Table R.2 compares typical values for steel, porcelain, and FRP.

**Table R.2—Typical values for steel, porcelain, and FRP**

Material	Young's modulus		Fracture toughness
Steel	210 GPa	30 000 ksi	100 MPa·m <sup>1/2</sup>
FRP (E glass)	8-48 GPa	1160-7000 ksi	20-60 MPa·m <sup>1/2</sup>
Porcelain	60-100 GPa	8700-14 500 ksi	0.1-10 MPa·m <sup>1/2</sup>

### R.1.2.4 Defining core strength

Identifying an allowable or design strength is difficult. The allowable or design strength is the value against which the calculated or tested stresses are compared. To use FRP allowable or design strength values, the reader should understand the mechanical behavior of composites.

The composite has four modes or levels of mechanical behavior, as follows:

- a) *Elastic behavior.* The fiberglass core deforms elastically under initial load. The duration of the load does not affect strength as long as the stresses remain in the elastic domain. When the load is removed, the core returns to its original position and there is no reduction of strength.
- b) *Damage limit behavior.* The transition zone between elastic behavior and plastic behavior is the damage limit zone. Below this limit, no fibers break. As one might expect, the actual damage limit is not well defined. Therefore, it is generally considered to be a range rather than a single point.
- c) *Plastic behavior.* When the damage limit is exceeded, fibers begin to break and the load is transferred from the broken fiber to the epoxy resin. The resin creeps under the additional load, transferring the load to surrounding undamaged fibers. Assuming the new surrounding fibers are overstressed, more fibers will break passing more load to the resin. This process may repeat until

the core fails. It should be noted that this does not happen suddenly, because this process involves creep. The time required to reach failure depends on the magnitude of the overload.

For failure to occur, three events must occur:

- 1) The load must be above the elastic limit.
- 2) The load must be large enough that the fiberglass structure will not stabilize.
- 3) The load must be held long enough for the process to go to completion.

However, if the load is not an overload and it is removed early enough during this process, the total strength capacity of the core generally will not dramatically change. This characteristic is important for seismic applications, because the dynamic loads due to earthquakes are short and the creep discussed above does not have sufficient time to progress. Thus, the structural load carrying capability of the insulator is not dramatically changed.

- d) *Instantaneous failure.* As can be seen, failure is possible in the plastic range, but it is time dependent. A significant amount of load above the damage limit must be applied to achieve instantaneous failure.

The insulator manufacturers provide two ratings, as follows:

- *SML.* The manufacturer specifies that the insulator will withstand this load without visual damage. This value is above the damage limit zone. This value is useful for short duration loads, such as short-circuit and seismic loads. The SML applies to the mechanical bending type test.
- *MML.* The manufacturer specifies this load as the maximum total mechanical service load. Total sustained service loads should not exceed the MML. The MML is 40% of SML per IEC 61462.

### R.1.3 Sheath-sheds

Elastomers, such as EPM, EPDM, and SR, are the main materials used for sheath-sheds of composite insulators. Some typical properties of SR and EPDM are given in Table R.3.

**Table R.3—EPDM and SR**

<b>Material</b>	<b>EPDM</b>	<b>SR</b>
Specific gravity	1.25-1.55	1.25-1.60
Hardness (Shore A)	75	25-75
Tensile strength	8.3-13.8 MPa (1200-2000 ksi)	5.5-6.9 MPa (800-1000 ksi)
Modulus of elasticity	4.8 MPa (700 ksi)	1.4-2.8 MPa (200-400 ksi)
Tear strength	3500-6130 kPa (200-350 ksi)	880-1750 kPa (50-100 ksi)

There are four general methods of applying sheath-sheds to the core, as follows:

- a) The sheath-sheds are placed over the fiberglass core, either one by one or multiple continuous sections. A thin layer of silicone grease is placed between the fiberglass and the sheath-sheds to eliminate air gaps and to maintain dielectric integrity. The sheath-sheds are also compressed axially on the core to prevent the core from being exposed to the environment during large deflections.
- b) A thin polymer sheath is extruded onto the core and partially cured. Sheds are placed along the sheath, and the entire assembly is completely cured. A chemical bond exists between the fiberglass and the sheath-shed material.
- c) The entire sheath-shed housing is formed, vulcanized, and bonded to the core and the metal end fittings.
- d) The sheath-sheds are extruded and helically wound on the core.

#### R.1.4 Metal end fittings

The end fittings are of extreme importance. The metal end fittings or their attachment to the core may be the weakest link in the structure. The end fittings perform the following functions:

- Transfer the load from the fiberglass core to the attachment point.
- Seal liquid or gas under pressure in hollow core insulators or bushings.
- Seal the ends of the fiberglass from the environment.

The metal end fittings are generally made from cast, forged, or machined aluminum; malleable iron; forged steel; or aluminum alloy.

There are various methods of attaching the metal end fittings to the core. The most used methods are as follows:

- Swaging or crimping (radial pressing). The metal end fitting is crimped onto the fiberglass core. This method is most often used for suspension insulators.
- Adhesive / shrink fitting. This method transfers load by an epoxy chemical bond between the metal flange and the fiberglass-polymer core. Because of a difference in coefficient of thermal expansion between the flange and the core, the flange is heated just before assembly so that during high temperature operation differential thermal expansion will not subject the epoxy bond to a tensile load. Under typical operating temperatures the shrink fit of the flange helps secure the connection. This method is used with hollow-core insulators.
- A third method no longer in common usage is potting. The metal end fitting is shaped like a cup, except the bottom of the cup is larger in diameter than the rim of the cup. The fiberglass core is inserted into the metal end fitting, and epoxy is injected into the void between the fiberglass and the metal fitting to form a wedge. The epoxy bonds to the fiberglass and is wedged in the metal fitting.

#### R.1.5 Seismic comparison of composite with porcelain

Composite insulators have the following characteristics relative to porcelain insulators:

- a) Composite insulators have the ability to absorb a greater degree of the vibrational energy due to their greater elasticity.
- b) Composite insulators are lighter and have lower stiffness compared to porcelain insulators of a given voltage and mechanical strength rating.
- c) Composite insulators are less prone to failure due to impact from blunt falling objects, but may be more prone to puncture or tearing from sharp objects.
- d) If the conductor that connects equipment is suddenly drawn tight or experiences resonance during earthquake shaking, then the equipment's insulators may be subjected to shock loading. This phenomenon is a common cause of failure in earthquakes. Composite insulators, by virtue of their greater fracture toughness, are better able to withstand the shock loads imparted by seismic conductor interaction. (Refer to 6.9 and R.1.6.)
- e) Evidence of structural failure of a composite insulator may not be as clearly evident as porcelain, which may lead to long-term problems as damage may propagate unseen.

## **R.1.6 Topics of special concern**

### **R.1.6.1 Environmental factors**

Damage of the sheath-sheds due to environmental factors, such as ultraviolet light, dry-band discharges, temperature, and humidity, have long been of concern. All materials degrade due to environmental conditions. The rate of degradation differs. Unlike porcelain, which is made of inert materials and degrades very slowly, polymer sheath-sheds may degrade more quickly due to environmental conditions. However, the question that must be asked is whether the material will remain fully functional over its required life.

Not all elastomer sheath-sheds resist aging at the same rate. The user must evaluate the materials to determine which are appropriate for their application. Therefore, it is recommended that the user require the manufacturer pass aging tests. IEEE Std 1133™ [B21], IEC 60587 [B13], IEC 61109 [B15], and ASTM D2303 [B5] are but a few of the standards defining requirements for aging. The user should adopt an aging testing program appropriate to their specific service conditions.

The sheath-sheds provide not only the necessary electrical clearances, but they also protect the fiberglass core from the environment. Careful attention should be given to the interface of the sheath-shed and the metal end fitting. Due to the differences in thermal expansion of the various materials, this area is the most likely avenue for the ingress of moisture.

### **R.1.6.2 Deflection**

Composites deflect more than porcelain of comparable diameter and size. This characteristic should be considered when providing adequate bus slack, maintaining electrical clearances, and designing for short-circuit interactions.

### **R.1.6.3 Creep**

Fiberglass creeps with time under sustained loads. If the load is maintained, the deflection will increase over time. This is generally not a problem in seismic events, because earthquake bending loads are transient. However, creep should be considered in the design if long-term loads are present, such as insulators mounted horizontally carrying significant vertical loads. If the loads are kept under the elastic limit, the insulator will return to its original position, after the load has been removed for a time.

### **R.1.6.4 Liners**

When sulfur hexafluoride ( $SF_6$ ) is used, there is a potential for fluoric acids to be present. A protective coating of the inside wall of the hollow core should be required. This coating should be acid resistant and maintain high surface resistance. It is also recommended that a long-term pressure test, such as given in NEMA SG 4 [B24], be required.

For oil-filled bushings or insulators, a protective inner liner or coating should be required to facilitate cleaning.

### **R.1.6.5 Fiberglass**

The fiberglass core provides a lightweight, strong structure that is lighter than porcelain and therefore easier to handle. The flexible characteristics of the core reduce the chance of damage during shipping,

handling, and mounting. Insulators should be handled with care by following the manufacturers' instructions.

#### **R.1.6.6 Metal end fittings**

The metal end fitting's capacity to transfer the load to the core is very important to the structural capacity of the insulator or bushing, especially for solid core insulators, where the metal end fitting may be the weakest link.

It is possible during testing/earthquakes that some debonding may occur in hollow core insulators between the metal end fitting and the core. Debonding may not affect the structural performance of the end fitting as long as there is no permanent deformation after testing/earthquakes.

#### **R.1.7 Related documents**

For further information, refer to Australian Standard AS 4435.4 [B6], IEC 61109 [B15], IEEE Std 1133 [B21], ANSI C2 National Electrical Safety Code® (NESC®) [B1], and IEC 61462.

### **R.2 Porcelain insulators**

Over the past century, porcelain insulators have proven to be strong, reliable, and durable when proper design practices are applied. As a ceramic, porcelain is a brittle material, and therefore, attention must be paid to how mechanical loads are transferred to it. Follow manufacturers' handling instructions to prevent damage.

The main components that make up porcelain insulators and bushings are porcelain body and metal end fittings. The mechanical strength of porcelain insulators and bushings depends on the following:

- a) The microstructure of the porcelain body and metal end fittings.
- b) Whether the porcelain is glazed or unglazed.
- c) The cross-sectional geometry of the porcelain body and metal end fittings.
- d) The load transfer mechanism employed between the porcelain body and the metal end fittings.

#### **R.2.1 Porcelain material**

The composition and microstructure of each manufacturer's porcelain will differ, and therefore, the strength will be different. However, porcelain material can be divided into three classifications: normal, high, and extra high strength.

IEC 60672-3 [B14] defines three classifications that are commonly used in high voltage insulators. These classifications are shown in Table R.4.

**Table R.4—Insulator strength**

IEC group	Approximate flexural strength (min)	
	Unglazed	Glazed
C110 (siliceous porcelains)	50 N/mm <sup>2</sup> (7250 psi)	60 N/mm <sup>2</sup> (8700 psi)
C120 (aluminous porcelains)	90 N/mm <sup>2</sup> (13 100 psi)	110 N/mm <sup>2</sup> (16 000 psi)
C130 (aluminous porcelains, high strength)	140 N/mm <sup>2</sup> (20 000 psi)	160 N/mm <sup>2</sup> (23 300 psi)

#### **R.2.2 Metal end fittings**

The mechanical strength of insulators and bushings is greatly affected by the type of end fittings and how uniformly the load is transferred to the porcelain body. An improperly designed end fitting can actually

decrease the strength of the insulator by concentrating stress in a narrow band or point. Porcelain is many times stronger in compression than in tension. Therefore, good end fitting design must make use of this fact.

There are three types of end fittings—center clamped, mechanical clamped, and cemented. It is important that the user understand the design considerations inherent with each type. They are discussed in Table R.5 and illustrated in Figure R.1, Figure R.2, and Figure R.3.

**Table R.5—Metal end fittings**

Type	Equipment	Advantages	Disadvantages
Center clamped (Bending capacity determined by prestress of center tension rod)	—Transformer bushing —Dead-tank breaker bushings	—Economical design —Compact design	—Potential of oil leak (i.e., as bushing rocks or slides off center, an opening between porcelain and the end fitting can occur) —Potential of cracking or breakage (i.e., concentration of stress at one point as the bushing rocks off-center)
Mechanically clamped	Measuring devices (Current transformer, Potential device, etc.) Bushing	—Economical design —Compact design	—Potential for breakage at a lower value than cemented type, due to a concentration of stresses at clamp
Cemented	All	—Minimizes potential for oil leakage. —Minimizes potential for breakage due to concentration of stresses.	—The overall length of the insulator or bushing must include the height of the metal end fittings at both ends, which means the insulator or bushing must be slightly longer than the center clamped type.

#### R.2.2.1 Center clamped fittings

Center clamped bushings and insulator have a pre-tensioned rod (normally the conductor) that runs down the center of the bushing. The rod is connected to each end fitting. The pre-tension in the center rod provides the moment resistance of the bushing. No chemical or mechanical bonds provide structural resistance. By tensioning the rod, the end fittings are pressed onto the ends of the porcelain body. Lateral loads, such as earthquake loads, must overcome the precompression in the interface between the metal end fitting and the porcelain before uplift of the bushing from the end fitting can occur. The end fittings are generally plates with nonmetal gaskets to cushion the interface between the metal end fitting and the porcelain. When this type of bushing fails in an earthquake, it is generally due to one of the following reasons:

- a) Oil leakage due to rocking or lifting of the bushing off the end fitting.
- b) Displacement of the porcelain relative to the flange.
- c) Protrusion of the gasket from between the porcelain and the flange.
- d) Cracking at one edge of the porcelain caused by rocking or tilting of the porcelain.

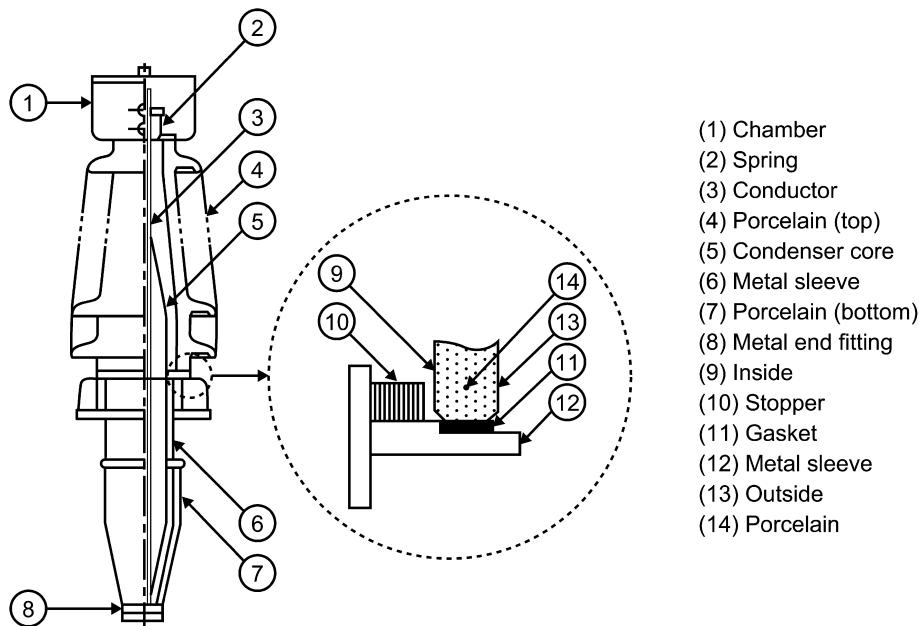


Figure R.1—Example of center clamped type

### R.2.2.2 Mechanically clamped fittings

The metal end fitting of the clamped type is attached to the porcelain by means of a mechanical clamping device. The main disadvantage of this method is that the full strength of the porcelain may not be achieved due to concentration of stresses in the porcelain at the clamp. The following special considerations must be given when designing the area labeled as "A" in Figure R.2.

- a) The clamping device should be designed to evenly and properly bear on the porcelain surface. If this cannot be done, the porcelain must be ground to achieve a proper bearing surface. No sharp corners should be allowed. Sharp corners are stress risers that may promote cracking. All corners should have as large a radius as possible.
- b) The bearing area of the clamp on the porcelain must be adequate.

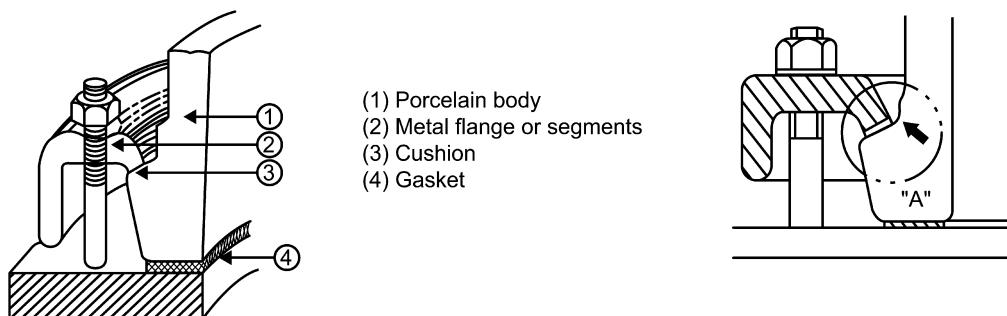


Figure R.2—Mechanically clamped type

### R.2.2.3 Cemented fittings

The third type of metal end fitting is the cemented metal socket or fitting. Here, the inside of the metal end fitting is contoured to translate tensile loads into compressive loads on the porcelain body.

A grout material is employed between the end fitting and the porcelain body. This material must be rigid enough to transfer the compressive loads and yet be pliable enough to prevent load concentrations on the porcelain. The most common material used for this purpose is Portland cement. Other materials used include alumina cement, sulfur cement, lead, and epoxy.

The strength of porcelain with a cemented fitting is markedly influenced by H/D (ratio of depth of engagement to the diameter of the porcelain). Should the H/D be too shallow, the load cannot be properly transferred from the metal end fitting, causing a concentration of stresses in the porcelain, resulting in failure at a lower value than the inherent strength of porcelain. To attain the inherent strength of the porcelain, it is recommended that the H/D be at least 0.45 for normal strength porcelain. This ratio must be increased for high strength porcelain proportionally to any increase in porcelain strength.

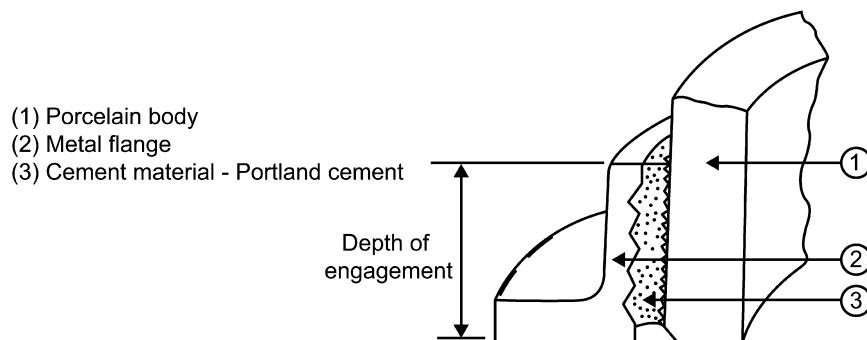
Four materials are generally used for cemented fittings: gray iron, ductile iron, aluminum alloy, and bronze. Aluminum and bronze are non-magnetic materials suitable for bushings and insulators under heavy current. A comparison of the materials used in cemented fitting is given in Table R.6.

**Table R.6—Cemented fittings**

Material	Approximate modulus of elasticity (MPa)	Approximate tensile strength obtained by test bars (MPa)	Approximate linear coefficient of thermal expansion at 20 °C/°C	Remarks
Gray iron casting	$98 \times 10^3$	More than 196	$10 \times 10^{-6}$	Magnetic material
Ductile iron casting	$157 \times 10^3$	More than 441	$10 \times 10^{-6}$	
Aluminum alloy casting	$69 \times 10^3$	More than 226	$22 \times 10^{-6}$	Non-magnetic material
Bronze casting	$78 \times 10^3$	More than 177	$18 \times 10^{-6}$	

The inside of cemented metal end fittings generally are one of two shapes: saw-tooth shape and rectangular-groove shape. The appropriate shape is dependent on the application of the insulators or the bushings. The saw-tooth design is applicable when the metal end fitting material has a low thermal expansion, such as gray iron and ductile iron. The saw-tooth design provides a uniform stress distribution.

The rectangular-groove shape is applicable where a material with a comparatively large thermal expansion is needed, such as aluminum alloy and bronze. This type provides for a small amount of sliding within the fitting for thermal expansion at elevated temperature.



**Figure R.3—Cemented type**

### R.2.3 Optional routine tests

The following routine tests may be considered in addition to the requirements specified in the relevant sections of the IEC and ANSI standards for improved assurance of acceptable mechanical performance of porcelain insulators and bushings:

- a) *Station post insulators.* Before assembly of end fittings:
  - 1) 8-direction uniform bending moment test at 70% rating
  - 2) Ultrasonic flaw detection test
- b) *Bushings.* Before assembly of fittings, inner pressure withstand test should be performed.

NOTE—Inner pressure withstand tests are applied for pressurized insulators only.

- c) *Bushings.* After assembly of fittings:
  - 1) 4-direction bending moment test
  - 2) Inner pressure withstand test

Users are cautioned that the implementation of such non-standard test programs may incur significant additional cost.

### R.2.4 Performance of porcelain compared with composites

When properly designed, equipment employing porcelain insulators can be made to withstand seismic forces.

Porcelain has the following advantages over composites:

- a) Slow aging and degradation of insulating material.
- b) Unlike composites, the inner-core strength member does not need to be protected from the environment or the formation of non-neutral pH solutions. The porcelain, which is inert and not subject to attack from any but a few of the most caustic solutions, provides the bulk of the mechanical strength of the insulator. Electrical components may need to be protected from the environment.
- c) Highly rigid. Therefore, interconnections and tolerance of mating parts are not as critical.
- d) Less chance of damage during high-pressure washing.
- e) Wide variation of configuration.

### R.2.5 Measures for improving porcelains performance in earthquakes

- a) *De-tune porcelain support.* As noted in 5.10, the equipment support may have a significant effect on the motion of the equipment. If the support can be designed such that its natural frequencies are away from the frequencies of higher acceleration, then the equipment will not need to withstand the higher dynamic loads.
- b) *Pre-stress the insulators and bushings in compression.* As the compressive strength of porcelain is very high, its apparent bending strength can be increased by imposing a compressive load (pre-stress).
- c) *Select high strength porcelain material.* Increases in strength can be obtained without an appreciable increase in mass.

- d) *Provide measures to prevent lateral movement of the upper porcelain unit relative to the flange during a seismic event.* This may prevent the core from impacting the inside surface of the flange or limit leakage at the joint.
- e) *Limit the number of mechanical joints.* As the joints in the insulator or bushing are the weakest link, limiting their usage will improve performance.

## Annex S

(informative)

### Analysis report template<sup>20</sup>

Report No. \_\_\_\_\_

## Seismic Analysis-Qualification Report

Qualified to Level \_\_\_\_\_ g ZPA of the \_\_\_\_\_ Level RRS  
High or Moderate Design or Performance

Equipment Designation \_\_\_\_\_

kV or equipment rating \_\_\_\_\_

Report Prepared by: \_\_\_\_\_

Date Signed or Revised: \_\_\_\_\_

Address of Preparer:  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

Equipment Manufactured by:  
\_\_\_\_\_  
\_\_\_\_\_

This is to certify that the above-named equipment and support, if support is required, meets or exceeds all of the requirements according to IEEE Std 693<sup>TM</sup>-(Edition Year).

Signed: \_\_\_\_\_

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2.0 Equipment data.....	
3.0 Method of analysis.....	
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.	
Additional sections, as required.	

## Appendices

Appendix A: Items as required in A.6.1.....	
Appendix B: Seismic outline drawing..... for insulator allowable/ultimates.....	
Appendix C: Model w/labeled nodes, member's types, and dimensions, if by dynamic analysis.....	
.	
.	
Additional appendices, as required.	

## Report content

- a) 1.0 General
  - 1) Identify the customer (if applicable)
  - 2) Statement of the qualification level within the body of the report
  - 3) General description of the equipment
  - 4) Statement identifying the type/manufacturer of the insulating elements
  - 5) Summary of maximum stresses
  - 6) A concluding statement regarding the outcome of the analysis
  - 7) Supplemental work and options
  - 8) Load cases considered, including operating, dead, live, seismic, etc.
  - 9) Equipment configurations considered, such as switch open or switch closed, with or without associated cabinet, etc.
  - 10) General or global assumptions used (detailed assumptions should be embedded in the report)
  - 11) Testing, if any (such as testing for damping, or testing of a component)
  - 12) Modifications required, if any, to pass the analysis
  - 13) Replica of identification tag
  - 14) Other topics, as required
- b) 2.0 Equipment data

- 1) Overall dimensions and weights
  - 2) Resonance frequencies, if by dynamic analysis
  - 3) Damping ratio, if by dynamic analysis or by Annex B
  - 4) Center of gravity of equipment and its components
  - 5) Maximum accelerations and displacements at critical points, if by dynamic analysis
  - 6) Equipment and structure reactions at support points, including magnitude and direction, at each reaction point
  - 7) Anchorage details, including size, location, and material strength for structural members, bolts, welds, and plates
  - 8) Maximum input (ground) accelerations
  - 9) Conductor load effects: MAF or ETF and value used
  - 10) Materials types and strengths
  - 11) Other topics, as required
- c) 3.0 Method of analysis
- 1) Method of analysis
  - 2) Name of computer program used, if any
  - 3) Assumptions made in modeling the equipment and supporting structure
  - 4) Other topics, as required

**Table S.1—Summary of maximum stresses, loads, etc.**

Summary of maximum stresses, loads, etc.*						
Component	Pg #	Location of component in equipment, location of stress in component, or both	Moment, shear, torsion, tension, combination, etc.	Calculated value (f)	Allowable value (F)	F --- f

\*List the 11 smallest [F/f] factors.

**Table S.2—Example (metric): Dynamic analysis—summary of maximum stresses, loads, etc.<sup>a</sup>**

Component	Pg #	Location of component in equipment, location of stress in component, or both.	Moment, shear, torsion, tension, combination, etc.	Calculated value (f)	Allowable value (F)	F---f
Porcelain insulator	27	Base of porcelain insulator #2	Moment	4.86 kN·m	4.86 kN·m	1
Steel support leg	30	Base of corner columns	Moment compression	193 MPa	193 MPa	1
Connection weld	19	Connecting brace frame bracket to vertical leg.	Shear and bending	138 MPa	145 MPa	1.05
Porcelain insulator	27	Base of porcelain insulator #3	Moment	4.18 kN·m	4.52 kN·m <sup>b</sup>	1.08
Connection bolts	21	Connecting insulators to base	Tension and shear	120.0 MPa	131 MPa	1.09
Porcelain insulator	25	Base of porcelain insulator #4	Torsion	4.07 kN·m	4.52 kN·m <sup>b</sup>	1.11
Porcelain insulator	24	Base of porcelain insulator #1	Moment	4.97 kN·m	5.65 kN·m	1.14
Aluminum bracket bolt	31	Interface between insulator and tank.	Shear	74.5 MPa	186 MPa	2.5
Steel frame	46	All symmetrical corners.	Bending	82.7 MPa	220 MPa	2.66
Anchor bolts	88	All anchor bolts	Shear and tension	34 MPa	138 MPa	4
Steel beam	7	Cross member between legs	Bending	42 MPa	120 MPa	4.75

<sup>a</sup> Include the eleven smallest F/f values.

<sup>b</sup> Note that the porcelain's ultimate strength is 9.04 kN·m. The allowable is 4.52 kN·m or  $0.5 \times 9.04$ . (Manufacturer's insulator data is in Appendix E.)

**Table S.3—Example (inch-pound): Dynamic analysis—summary of maximum stresses, loads, etc.<sup>a</sup>**

<b>Component</b>	<b>Pg #</b>	<b>Location of component in equipment, location of stress in component, or both.</b>	<b>Moment, shear, torsion, tension, combination, etc.</b>	<b>Calculated value (f)</b>	<b>Allowable value (F)</b>	<b>F---f</b>
Porcelain insulator	27	Base of porcelain insulator #2	Moment	43 in-k	43 in-k	1
Steel support leg	30	Base of corner columns	Moment compression	28 ksi	28 ksi	1
Connection weld	19	Connecting brace frame bracket to vertical leg.	Shear and bending	20 ksi	21 ksi	1.05
Porcelain insulator	27	Base of porcelain insulator #3	Moment	37 in-k	40 in-k <sup>b</sup>	1.08
Connection bolts	21	Connecting insulators to base	Tension and shear	17.4 ksi	19 ksi	1.09
Porcelain insulator	25	Base of porcelain insulator #4	Torsion	36 in-k	40 in-k <sup>b</sup>	1.11
Porcelain insulator	24	Base of porcelain insulator #1	Moment	44 in-k	50 in-k	1.14
Aluminum bracket bolt	31	Interface between insulator and tank.	Shear	10.8 ksi	27 ksi	2.5
Steel frame	46	All symmetrical corners.	Bending	12 ksi	31.9 ksi	2.66
Anchor bolts	88	All anchor bolts	Shear and tension	5 ksi	20 ksi	4
Steel beam	7	Cross member between legs	Bending	6.1 ksi	29 ksi	4.75

<sup>a</sup> Include the eleven smallest F/f values.

<sup>b</sup> Note that the porcelain's ultimate strength is 80 in-k. The allowable is 40 in-k. or  $0.5 \times 80$ . (Manufacturer's insulator data is in Annex E.)

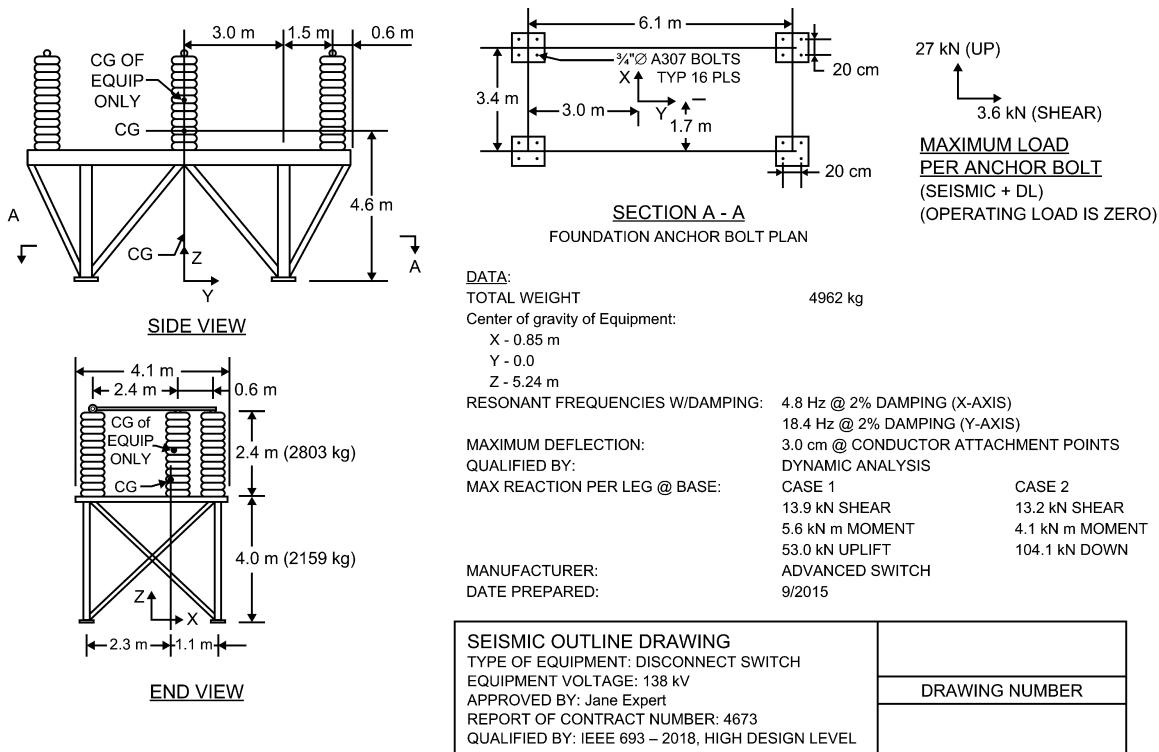


Figure S.1—Example (metric) of seismic analysis-qualification report

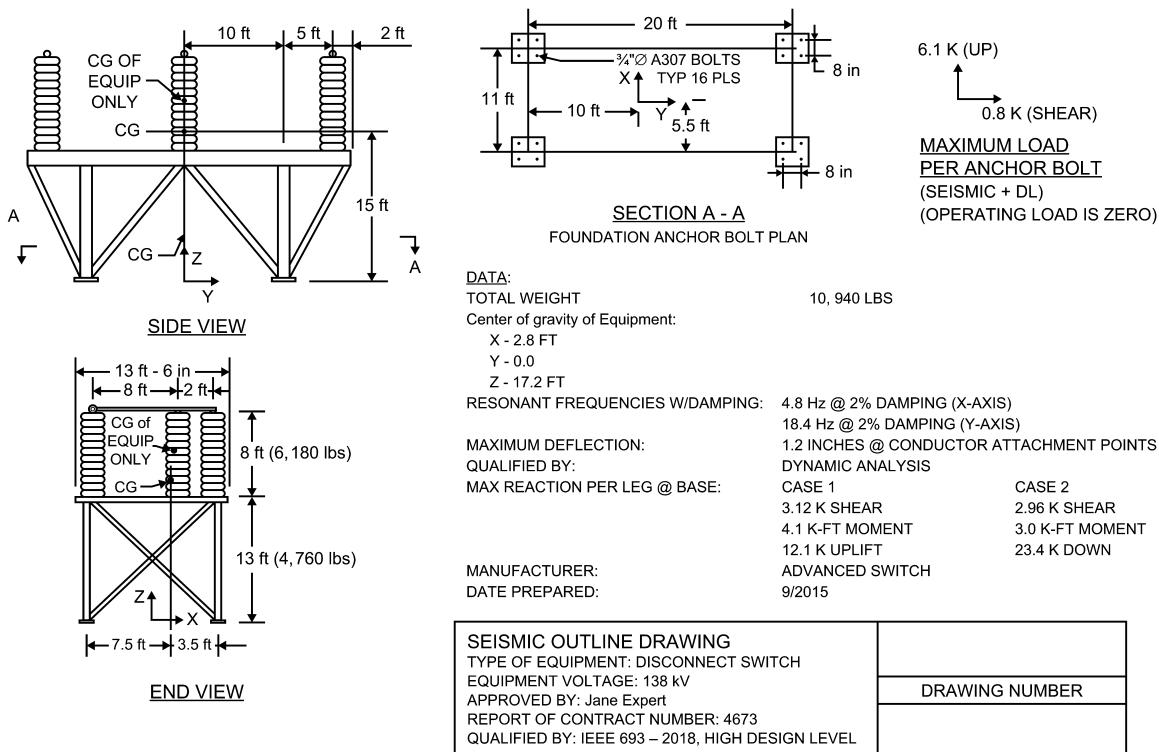


Figure S.2—Example (inch-pound) of seismic test-qualification report

## **Annex T**

(informative)

## Test report template<sup>21</sup>

Report No. \_\_\_\_\_

# **Seismic Test-Qualification Report**

Qualified to Level \_\_\_\_\_ g ZPA of the \_\_\_\_\_ Level RRS  
High or Moderate Design or Performance

## Equipment Designation

### kV or equipment rating

Report Prepared by:

Date Signed or Revised:

**Address of Preparer:**

---

ANSWER

**Equipment Manufactured by:**

This is to certify that the above-named equipment and support, if support is required, meets or exceeds all of the requirements according to IEEE Std 693™-(Edition Year).

Signed: \_\_\_\_\_

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a) Table of contents

- 1) Key information and results
- 2) Main test results and test configuration
- 3) Detailed test results and supporting data (shake table test)
- 4) Functional requirements (Appendix I)
- 5) Video
- 6) Additional sections as required.

b) Appendices

- 1) Drawings describing equipment that was tested
- 2) Detailed description of shake table
- 3) Data and calculations supporting summary of results and determination of controlling variables
- 4) Instrument calibration data
- 5) Pictures showing test setup and instrumentation
- 6) Calculations supporting determination of frequencies and damping and reference to source data in test laboratory report
- 7) Calculations supporting data in table listing maximum accelerations, stresses, and displacements (if required) and citations of source data
- 8) Calculations supporting determination of anchorage loads
- 9) Data sheets showing certification of functional tests
- 10) Additional appendices as required.

### **Report content**

(Note that the appendices shown in parentheses contain supporting calculations.)

It is recognized that this template may not be compatible with some types of equipment or qualification methods and should be appropriately modified.

a) Key information and results

- 1) Description of the equipment to be tested (Appendix A) and critical load limits (Appendix C).
- 2) Describe the equipment configurations to be considered, such as switch open and/or switch closed, with or without associated cabinet, grounding links, etc.
- 3) Level to which the equipment has been qualified.
- 4) Modifications required, if any, to pass the test.
- 5) Anomalies or damage observed during the tests. (Identify and indicate their significance to the qualification.)
- 6) List supplement work and options (see A.5.6).

- 7) List of witness(es), if any, and the company(ies) the witness(es) represented.
  - 8) Test facility, name, location, telephone and fax numbers, email address, test engineers name and title, and test dates.
  - 9) Except for the pull test, description of shake-table testing equipment (such as 2-D or 3-D) (Appendix B).
  - 10) Summary of results of supplemental work and options as listed in A.5.6 (Appendix C).
  - 11) Replica of identification plate.
  - 12) Seismic outline drawing.
  - 13) Except for the pull test, plots of the comparison of the TRS with the RRS.
  - 14) Tabulate summary table of maximum controlling stress, loads, and displacements (Appendix G).
- b) Main test results and test configuration
- 1) Create an instrumentation diagram showing the location of all instruments (Pictures in Appendix E, Calibration data in Appendix D).
  - 2) Test method.
  - 3) Functional tests needed.
  - 4) Except for the pull test, test sequence.
  - 5) Installation (support and anchorage).
  - 6) Other topics as requested or required.
- c) Detailed Test Results and Supporting Data (shake-table test)
- 1) Except for the pull test, frequencies and damping (Appendix F).
  - 2) Except for the pull test, input time histories (table accelerations).
  - 3) Tabulated list of maximum accelerations, stresses, and displacements at measuring points of all controlling tests (Appendix G).
  - 4) Summarize anchorage loads (Appendix H).
  - 5) Other topics, as requested or required.
- d) Functional requirements (Appendix I)
- e) Video (not required for the pull test)

#### **Detailed guide to report contents**

a) Key information and results

(Note that template contains additional information to that identified in A.5.3 to reflect the “as-tested configuration.” Items such as serial numbers, details of the support structure and anchorage, and the shake-table specifications, and instrument calibration have been added.)

- 1) Description of the equipment to be tested. This should include the general description, its operating voltage, its rated capacity, the drawing numbers for major seismically vulnerable components (such as the box and lid for instrumentation transformers, drawing numbers for porcelain or composite insulator components), the rated strength of critical components (such as porcelain insulators or the SML of composite insulator), serial number(s) of items that were tested. In Appendix A, show manufacturer's drawings of critical items with load limits, such as SML for composite insulators or ultimate strength of porcelain members. If static tests were done to establish capacity of complex components (see A.3) these tests should be

described in Appendix C and the results summarized in the body of the report. If drawings contain proprietary information, such as an instrumentation transformer box and lid, only the drawing number needs to be provided.

- 2) Describe the equipment configurations to be considered, such as switch open and/or switch closed, with or without associated cabinet, grounding links, etc. If the unit was tested with a corona ring, this should be noted along with its weight as well as weight, if any, that was added to the account for conductor connection pad and cable connection hardware.
- 3) Level to which the equipment has been qualified (i.e., High or Moderate; Performance Level or Design level Response Spectra), MAF or ETF value used).
- 4) Modifications required, if any, to pass the test.
- 5) Anomalies or damage observed during the tests. (Identify and indicate their significance to the qualification.)
- 6) List supplemental work and options (see A.5.6).
- 7) List of witness(es), and the company(ies) the witness(es) represented.
- 8) Test facility, name, location, telephone and fax numbers, email address, test engineer's name and title, and test dates.
- 9) Description of shake-table testing equipment (such as 2-D or 3-D) Detailed description should be placed in Appendix B.
- 10) Summary of results of supplemental work and options as listed in A.5.6 with supporting worksheets in Appendix C. (This might also include data associated with a pull test of composite insulator or the test of a complex component as described in A.3.)
- 11) Replica of identification plate.
- 12) Seismic outline drawing should be a full page drawing that contains all of the information called for in A.5.5. See example at the end of this annex.
- 13) Plots of the comparison of the TRS to the RRS of the qualifying input time histories and comments about the comparison if appropriate.
- 14) Tabulate summary table of maximum controlling stress, loads, and displacements (F), allowable capacities (f), and their margin (F/f), starting in order with the equipment component's smallest margin, for the support structure and equipment. (See the "Example of the Shake-Table—Summary of Maximum Controlling Stresses, Loads, etc." in this annex). The page numbers for the sources of these values should be extracted from the Laboratory Test Report (LTR) and cited in the table. Affiliated with this table should be a worksheet showing the calculation, where calculations are needed, and the allowable values should also be referenced to material contained in the document. This material should be placed in Appendix H. Also, document justification of the ultimate porcelain strength or maximum observed deflections of composites with pre- and post-vibration test pull test data. Measured critical variables associated with tests of parts with complex components should be compared with proof loads and shown in the table. The results of tests associated with parts with complex shapes should be summarized in the body of the report and data and supporting calculations contained in Appendix C.

[Note that the comparisons of the TRS and the RRS are given in Section a) 13) of this report.]

- b) Main test results and test configuration
  - 1) Create an instrumentation diagram showing the location of all instruments (strain gages, accelerometers, load bolts, etc.) on the equipment and support structure as they were installed during the test. Assign a number with each measuring device consistent with the nomenclature used in the test-laboratory report. Identify directions used in the report, such as front-back and side-side or x and y and show them on the instrumentation diagram. Generate a table, to be placed in Appendix D, giving the instrument number, instrument type (strain

gage or accelerometer, etc.), and date of calibration of all instrumentation. In Appendix E, show pictures extracted from the (LTR) or taken at the time of the test set up and instrumentation. Also, list other instrumentation that was used, such as that used for a pull test of composite insulators.

- 2) Test method (For example, time history and/or sine beat and 3-D or 2-D. If 2-D testing is used, this should be justified.)
  - 3) Functional tests needed (such as resistance of disconnect switch, or normal electrical test for capacitive-coupled voltage transformers).
  - 4) Test sequence Generate a table listing the test sequence and the excitation level associated with each test.
  - 5) Installation (support and anchorage) details including support structure plans, size, location, and material strength of the structural members, bolts, welds and plates. Note that the bolt pattern for the base plate and equipment support plate should also be shown on the seismic outline drawing.
  - 6) Other topics as requested or required.
- c) Detailed test results and supporting data (shake-table test)
- 1) Frequencies and damping from frequency search for pre- and post-tests (if conducted). Plots of search data from LTR should be referenced by page number from the LTR. Also, show results from man-shake and snapback test results and reference source data in the LTR, if applicable. Include calculations for damping estimates in Appendix F. These results should also be shown on the Seismic Outline Drawing.

[Note that the comparisons of the TRS and the RRS are given in Section a) 13) of this report.]
  - 2) Input time histories (table accelerations), and the various other response variable time histories that are used to support calculations not referenced elsewhere should be cited and calculations placed in Appendix G.
  - 3) Tabulated list of maximum accelerations, stresses, and displacements at measuring points of all controlling tests, including the results from the natural frequency search (See “Example of Data Measurement Points” in this annex). The response data supporting calculations, where needed, should be placed in Appendix G. All calculations should explicitly reference the data source from the LTR by page number.
  - 4) Summarize anchorage loads. The calculations used to obtain the reactions at the equipment and support anchorage should be in Appendix H. Source data supporting these calculations should be referenced by page number from the LTR. These results should be shown on the Seismic Outline Drawing.
  - 5) Other topics, as requested or required.
- d) Functional requirements: List of functional tests performed and all other required non-shake-table tests or monitoring, such as timing, resistance, or any production test. Certifications of functional or other tests needed to demonstrate functionality are to go into Appendix I.
- e) Video

**Table T.1—Shake-table tests—Summary of maximum stresses, loads, etc. (Appendix C)**

Component	Pg #	Location of component in equipment. Discussion of value	Type of test	Measured value (f)	Allowable value (F)	F---f

**Table T.2—Example (metric): Shake-table tests—Summary of maximum stresses, loads, etc. (Appendix C)**

Component	Pg #	Location of component in equipment. Discussion of value	Type of test	Measured value (f)	Allowable value (F)	F---f
Porcelain insulator	24	Base of porcelain insulator #1	Design level time history	3.62 kN-m	3.62 kN-m <sup>a</sup>	1.00
Porcelain insulator	25	Base of porcelain insulator #2	Design level time history	3.55 kN-m	3.62 kN-m <sup>a</sup>	1.02
Porcelain insulator	27	Base of porcelain insulator #3	Design level time history	3.25 kN-m	3.62 kN-m <sup>a</sup>	1.11
Steel support leg	30	Base of corner columns	Design level time history	175.1 MPa	200 MPa	1.14
Composite insulator	36	Insulator #4. Measured base moment test. Allowable values based on SML from insulator manufacturer	Design level time history	3.62 kN-m	3.62 kN-m <sup>b</sup>	1.00

<sup>a</sup> Porcelain insulator ultimate strength is 7.24 kN-m. Time history allowable moment =  $0.5 \times 7.24 = 3.62$  kN-m.

<sup>b</sup> Composite insulator SML moment is 7.24 kN-m. Allowable moment =  $0.5 \times 7.24 = 3.62$  kN-m.

**Table T.3—Example (inch-pound): Shake-table tests—summary of maximum stresses, loads, etc. (Appendix C)**

<b>Component</b>	<b>Pg #</b>	<b>Location of component in equipment. Discussion of value</b>	<b>Type of test</b>	<b>Measured value (f)</b>	<b>Allowable value (F)</b>	<b>F---f</b>
Porcelain insulator	24	Base of porcelain insulator #1	Design level time history	32 in-k	32 in-k <sup>a</sup>	1.00
Porcelain insulator	25	Base of porcelain insulator #2	Design level time history	31.4 in-k	32 in-k <sup>a</sup>	1.02
Porcelain insulator	27	Base of porcelain insulator #3	Design level time history	28.8 in-k	32 in-k <sup>a</sup>	1.11
Steel support leg	30	Base of corner columns	Design level time history	25.4 ksi	29 ksi	1.14
Composite insulator	36	Insulator #4. Measured base moment test. Allowable values based on SML from insulator manufacturer	Design level time history	32 in-k	32 in-k <sup>b</sup>	1.00

<sup>a</sup> Porcelain insulator ultimate strength is 64 in-k. Time history allowable strength =  $0.5 \times 64 = 32$  in-k.

<sup>b</sup> Composite insulator SML moment is 64 in-k. Allowable moment =  $0.5 \times 64 = 32$  in-k

**Table T.4—Tabulated list of maximum accelerations, stresses, and displacements for a CVT (Appendix G)**

Accelerometer	Direction	Location	Resonant	Page	Time history	Page
A1	FB	Table	-.71	52	-.71	90
A2	V	Table	.40	74	.40	85
A3	FB	Top of tank	-1.1	28	-1.1	115
A4	SS	Top of tank	-.13	96	-.13	32
A5	FB	Bushing (c.g.)	-1.4	81	-1.4	54
A6	SS	Bushing (c.g.)	.23	106	.23	67
A7	FB	Top of bushing	-2.0	37	-2.0	98
A8	SS	Top of bushing	.61	149	.61	2
A9	V	Top of bushing	.77	174	.77	34
Strain gauges (micro-strain) stresses—psi and bolt loads—lbs						
S1	FB	Pedestal base	12 354	15	12 354	99
S2	SS	Pedestal base	3509	29	3509	12
S3	FB	Bottom of bushing	3060	77	3060	56
S4	SS	Bottom of bushing	537	82	537	78
S Bolt	FB	Pedestal base	1822	66	1822	108
Displacements (inches)						
@A3	FB	Top of tank	1.6	130	1.6	24
@A5	FB	C.G. of bushing	1.5	44	1.5	56
@A7	FB	Top of bushing	-2.4	92	-2.4	79
@A8	SS	Top of bushing	1.0	37	1.0	156
@A9	V	Top of bushing	0	89	0	37

### Example of minimum information for test plan

- a) Description of equipment.
- b) Test facility name, location, telephone number, e-mail address, and test dates.
- c) Equipment (and support) set-up. Provide description and sketches or pictures.
  - 1) Setup in-service configuration.
  - 2) Anchorage of equipment base to shake-table (or to an adapter plate attached to shake-table) to be same as in-service configuration. (If adapter plate between equipment and table, then provide attachment details of adapter plate to table.)
  - 3) Discussion of equipment to be pressurized, filled with oil, gas, etc. and other conditional requirements, as applicable.
  - 4) Test equipment description (see 4.9) and calibration.
  - 5) Test method. Describe all tests to be performed (e.g., time history shake-table testing, resonant frequency search tests, and any other auxiliary tests required (refer to A.5).
- d) Functional test. Description of functional tests, including electrical hoop-ups, if any, and where test will be performed.
- e) Qualification level (moderate or high; performance or design level).
- f) Monitoring. Provide sketch(es) that show location of strain gauges, accelerometers, and displacement gauges, if any.
- g) Provide testing program sequence.

(Example: Disconnect switch with grounding switch and porcelain insulators. Test to be conducted on steel support structure at high performance level. Triaxial shake table is used. After each test, equipment to be inspected and results logged.)

- 1) Functional tests and setup equipment/support, install monitoring (E.4.1.2), and develop TRS (A.1.2.6).
  - 2) Static pull tests of porcelain insulators to calibrate strain gauges. Log data.
  - 3) Perform sine sweep in x, y, and z directions at 0.1 g and one octave per minute (A.1.2.5) with main contact closed/ground switch open (C-O). Repeat for main contact open/ground switch open (O-O), and main contact open/ground switch closed (O-C).
  - 4) Determine resonant frequencies and damping in x, y, and z directions.
  - 5) Perform time history in using High Performance Level input in 3 directions (C-O).
  - 6) Perform sine sweep in x, y, and z directions at 0.1 g and one octave per minute.
  - 7) Determine resonant frequencies in y axis and damping. Compare with pre-time history test measurements.
  - 8) Operate main contact and ground switch to ensure proper operation.
  - 9) Perform millivolt drop test. Verify that continuity during time history test. Visually inspect the equipment and document observations and anomalies.
  - 10) Repeat 3) through 9) for O-O and O-C positions.
- h) Video. Provisions made for video recording of all tests.

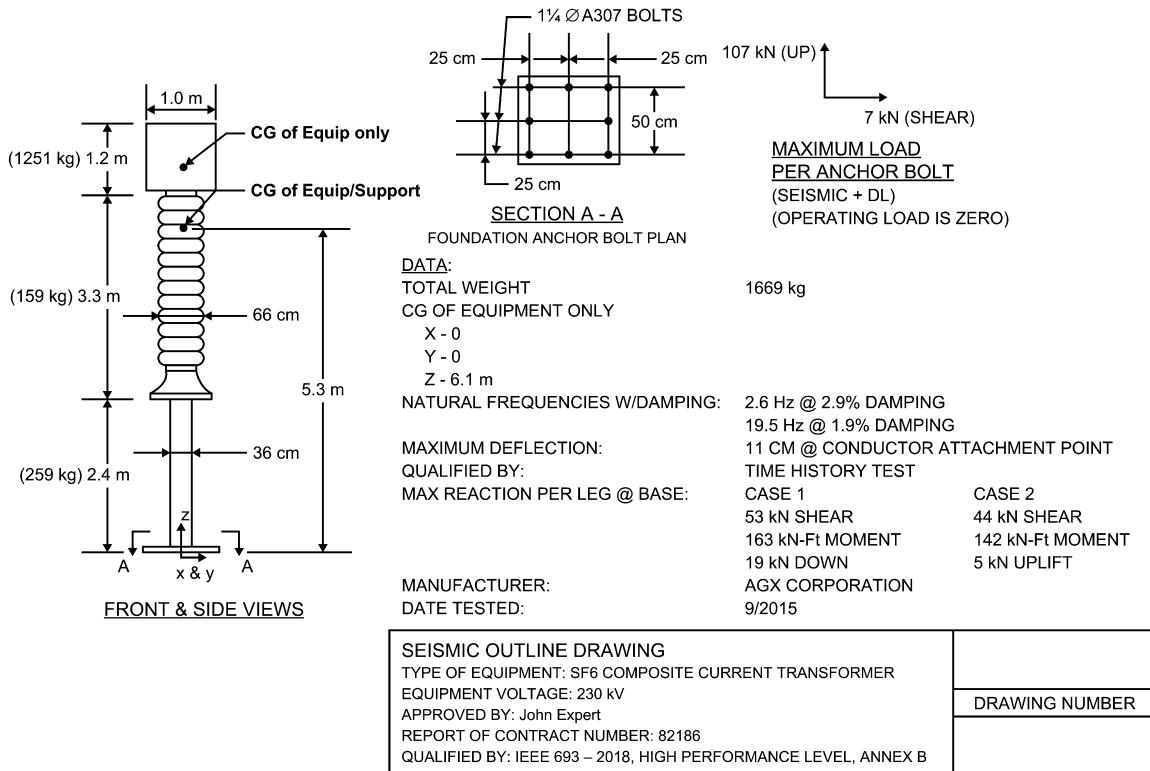


Figure T.1—Example (metric) of seismic test-qualification report

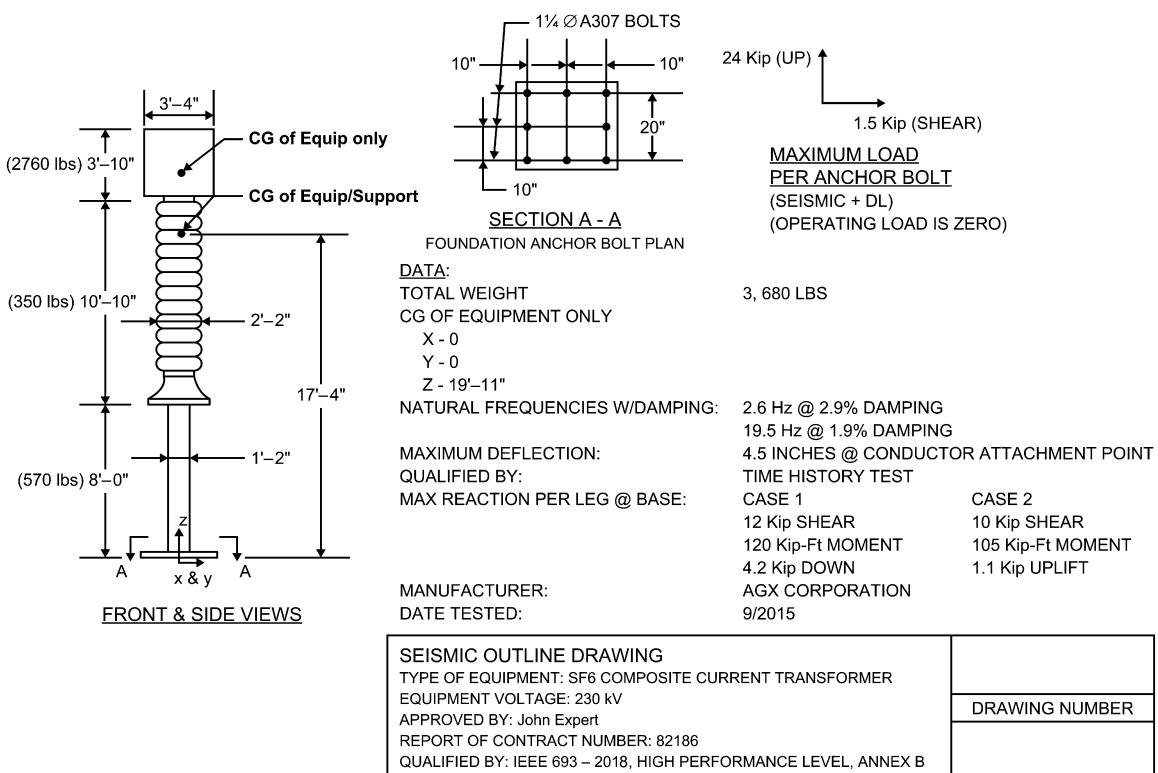


Figure T.2—Example (inch-pound) of seismic test-qualification report

## Annex U

(informative)

### Specifications

Subclause 4.3 provides the recommended wordage for specifying IEEE Std 693. This annex provides templates of that wordage in English.

This template may be translated into other languages as needed.

#### Specifying IEEE 693

##### ***For the following equipment (Annexes C through Annex P, Annex V, and Annex W):***

Circuit breakers Transformers Liquid filled reactors Disconnect switches Grounding switches Voltage transformers Capacitor voltage transformers Coupling capacitor voltage transformer Current transformer Station service voltage transformers Air core reactors Circuit switchers Suspended equipment Station batteries and battery racks	Surge arresters Remote terminal units Digital fault recorders Sequence of events recorders Intelligent electronic devices Distribution panels Switchboards Solid state rectifiers Metalclad switchgear Cable terminators (potheads.) Capacitors, series and shunt compensation Gas-insulated switchgear Low-voltage control, instrumentation, and power supply equipment DC equipment Equipment with seismic protective devices
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##### ***Use the following specification:***

The \_\_\_\_\_ shall

Insert one or more of the equipment types given above; include the support description, if a support is required.

**Be qualified according to the requirements of IEEE 693-201x and shall meet the requirements of the \_\_\_\_\_ qualification level. (See Figure 1.1—Using the recommended practice)**

Insert High or Moderate

*(If qualification is by testing, include the following): The test plan shall be submitted within \_\_\_\_\_ calendar days of award of contract and the test shall be completed within calendar days of award of contract. The report shall be submitted within \_\_\_\_\_ calendar days after testing is complete.*

*(If by analysis, include): The report shall be submitted calendar days after award of contract.*

##### ***For equipment not listed above, such as voltage divider or voltage regulator, use the following (Annex B):***

The \_\_\_\_\_ shall

Insert one or more of the equipment types given above; include the support description, if a support is required.

**Be qualified according to the requirements of IEEE 693-201x and shall meet the requirements of the \_\_\_\_\_ qualification level. This equipment requires the use of Annex B.**

Insert High or Moderate

**(See Figure 1.1—Using the recommended practice)**

**Qualification shall be by \_\_\_\_\_**

Method: such as time history testing, sine-beat testing, static analysis, coefficient analysis, or dynamic analysis.

**Monitoring shall be \_\_\_\_\_**

Monitoring requirements for qualification by test.

**Functional tests \_\_\_\_\_**

Give function tests requirements qualification by test or state "Functional tests are not required."

*(If qualification is by testing, include the follow): The test plan shall be submitted within \_\_\_\_\_ calendar days of award of contract and the test shall be completed within calendar days of award of contract. The report shall be submitted within \_\_\_\_\_ calendar days after testing is complete.*

*(If by analysis, include): The report shall be submitted calendar days after award of contract.*

## Annex V

(normative)

### DC equipment

#### V.1 General

##### V.1.1 Scope of applicability

The requirements of this annex are applicable to dc equipment in high voltage dc (HVDC) and flexible ac transmission systems (FACTS) substations. This annex applies to the equipment types listed in Table V.1 with the following conditions.

- For dc transformers and liquid filled reactors, wall/roof bushings, disconnect/grounding switches, air core reactors/smoothing reactors, surge arresters, and voltage dividers (items 1, 2, 3, 4, and 6 of Table V.1), the voltage level used to define the qualification method should be the next higher ac voltage class compared to the dc system voltage.
- Shake-table testing should be used for dc high-speed switches (item 5 of Table V.1), and the ac voltage classes of Annex C should be disregarded.

**Table V.1—Seismic qualification methods for dc equipment**

Type	Substation category	Reference
DC transformers and liquid filled dc reactors	HVDC/FACTS	Annex D
DC wall / dc roof bushings	HVDC/FACTS	Annex D
DC disconnect switches / dc grounding switches	HVDC	Annex E
DC air core reactors / smoothing reactors	HVDC	Annex G
DC high speed switches	HVDC	Annex C
DC surge arresters / voltage dividers	HVDC	Annex K
DC filters		
7.1 DC filters towers	HVDC	Table V.2
7.2 Capacitor cans	HVDC	Table V.2
HVDC converters		
8.1 Valve towers	HVDC	Table V.2
8.2 Valve modules	HVDC	Table V.2
9. SVC converters		
9.1 Converter racks	FACTS	Table V.2
9.2 Power modules	FACTS	Table V.2
10. Cooling systems		
10.1 Cooling and protection cubicles	HVDC/FACTS	Annex L
10.2 Piping	HVDC/FACTS	Table V.2
10.3 Pump skids	HVDC/FACTS	Table V.2
10.4 Coolers	HVDC/FACTS	Table V.2
11. Control systems	HVDC/FACTS	Annex L

##### V.1.2 High seismic qualification level

The requirements of Annex V, with the exception of V.1.3 and V.1.4, are applicable to all dc equipment for qualification to the high seismic level.

### **V.1.3 Moderate seismic qualification level**

The requirements of Annex V, with the exception of V.1.2 and V.1.4, are applicable to all dc equipment for qualification to the moderate seismic level.

### **V.1.4 Low seismic qualification level**

Only the requirements of A.1.1.9 are applicable all dc equipment for qualification to the low seismic level.

## **V.2 Operational requirements**

The equipment and supporting structure shall be designed to meet the seismic qualification objectives described in 5.2. In addition, equipment shall maintain the correct operational state during the seismic event.

## **V.3 Seismic qualification methods and finite element analysis modeling techniques**

### **V.3.1 Seismic qualification methods for equipment comparable to ac equipment**

DC equipment that is comparable to ac equipment shall be qualified in accordance with the applicable annex shown in Table V.1.

### **V.3.2 Seismic qualification methods and techniques for equipment not comparable to ac equipment**

#### **V.3.2.1 Seismic qualification methods**

Seismic withstand capability for equipment not comparable to ac equipment shall be demonstrated according to the methods tabulated in Table V.2.

**Table V.2—Qualification methods**

Type	Method	Acceptance criteria
DC filters		
7.1 DC filter towers	Dynamic analysis	A.2.1
7.2 Capacitor cans	Dynamic analysis	A.2.1
HVDC converters		
8.1 Valve towers	Dynamic analysis	A.2.1
8.2 Valve modules	Performance level time history shake-table test	A.2.2
SVC converters		
9.1 Converter racks	Dynamic analysis	A.2.1
9.2 Power modules	Performance level time history shake-table test	A.2.2
Cooling systems		
10.2 Piping	Dynamic analysis	A.2.1 (see NOTE 1)
10.3 Pump skids	Dynamic analysis	A.2.1 (see NOTE 2)
10.4 Coolers	Dynamic analysis	A.2.1 (see NOTE 2)

NOTE 1—Nominal loads from the appropriate code should be considered in combination with the seismic loads.

NOTE 2—While both earthquake loads and acceptance criteria are determined from this recommended practice, normal operating loads may be referenced from other appropriate codes and should be combined as specified in A.2.1.

### **V.3.2.2 Equipment supported in buildings or elevated structures**

In cases where the equipment, or the equipment with its dedicated support, are supported in a building or elevated structure (that is they are not subjected to the ground accelerations), an, in-structure response spectra or in-structure time history input motion may be used for qualification (refer to ASCE 4-16, Section 6.2 and Section 6.3). In-structure spectra or motions shall be developed through time history ground motions using the damping values appropriate for the type of building or structure (refer to ASCE 4-16, Section 3.2.2 or ASCE 113). The damping parameters assigned to the equipment and its dedicated support shall conform to the requirements of A.1.1.6.

### **V.3.2.3 Equipment/supports with tension-only members**

Systems that are qualified by analysis and have tension-only members shall be qualified by nonlinear time history analysis unless it is demonstrated that such members will not be subjected to compression forces up to performance level loading. This type of system is often used for bracing of converter racks, standing thyristor valve towers, and standing dc filters.

### **V.3.2.4 Suspended equipment**

In case of HVDC suspended systems, seismic qualification is achieved via a direct integration time history analysis. Examples of HVDC suspended systems include suspended valve towers and suspended dc filters. In some cases, additional restraints at the bottom of the equipment may be required to limit horizontal displacements or uplift.

### **V.3.2.5 Equipment integrated multiple times into the main equipment**

The applied response spectra shall be an envelope of all in-structure response spectra of all attachment points to reduce the number of tests or analyses. This type of system includes the capacitors of the dc filter, the valve modules of the valve tower and the power modules of the converter.

### **V.3.2.6 Equipment with in-structure acceleration demands too high to be tested at the performance level**

The preferred testing for equipment is always at the performance level. However, if the performance level in-structure response spectrum is too high to be tested, a design level in structure response spectra may be used. Should design level testing be required, the acceptance criteria should revert to that specified in A.2.1.4.

### **V.3.2.7 Equipment with frequency demands too low to be tested**

In the case that the first mode of the equipment is too low to be tested (that is the TRS cannot be enveloped in the low frequency range), the qualification shall be done by a combination of testing and analysis provided that the shake table test can, as a minimum, envelope the TRS at 1 Hz.

The results of the modified shake-table tests shall compare favorably to the projections of a theoretical model of the equipment. The judgment of reasonable concordance between the results shall be agreed upon by the end user. Upon verification of the accuracy of model, an analysis will be conducted to simulate the equipment to the full spectrum/time history.

### V.3.3 Finite element analysis modeling techniques

#### V.3.3.1 Simplifications to FE analysis model

The allowable simplifications for finite element analysis models are summarized in Table V.3.

**Table V.3—Simplifications for FE model**

Type	Acceptable simplifications
DC filters	
DC filter towers	—Separation between gantry and dc filter FEM —The capacitor cans are modeled as lumped mass
Capacitor cans	—The mass of the internal parts are modeled as distributed mass in the cover of the cans
HVDC converters	
Valve towers	—Separation between building and valve tower FEM —The valve modules are modeled as lumped mass
Valve modules	—In case that analysis is required (V.3.2.1), a separation between the valve tower and the valve modules is acceptable
SVC converters	
Converter racks	—Separation between building and converter rack FEM —The power modules are modeled as lumped mass
Power modules	—In case that analysis is required (V.3.2.1), a separation between the converter rack and the power module is acceptable
Cooling systems	
Piping	—The pipes are modeled as frames —The flange connections are checked using cross-sectional loads
Pump skids	—The pipes are modeled as frames —The pipe flange connections are checked using cross-sectional loads —The pump is modeled as lumped mass —The fluid is modeled as line mass
Coolers	—The internal pipes are modeled as lumped mass at the attachment points to the structural elements of the cooler

#### V.3.3.2 Criteria to combine or separate building/structure and equipment FEM

One option is to develop a combined model of the building including the valve tower (or the gantry including the dc filter). In this case, a detailed model of the building (or gantry) is not required, provided that the simple model adequately represents the major effects of interaction between the two components.

If the criteria for a decoupled model between equipment and building according to ASCE 4-16, Section 3.7 are fulfilled, the finite element model of the building (or gantry) can be decoupled from the FE-model of the equipment. In this case, an in-structure response spectra or in-structure time history input motion needs to be developed as described in V.3.1.

## V.4 Qualification procedures

### V.4.1 Qualification procedure for time history shake-table testing

#### V.4.1.1 General

The qualification procedures shall be according to the requirements of A.1. The equipment shall be tested according to the requirements of A.1.2. A resonant frequency search shall be performed according to the requirements of A.1.2.5.

#### V.4.1.2 Monitoring requirements for time history shake-table testing

Monitoring requirements are described in A.2.2 and A.2.4.5.

### V.4.2 Qualification procedure for dynamic response spectrum analysis

Dynamic response spectrum analysis shall be performed in accordance with A.1.4.7.

### V.4.3 Qualification procedure for linear time history analysis

Linear time history analysis shall be performed in accordance with A.1.4.8.

### V.4.4 Qualification procedure for nonlinear time history analysis

A minimum of three triaxial earthquake ground motion records, determined in accordance with the requirements of A.1.4.8.3, shall be used. Critical values used in the resulting qualification shall be taken as the maximum determined from the three records.

### V.4.5 Qualification procedure for static coefficient analysis

Static coefficient analysis shall be performed in accordance with the requirements of A.1.4.6.

### V.4.6 Qualification procedure for static analysis

If the equipment is deemed to be rigid, a static analysis in accordance to A.1.4.5 may be used.

## V.5 Acceptance criteria

The qualification will be considered acceptable if the requirements given in A.2 are met. Additional guidance with regards to the acceptance criteria for equipment not comparable to ac equipment is tabulated in Table V.2.

Maximum deflections for suspended and suspended restraint components shall be checked at the performance level against the electrical clearance requirements (6.8).

## **V.6 Design requirements**

The equipment shall be designed in accordance with A.4. For equipment not comparable to ac equipment, additional design requirements may apply as referenced in Table V.2.

## **V.7 Report**

### **V.7.1 Report for seismic test qualification**

The report shall be in accordance with the requirements of A.5.

### **V.7.2 Report for seismic analysis qualification**

The report shall be in accordance with the requirements of A.6.

## **V.8 Seismic identification plate**

A seismic identification plate shall be attached to each piece of equipment supplied. The plate shall be as specified in A.7.

## Annex W

(normative)

### Equipment with seismic protective devices

#### W.1 General

##### W.1.1 General requirements

The requirements of Annex W are applicable to the seismic qualification of equipment which makes use of seismic isolation or damping devices as defined in W.1.3. In this recommended practice, seismic isolation and damping devices are referred to as “seismic protective devices” and the collection of seismic protective devices is referred to as a “seismic protective system.”

##### W.1.2 Application of seismic protective devices

The use of seismic protective devices can produce lower seismic demands on equipment and its supports, and thus seismic protective devices may allow for the qualification of equipment that may otherwise not be able to be qualified. Examples of substation equipment that may benefit from the use of seismic protective devices include transformers and circuit breakers.

##### W.1.3 Types of seismic protective devices

Seismic protective devices for substation equipment may be classified into three groups, as defined below. It may be that a device has features that make it suitable for use in more than one group.

- a) *Seismic isolation devices*: Used to uncouple the supported equipment from the earthquake ground motion. The use of this type of seismic protective device creates an “isolated” response with a frequency lower than the natural frequency of the equipment itself and results in lower seismic forces experienced by the equipment. Seismic isolation devices usually also possess some damping to moderate the displacement response. It is usual that seismic isolation will significantly reduce the horizontal forces experienced by the equipment. Examples of seismic isolation devices include elastomeric and sliding bearings.
- b) *Rocking seismic isolation devices*: Used to uncouple the supported equipment from the earthquake ground motion and create a primarily rigid-body rocking mode of response. This rocking response has a frequency lower than the natural frequency of the equipment and results in lower seismic forces experienced by the equipment. Rocking seismic isolation devices may possess some damping. Examples of rocking seismic isolation devices include wire rope isolators and spring isolators.
- c) *Damping (or energy dissipation) devices*: Used to add supplemental damping to the equipment. The additional damping dissipates seismic energy and reduces the force and deformation demands on the equipment. Damping devices may also cause some change in equipment response frequencies, but this change is not the primary feature of this type of seismic protective device. Examples include viscous dampers, metallic hysteretic dampers, and friction dampers.

#### **W.1.4 User specified criteria for seismic protective devices**

Design criteria for the seismic protective devices not defined in this annex or elsewhere in this recommended practice shall be specified by the user. Such criteria may include deflection limits and/or non-movement criteria under non-seismic loads such as wind.

### **W.2 Seismic qualification methods**

For seismic isolation and rocking seismic isolation devices, the change in frequency of the equipment with the devices may be such that performance level shake table qualification testing may be not be feasible due to shake-table limitations. The most common shake-table limitation is insufficient displacement capacity for the lower frequency motion necessary to satisfy the requirement of A.1.2.6.d). As such, a specialized qualification program is described in this annex to allow for qualification of equipment with these types of devices.

For equipment protected with damping devices, shake-table performance limits are generally not a limitation. Therefore, when only damping devices, and no other type of seismic protective device, are used, the requirements of the applicable equipment annex shall apply, including any requirements for shake-table testing.

The qualification method for equipment with seismic protective devices depends on the equipment classification as follows:

- a) *Category 1* equipment is that for which the recommended practice allows qualification by analysis. This includes equipment of voltage ratings less than 170 kV and equipment that is too heavy or too complex to allow for shake-table testing.
- b) *Category 2* equipment is that for which the recommended practice requires qualification by shake-table testing, and which is able to be tested considering the seismic protective system characteristics and shake-table performance limits.
- c) *Category 3* equipment is that for which the recommended practice requires qualification by shake-table testing, but which is not able to be tested considering the seismic protective system characteristics and shake-table performance limits.

### **W.3 Qualification procedures**

#### **W.3.1 Seismic qualification of Category 1 equipment**

##### **W.3.1.1 General requirements for Category 1**

The seismic qualification method for Category 1 equipment shall be by a combination of dynamic analysis and testing of the seismic protective devices.

##### **W.3.1.2 Dynamic analysis**

Analysis of Category 1 equipment shall comply with the requirements of W.5.

### **W.3.1.3 Testing of seismic protective devices**

All seismic protective devices for Category 1 equipment shall be tested in accordance with the requirements of W.4.1 through W.4.3. The test results shall be used to establish the device force-displacement relationship for the dynamic analysis, and shall verify that the seismic protective devices have the required displacement and force capacities determined from the analysis.

### **W.3.1.4 Acceptance criteria**

The design level acceptance criteria defined in the relevant equipment annex shall be satisfied.

Evaluation of equipment forces or stresses, including appendages and their connections to transformers and liquid-filled reactors, shall be made for the demands resulting from analysis at the design level of the equipment with the seismic protective system.

Equipment displacements shall be those obtained from an analysis of the equipment with the seismic protective system at the performance level.

The seismic protective device tests shall satisfy the acceptance criteria requirements of W.4.2.3 and W.4.3.

## **W.3.2 Seismic qualification of Category 2 equipment**

### **W.3.2.1 General requirements for Category 2**

The seismic qualification method for Category 2 equipment shall be by shake-table testing per requirements of A.1.2. The complete equipment, including the seismic protective system, shall be tested. In addition, tests of the seismic protective devices shall be separately conducted as outlined in W.3.2.

### **W.3.2.2 Shake-table test level**

Shake-table tests shall be conducted to the performance level. Testing shall be in accordance with the requirements of A.1.2.

### **W.3.2.3 Testing of seismic protective devices**

All seismic protective devices for Category 2 equipment shall be tested in accordance with the requirements of W.4.1 through W.4.3.

### **W.3.2.4 Acceptance criteria**

The acceptance criteria defined in the relevant equipment annex of the recommended practice shall be satisfied. The acceptance criteria for performance level tests shall be as specified in A.2.2. The seismic protective device tests shall satisfy the acceptance criteria requirements of W.4.2.3 and W.4.3.

### **W.3.3 Seismic qualification of Category 3 equipment**

#### **W.3.3.1 General requirements for Category 3**

The seismic qualification method for Category 3 equipment shall use a combination of equipment shake-table testing, seismic protective device testing, and dynamic analysis of the seismically protected equipment. This method is included in the recommended practice to allow the implementation of a seismic protective system for equipment when it is not possible to perform shake-table tests due to shake-table performance limitations (e.g., in the case of protected equipment with a fundamental frequency such that it is not possible to satisfy the requirement of A.1.2.6.d). The specific details of this qualification method shall be at the discretion of the user or the user's agent.

#### **W.3.3.2 Testing of seismic protective devices**

All seismic protective devices for Category 3 equipment shall be tested in accordance with the requirements of W.4.1 through W.4.3.

#### **W.3.3.3 Shake-table testing**

Conduct shake-table testing of the equipment not including the seismic protective devices and qualify the equipment to a chosen ZPA level using the procedure of Annex A. The level need not correspond to one of the discrete qualification levels (0.25 g, 0.5 g). The test response spectrum shall satisfy the requirements of A.1.2.6 except that the spectral ordinates shall be scaled by a single scale factor to achieve the chosen ZPA.

#### **W.3.3.4 Analysis of equipment not including seismic protective devices**

Perform dynamic analysis of the equipment not including the seismic protective devices to the chosen ZPA level achieved in the shake-table testing in W.3.3.3. Use the shake-table test results to validate the numerical model of the equipment that will subsequently be used for the dynamic analysis of the equipment with the seismic protective devices. All significant modeling assumptions required to obtain adequate comparison with the shake-table test results shall be described in the qualification report. The method of validation and the adequacy of the model should be subject to the review and approval of the design review of W.7.2, if undertaken.

#### **W.3.3.5 Dynamic analysis of equipment with seismic protective devices**

Perform dynamic analysis of the equipment with the seismic protective devices to the desired qualification level, in accordance with the requirements of W.5.

#### **W.3.3.6 Acceptance criteria**

The equipment with the seismic protective devices is qualified to the desired qualification level if the key equipment responses (displacements, forces, stresses, accelerations, reactions, etc.) resulting from the dynamic analysis of W.3.3.5 at the desired qualification are not greater than the corresponding responses that have been shown to be acceptable from the shake table testing of W.3.3.3. If analysis is conducted to the performance level, acceptance criteria for the shake table testing of W.3.3.3 shall meet performance level criteria.

The seismic protective device tests shall satisfy the acceptance criteria requirements of W.4.2.3 and W.4.3, as applicable.

## **W.4 Requirements for testing of seismic protective devices**

### **W.4.1 General requirements**

The requirements for testing of seismic protective devices as required by W.3.1, W.3.2, and W.3.3, are defined in W.4.1 through W.4.5. Devices shall be subjected to two types of test: prototype tests and production tests.

Prototype tests are performed to identify properties and confirm capacity to resist the required design forces and displacements. In lieu of prototype testing of devices for each equipment application, data from previous testing of similar devices may be considered, subject to the approval of the user or the user's agent. Minimum prototype testing requirements shall comprise the tests defined in W.4.2.

Production tests are performed on all devices to be used in the construction. Minimum production testing requirements shall comprise the tests defined in W.4.3.

Prototype and production tests are defined in terms of increments of the performance level displacement,  $D_{PL}$ , which is the maximum seismic protective device displacement determined from the shake-table tests, or analyses, depending upon the applicable equipment category.

### **W.4.2 Prototype tests**

#### **W.4.2.1 General**

Prototype tests shall be performed separately on two full-size specimens of each type and size of seismic protective device in the protective system.

The protective system components to be tested shall include those components, if any, included in the system to resist wind loads.

Specimens tested shall not be used for construction unless accepted by the designer of the equipment and protective system and the user or the user's agent.

For each cycle of each test, the force-deflection behavior of the test specimen shall be recorded.

#### **W.4.2.2 Sequence and cycles**

The following sequence of tests shall be performed:

- a) Five fully-reversed cycles of loading at each of the following increments of the performance level displacement,  $D_{PL}$ ,—0.25, 0.5, and 1.0.
- b) Five fully-reversed cycles of loading at 1.1 times  $D_{PL}$ .
- c) Fifteen fully-reversed cycles of loading at 0.75 times  $D_{PL}$ .
- d) If a seismic protective device is also a vertical-load-carrying element, then one fully-reversed cycle of loading at 1.1 times  $D_{PL}$  and with a vertical load of 1.0 times the vertical load including the

effects of seismic overturning, where the vertical load is the maximum for all devices of a common type and size.

- e) If the specified wind load on the equipment results in movement of the seismic protective device, twenty fully-reversed cycles of loading at a lateral force corresponding to the specified wind load.

The tests of items a) through c) above shall be performed at a frequency equal to the frequency of the fundamental mode of the protective system. In the case of damping devices, the test frequency shall be the equipment frequency associated with the predominant response of the damping devices. If the force-deflection properties of the seismic protective device are not dependent on rate of loading, the tests of items a) through c) above need not be dynamic.

If a seismic protective device is also a vertical-load-carrying element, then item a) of the sequence of cyclic tests specified above shall be performed for the following:

- The average dead load on all devices of a common type and size.
- The maximum vertical load including the effects of seismic overturning. The vertical load shall be taken as the average maximum downward force on all devices of a common type and size.
- The minimum vertical load including the effects of seismic overturning. The vertical load shall be taken as the average minimum downward force on all devices of a common type and size.

If the seismic protective device properties are sensitive to direction of loading, then the tests of items f) through h) above shall be performed in the primary directions of sensitivity to appropriately characterize the device properties.

#### **W.4.2.3 Acceptance criteria**

The performance of the prototype test specimens shall be evaluated in terms of effective stiffness, energy dissipated per cycle and stability, where:

- The effective stiffness of a device is  $(|F^+| + |F^-|) / (|D^+| + |D^-|)$ , where  $F^+$  and  $F^-$  are the positive and negative forces at displacements  $D^+$  and  $D^-$ , respectively.
- Energy dissipated per cycle is the area of the device force-displacement hysteresis loop for one fully-reversed cycle of loading.

The following conditions shall be satisfied:

- a) The average device effective stiffness and energy dissipated per cycle for the five cycles of test of item a) of W.4.2.2 at a displacement of 1.0 times  $D_{PL}$ , shall be within 15% of the values used in the design.
- b) For each increment of test displacement specified in item a) of W.4.2.2, and for each vertical load case specified in W.4.2.2, if applicable.
  - 1) For each test specimen, the difference between the effective stiffness at each the five cycles of test and the average value of effective stiffness is no greater than 15%.
  - 2) For each cycle of test, the difference between effective stiffness of the two test specimens of a common type and size of seismic protective device and the average effective stiffness is no greater than 15%.
- c) For each specimen there is no greater than a 20% change in the initial effective stiffness over the cycles of test specified in item c) of W.4.2.2.
- d) For each specimen there is no greater than a 20% decrease in the initial effective damping over the cycles of test specified in item c) of W.4.2.2.

- e) All specimens of vertical-load-carrying seismic protective devices remain stable for item d) of W.4.2.2.
- f) The maximum device deformation under the lateral load corresponding to the specified wind load shall be identified from the test data and confirmed as acceptable by the user or the user's agent.

#### **W.4.2.4 Similarity**

Prototype tests need not be performed if a seismic protective device, when compared to another tested device, complies with all of the following criteria:

- a) The device design is not more than 15% larger nor more than 30% smaller than the previously tested prototype, in terms of governing device dimensions; and
- b) Is of the same type and materials; and
- c) Has an energy dissipated per cycle that is not less than 85% of the previously tested device; and
- d) Is fabricated by the same manufacturer using the same or more stringent documented manufacturing and quality control procedures.

The prototype testing exemption above shall be approved by the user or the user's agent, and the design review of W.7.2, if undertaken.

#### **W.4.3 Production tests (routine tests)**

All seismic protective devices used in the construction shall be subjected to a production test program prior to installation. The production test program may be incorporated in the device manufacturer's quality control program, and shall evaluate the consistency of the properties of the devices used in the construction with those properties assumed in the design. Unless otherwise approved, at a minimum, the production test program shall comprise three fully-reversed cycles of loading 1.0 times the performance level displacement,  $D_{PL}$ . If the force-deflection properties of the seismic protective device are not dependent on rate of loading, the production tests need not be dynamic. Unless otherwise permitted by the designer of the protective system and the independent design review, the results of the production test of each device shall be within 15% of the value assumed in the design. For devices with characteristics based upon metallic yielding, the above test may not be appropriate (for devices to be used in the construction) and alternative production testing procedures should be defined in accordance with W.4.4.

#### **W.4.4 Other types of devices**

For any type of seismic protective device or system that cannot be adequately characterized and tested in accordance with W.4.2 and W.4.3, alternate prototype and production test programs may be proposed by the device manufacturer. Any alternative test program shall be approved by the user or the user's agent, and the design review of W.7.2, if undertaken.

#### **W.4.5 Additional test requirements**

Prototype tests of seismic protective devices shall be performed by, and reported on, by an independent testing facility; or if performed by the manufacturer, the tests shall be observed by an independent third-party who shall also verify the accuracy of the test report. Prototype and/or production tests may be observed by and at the discretion of the user or the user's agent.

Sufficient instrumentation shall be used in the device prototype and production tests to ensure that the force-deflection properties of the device are accurately measured for all cycles of all tests.

## **W.5 Dynamic analysis**

### **W.5.1 Analysis method**

#### **W.5.1.1 General**

Methods and modeling procedures for dynamic analysis as required by W.3.1, W.3.2, and W.3.3 are defined in the W.5.1.1 through W.5.1.3. A dynamic method of analysis shall be used for equipment with seismic protective devices. As permitted below, response spectrum analysis may be used for some types of equipment and seismic protective devices, otherwise time-history analysis shall be used in all cases.

#### **W.5.1.2 Response spectrum analysis**

Response spectrum analysis, in accordance with the requirements of A.1.4.7, may be used when all of the following conditions are satisfied:

- a) The force-deformation characteristics of the seismic protective devices are amenable to modeling by equivalent linearization;
- b) The equipment is regular in configuration, and geometric nonlinearities associated with large deformations (such as P-delta effects and others) are not expected;
- c) In the case of isolation-type protective systems, the maximum seismic response does not develop tension or uplift forces that cause separation at the devices or equipment supports; and
- d) The use of response spectrum analysis is approved by the user or the user's agent, and the design review of W.7.2, if undertaken.
- e) The combined damping of the equipment and protective devices in the important modes of responses does not exceed 20%.

#### **W.5.1.3 Time-history analysis**

As required for Category 1 and Category 3 equipment, time-history analysis at both the design and performance levels is required for qualification of the equipment with the seismic protective system.

Time-history analysis shall be performed in accordance with the requirements of A.1.4.8.

## **W.5.2 Equipment modeling**

The equipment may be modeled as linear if analysis shows that the equipment remains elastic. If the behavior of any components of the equipment is expected to be in the inelastic range, then such components shall be modeled as nonlinear.

## **W.5.3 Seismic protective device modeling**

The seismic protective devices shall be modeled considering the force-deformation and force-velocity characteristics demonstrated by the seismic protective device tests of W.4, as applicable.

For response spectrum analysis as allowed under W.5.1.2, appropriate equivalent linear properties of the seismic protective devices shall be determined consistent with the level of expected device deformation under seismic loading.

#### **W.5.4 Damping**

For time-history analysis, an inherent damping of 2% (unless a different value is substantiated per A.1.1.6) shall be used for the equipment, not including the seismic protective devices.

For response spectrum analysis, equivalent modal damping shall be established from the results of the seismic protective device tests of W.4 and A.1.1.6, as applicable, and subject to the review and approval of the design review of W.7.2, if undertaken.

#### **W.5.5 Bounding analysis**

To account for variations in the seismic protective device properties due to effects such as manufacturing variability, environmental and aging effects, and property variability due to loading frequency, temperature or other phenomena, bounding analysis shall be performed. Variations in device properties such as stiffness and damping shall be determined from manufacturer's test data, and component tests of the seismic protective devices. Engineering evaluations and additional analyses, called bounding analyses, shall be performed for appropriate values of the expected upper and lower bound values of the device properties. The lower bound value of device property shall not be greater than 85% of the nominal value and the upper bound of device property shall not be less than 120% of the nominal value, where the nominal value of any device property is the manufacturer's recommended, standard design value, or the mean value obtained from the device prototype tests.

The equipment, seismic protective devices, and the connections between the seismic protective devices and the equipment or foundations shall be designed for the maximum forces resulting from the bounding analysis.

#### **W.5.6 Input motion**

##### **W.5.6.1 Response spectrum analysis**

The response spectrum of Figure A.1 or Figure A.2, applicable to the intended level of qualification, shall be used.

##### **W.5.6.2 Time-history analysis**

A minimum of three sets of triaxial earthquake ground motion records, determined in accordance with the requirements of A.1.4.8.3, shall be used.

It is recognized that ground motion time histories compatible with the spectra of Figure A.1 or Figure A.2 may not include appropriate shaking characteristics for special conditions such as very near-fault locations or long-duration, subduction-type events. For design locations subject to such special conditions, it may be appropriate to develop site-specific, time-history records for design. The development and application of such site-specific records shall be subject to the review and approval of the user or the user's agent, and the design review of W.7.2, if undertaken.

## **W.6 General requirements for seismic protective devices**

### **W.6.1 Displacement capacity**

The seismic protective devices shall have a displacement capacity (and velocity capacity for velocity-dependent devices) of at least 1.1 times the performance level displacement,  $D_{PL}$ . The calculation of maximum displacement shall use those device property values from the bounding analyses per W.5.5 that result in the largest displacement values.

### **W.6.2 Vertical stability**

Seismic protective devices that carry equipment gravity loads shall have either uplift resistance capability or provisions to accommodate the expected uplift displacement without compromise to the device behavior.

### **W.6.3 Re-centering**

The seismic protective system shall have sufficient restoring capability to return the equipment to its original position after a performance-level seismic event. A residual displacement at the equipment-conductor attachment location(s) of not more than 0.1 times the performance level displacement,  $D_{PL}$ , is considered acceptable subject to review and approval of the user or the user's agent, and the design review of W.7.2, if undertaken.

### **W.6.4 Wind, fault, and other loads**

The seismic qualification method for Category 1 equipment shall be by a combination of dynamic analysis and testing of the seismic protective devices.

### **W.6.5 Equipment interconnection and clearances**

Conductors and other equipment interconnection shall be designed to accommodate at least 1.1 times the performance level displacement,  $D_{PL}$ . If equipment component flexibility contributes to interconnection demands, the additional displacement due to component flexibility shall also be accommodated.

### **W.6.6 Long-term variation of device properties**

The variation of the seismic protective device stiffness and damping properties over the life of the equipment shall be accounted for in the bounding analysis.

### **W.6.7 Variation of device properties due to temperature and other environmental factors**

Variation of device properties considered under W.5.5 shall include seasonal temperature effects for the equipment installation location, as defined by the user or the user's agent. This variation shall be accounted for in the bounding analysis. As defined by the user or the user's agent, the devices shall have proper protection from moisture, rain, snow, ice and other environmental factors if their properties can be affected by these factors. If the environmental protection cannot be provided, the variation of the device properties shall be accounted in the bounding analysis.

## **W.6.8 Installation quality assurance**

The manufacturer shall provide an installation manual that describes all requirements for installation of the seismic protective devices, including requirements for alignment and adjustment at the time of installation, if necessary. The seismic protective devices shall not require long-term adjustment after initial installation.

## **W.6.9 Maintenance**

Seismic protective devices shall be designed for the expected life of the equipment. The expected life shall be taken as 30 years, or as defined by the user or the user's agent. Maintenance requirements shall be considered by the designer, and such requirements shall be clearly defined to the user or the user's agent. The device manufacturer shall provide a periodic inspection and maintenance manual to the user or the user's agent as part of the supply of the devices. The manual shall include any special requirements for post-earthquake inspection of the devices.

# **W.7 Designer qualifications and review**

## **W.7.1 Designer qualifications**

The designer of the seismic protective system for the equipment shall be an engineer with expertise in the use of seismic protective devices and systems and the seismic design and analysis of the equipment.

## **W.7.2 Design review**

In consideration of the complexity of much substation equipment and the application of seismic protective devices thereto, it is highly recommended that a third-party review of the design of the seismic protective system be undertaken. The review should be performed by an expert in the use of seismic protective devices who is independent of the manufacturer(s) of the equipment and the seismic protective system, and who is selected by the user or the user's agent. The scope of the review should include the modeling of the devices and analysis, the results of the testing of the seismic protective devices, the results of shake-table testing of the equipment if performed, and the general suitability for use of the seismic protective system considering site-specific conditions such as site response and input motion.

## Annex X

(normative)

### Insulator seismic strength criteria

#### X.1 General

This annex is a normative annex and establishes the criteria for the determination of the strength capability of insulators or bushings subjected to stresses dominated by bending. Suspension-type insulators and uncemented center-clamped porcelain bushings (X.8.1.3, X.9.1.2) are not covered by this annex. These strength capabilities will be the basis of the determination of the acceptability of the insulator or bushing in conjunction with the acceptance criteria given in A.2.1.2.a) and A.2.1.2.b).

Insulator strength criteria have traditionally been developed for load conditions that occur regularly during the insulator life cycle (e.g., gravity, line tension, or frequently-occurring wind). Insulators and other load-carrying structural elements should be designed with elevated factors of safety against their ultimate capacities when subjected to such ordinary or normal load conditions in order to achieve adequate performance and low risk of failure. For extreme load conditions such as large earthquake, the design of insulators and other structural elements may employ lower factors of safety against their ultimate capacities since the risk of their failure is mitigated by the low occurrence rates of such extreme events.

Insulator strength ratings may sometimes be based upon a limited sample size, or tied to technical reference standards. In these situations, the rated strength may not reliably reflect the capacities that occur in practice.

For design level seismic qualifications, this recommended practice specifies a factor of safety of 2 to 3 on the breaking strength of insulators to determine the allowable strength, depending on the availability of strength tests. For performance level seismic qualifications, insulator capacities are twice the aforementioned allowable strengths. These insulator strengths differ from those specified in other reference standards (see X.4) which were generally developed for non-seismic load conditions.

Annex X provides insulator strength criteria for seismic design, that are intended to recognize the issues described in the foregoing paragraphs. The insulator strength criteria specified in this annex are intended for use in cases where the applied loads are dominated by earthquake forces. These criteria are not intended to supersede or replace strength criteria specified by other standards (see X.4) for other loading conditions.

General information with regard to insulating technologies is given in the informative Annex R.

#### X.2 Terminology

##### X.2.1 Insulator

Within the context of this annex, the term “insulator” shall apply to electrical insulating/dielectric components of substation equipment and shall apply to both insulators and bushings.

Note that in context of this annex, for equipment that use hollow insulators (e.g., bushings, instrument transformers, etc.) the prescribed requirements are only applicable to insulating component of the product (in some standards this is termed the “insulating body”). It is not intended that these requirements be conducted on the entire equipment (e.g., a porcelain transformer bushing or instrument transformer should be tested without its internal components, base boxes, etc.).

## X.2.2 Insulator materials

Insulators are typically comprised of several different materials, but within the scope of this annex, insulator material shall be in reference to the structural material that makes up the body of the insulator and provides the dielectric capacity of the insulator.

## X.3 Scope

### X.3.1 Insulator materials within scope

The following insulating materials are within scope of this annex:

- a) Porcelain
- b) Composites

### X.3.2 Insulator materials beyond scope

Other insulating materials: Any other insulating material not listed in X.3.1 shall be considered beyond the scope of this annex and need only meet the following requirements:

- a) Where other insulating materials are used, the acceptance criteria used shall be consistent with the objectives of this recommended practice (5.2).
- b) The use of other insulating materials and the criteria of their use are subject to the formal agreement of the user.

## X.4 Reference standards

### X.4.1 Porcelain

- a) ANSI/NEMA C29.9
- b) IEC 62155

### X.4.2 Composites

- a) IEC 61462
- b) IEC 62231-1

## X.5 Overview of the establishment of requirements

### X.5.1 General

This recommended practice specifies rigorous insulator material strength requirements based upon the considerations described in this subclause. The seismic strength design criteria given in this annex have been developed based upon the following:

- Insulators are vital to the functionality of substation equipment (see 5.2), and it is appropriate to specify rigorous requirements to help ensure acceptable performance of the equipment.
- The mechanical properties and characteristics of insulators, which have good insulating/dielectric properties, are different from materials typically used as load-resisting structures. Codes and standards for seismic design (e.g., ACI 318, AISC 341, ASCE 7, ADM) were developed to address commonly used structural materials (e.g., concrete, steel, aluminum) and do not address the design of insulator materials.
- Existing reference standards (see X.4) for insulator strength are typically structured for non-seismic load applications, although exceptions exist.
- The transient nature of seismic loading influences the strength of composite insulators. The strength of composite insulators is influenced by the duration and magnitude of loading, and is addressed in this annex.
- This annex attempts to objectively assess the unique characteristics (X.5.2) of different insulating materials, and specify suitable strength design criteria for resisting seismic loads.

## X.5.2 Insulator material characteristics

### X.5.2.1 Porcelain

Characteristics of porcelain insulators are summarized in the following:

- a) Brittle: Porcelain typically has a brittle failure characteristic while many common structural materials tend to be ductile in nature.
- b) Strength: Porcelain has low tensile strength relative to common structural materials.
- c) Stiffness: Porcelain has modest flexibility relative to common structural materials.
- d) Porcelain strength has historically been sensitive to manufacturing processes, resulting in relatively large variability as compared to common structural materials.

### X.5.2.2 Composite

Characteristics of composite insulators are summarized in the following:

- a) Complex failure mechanism: Composites can have complex failure mechanisms that may be brittle or ductile in nature. Many common structural materials tend to have a ductile failure.
- b) Duration of loading: The strength of composite insulating materials is significantly influenced by the duration of applied loads. In general, the strength of composite insulators is greater when subjected to a short duration load (such as earthquake) compared to sustained or long-duration loads. The strength of most common structural materials tends to exhibit little dependence on load duration.
- c) Flexibility: Composite insulating materials are generally more flexible than traditional structural materials such as steel. It should be noted that although the modulus of elasticity of composite materials can be varied, the range of the modulus of elasticity is typically still less than common building materials.
- d) Composite material properties may vary depending on the manufacturer-specific chemical formulation, base material quality and manufacturing process.

## X.6 Insulator failure modes

Insulators may fail under different types of loading. Insulator strengths are commonly defined by utilizing the following tests:

- Cantilever
- Compression
- Tension
- Torsion

Resistance to cantilever loading is the strength parameter of interest for the vast majority of equipment types.

## X.7 Material-dependent measures of strength

### X.7.1 Porcelain

The maximum load at the instant of brittle fracture in an insulator load test (see X.4.1, X.8.3.6) is taken as the ultimate strength of the insulator. As an objective quantity, it is amenable to statistical analysis.

### X.7.2 Composites

The industry norm for defining the ultimate strength of a composite insulator, because of its strength/load duration dependence (X.5.2.2.b) is the Specified Mechanical Load (SML) or Specified Cantilever Load (SCL). Within the context of this recommended practice, the terms SML and SCL are taken as synonymous and the former term will be used. The SML, in brief, is a load that the insulator can maintain for a period of 1 min. It is a “rated” load, which is confirmed by test to be achievable, but it is important to recognize that it is a subjective rather than an objective quantity. The actual threshold of the SML load is not normally determined. As a rated load, it is not suitable for statistical analysis.

## X.8 Porcelain insulator strength criteria

### X.8.1 Porcelain general assumptions

#### X.8.1.1 Level of assurance vs. allowable load/stress

The allowable load/stress of a porcelain insulator is related to the level of assurance of performance (e.g., a porcelain insulator deemed to have a high level of assurance will have a higher allowable load/stress in comparison to an insulator that is deemed to have a low level of assurance). The concept of “assurance” and the correlation to an allowable stress are defined herein.

#### X.8.1.2 Strength parameter

For the purposes of a uniform comparison measure, porcelain insulator performance will be based on the porcelain ultimate cantilever capability (refer to X.8.2) except as identified in X.8.1.3.

### **X.8.1.3 Exceptions to strength parameter**

#### **X.8.1.3.1 Suspension insulators**

Porcelain suspension insulators are not addressed in these requirements.

Failure of suspended insulators is normally associated with tensile loading and is therefore not directly comparable to the cantilever performance criteria established in these requirements.

#### **X.8.1.3.2 Un-cemented, center clamped porcelains**

Un-cemented, center clamped porcelains are not addressed in these requirements.

Failure of un-cemented, center clamped porcelains is normally associated with the loss, or partial loss, of the compressive clamping mechanism and is therefore not directly comparable to the cantilever performance criteria established in these requirements.

Note that cemented center clamped porcelains and edge clamped porcelains may be limited by porcelain strength when subjected to cantilever loads and are consequently within the scope of these requirements.

### **X.8.2 Porcelain ultimate cantilever capability**

#### **X.8.2.1 Intent of ultimate cantilever capability**

The intent of the ultimate cantilever capability is to define the maximum cantilever load that the porcelain insulator can withstand in a repeated manner such that it returns to the state it was in before the commencement of the loading.

#### **X.8.2.2 Definition of ultimate cantilever capability**

Ultimate cantilever capability shall be considered to be the lowest cantilever force that causes any of the following:

- a) The rupture of the porcelain
- b) Elastic limit of an end fitting (where applicable)
- c) Elastic limit of a fastener
- d) The rupture of the cement (where applicable). Note that minor cracking of the grout is deemed acceptable provided that insulator retains its mechanical and electrical functionality
- e) Any other non-elastic phenomena

#### **X.8.2.3 Determination of ultimate cantilever capability**

Testing shall be used to determine the ultimate cantilever capability of a porcelain insulator.

Similar insulators may be grouped and assigned the same ultimate cantilever capability within the limits defined in X.8.3.7.

#### **X.8.2.4 Forms of expression of the ultimate cantilever capability**

The ultimate cantilever capability may be expressed in terms of the following:

- a) A load applied upon the free end of the insulator normal to the axis of the porcelain body.
- b) A stress at the critical cross-section. If it is expressed as a stress, the critical cross section in cantilever loading must be identified.
- c) For a multi-section insulator, an ultimate cantilever strength can be assigned to each section of the insulator.
- d) For tapered insulators, an ultimate cantilever strength can be assigned to each end when deemed critical by the user.

### **X.8.3 Porcelain testing and rating parameters**

#### **X.8.3.1 Sample restrictions**

Test specimens within a sample shall adhere to the following restrictions:

- a) All test specimens must be made of the same porcelain body composition and firing profile,
- b) All test specimens must be made with the same grout material if cemented end fittings are used,
- c) All test specimens must have common porcelain geometry at the clamped end of the insulator. Judgment of geometry shall be based on nominal dimensions as opposed to actual produced dimensions (e.g., discounting production tolerances),
- d) All test specimens must have a common end fitting geometry if supplied with an end fitting,
- e) All test specimens must have a common clamping geometry in the case of mechanically clamped fitting,
- f) All test specimens must be produced by the same manufacturing process and a process that is representative of the process which will be used for production,
- g) All test specimens must be produced by the same manufacturing facility,
- h) No properly conducted test upon a specimen can be omitted from the sample (e.g., a test where all instrumentation is functioning correctly must be included in the sample irrespective of the result).

#### **X.8.3.2 Mean**

The mean shall be the arithmetic mean of the test.

#### **X.8.3.3 Sample standard deviation**

Standard deviation shall be the sample standard deviation of a population (i.e.,  $n-1$ ).

#### **X.8.3.4 Second standard deviation strength**

The second standard deviation strength shall be the mean minus two times the sample standard deviation.

Assuming a normal distribution this corresponds to 97.7% of the insulators having a capability in excess of the second standard deviation strength.

### **X.8.3.5 Sample size**

The sample size is taken as the number of data points in the sample.

### **X.8.3.6 Rate of applied loading**

The rate of application of cantilever loading on a sample should be smooth and may be ramped up to 75% of rated strength of the insulator but shall then proceed at a rate of between 30% and 60% of the rated strength per minute until failure.<sup>22</sup>

### **X.8.3.7 Grouping of insulators**

Where ultimate cantilever tests have shown that the critical cross section corresponds to the interface between the porcelain and the end fitting, it will be permitted to group insulators provided that all insulators within a group have:

- a) A common end fitting,
- b) A common porcelain core diameter in the fitting in the case of cemented fittings or a common clamping geometry in the case of mechanically clamped fittings,
- c) A height variance of +/- 20% of the average height of all insulators in the group.

## **X.8.4 Levels of assurance of ultimate cantilever capability for porcelain insulators**

### **X.8.4.1 Statistically based vs. non-statistically based**

Statistically based ultimate cantilever capability will be deemed to give a higher level of assurance of performance in comparison to non-statistically based cantilever capability (refer to X.8.1.1).

In the context of porcelain insulator acceptance criteria, the word “statistical” is not used in the strictest mathematical sense. Economic realities dictate that the minimum prescribed sample sizes for destructive porcelain tests are not statistically significant.

### **X.8.4.2 Sample size and assurance**

Larger sample sizes will be deemed to give a higher level of assurance of performance in comparison to data obtained from smaller sample sizes (refer to X.8.1.1).

### **X.8.4.3 Recognized classifications of sample size**

Samples sizes are established based on the pragmatic recognition of the broad scope of the porcelain insulator industry. Production runs can range from relatively numerous lots of standardized products made in conformance to international standards, to a few pieces of a customized design made for a sole user. Accordingly, three classifications of sample sizes are recognized:

- a) Sample sizes greater than or equal to ten.
- b) Sample sizes greater than or equal to three, but less than ten.
- c) Sample size of one (which shall be considered non-statistically based).

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<sup>22</sup> ANSI C29.1-1988 is an example of a standard with suitable cantilever test provisions.

## X.8.5 Porcelain acceptance criteria

### X.8.5.1 Design level qualifications

The porcelain ASD acceptance criteria for design level qualifications shall be as follows:

- a) Statistically based ultimate cantilever capability from a sample size greater than or equal to ten: Critical loads/stresses shall not exceed 50% of the second standard deviation strength,
- b) Statistically based ultimate cantilever capability from a sample size greater than or equal to three, but less than ten: Critical loads/stresses shall not exceed 40% of the second standard deviation strength,
- c) Ultimate cantilever capability from a sample size of one: Critical loads/stresses shall not exceed 33% of the tested strength.

No porcelain insulator acceptance criteria have been established for load and resistance factor design (LRFD).

### X.8.5.2 Performance level qualifications

The porcelain acceptance criteria for performance level qualifications shall be as follows:

- a) Statistically based ultimate cantilever capability from a sample size greater than or equal to ten: Critical loads/stresses shall not exceed 100% of the second standard deviation strength,
- b) Statistically based ultimate cantilever capability from a sample size greater than or equal to three, but less than ten: Critical loads/stresses shall not exceed 80% of the second standard deviation strength,
- c) Ultimate cantilever capability from a sample size of one: Critical loads/stresses shall not exceed 66% of the tested strength.

### X.8.5.3 Porcelain additional acceptance criteria

#### X.8.5.3.1 Other directions of loading

Should a porcelain insulator loading not be dominated by bending loads, then it may be necessary to consider additional sufficiency criteria.

Additional sufficiency criteria shall be such that the seismic qualification objective (refer to 5.2) is maintained:

- a) For performance level qualifications, the use of any additional sufficiency criteria shall be such that the projected value at the appropriate (either high or moderate) performance level of excitation does not exceed the established limit.
- b) For design level qualifications, the use of any additional sufficiency criteria shall be such that the projected value at the appropriate (either high or moderate) design level of excitation does not exceed 50% of the established limit.

Where additional sufficiency data is required, it is suggested that the porcelain manufacturer be contacted for guidance (e.g., large tensile loads that may cause grout rather than porcelain failure).

### **X.8.5.3.2 Other forms of loading**

Other forms of loading such as impact, thermal, hydraulic, and long-term vibration loading are not considered in these provisions and should be studied and accounted for if such loading is anticipated. Note that seismic loading is not considered to be a long-term vibration load nor an impact load.

### **X.8.5.3.3 Deflection limitations**

Deflection limitations are not considered in these provisions and should be studied and accounted for if such limitations are anticipated.

## **X.9 Composite insulator strength criteria**

### **X.9.1 Composite insulator general assumptions**

#### **X.9.1.1 Strength parameter**

For the purposes of a uniform comparison measure, composite insulator performance will be based on the specified mechanical load (refer to X.9.2) except as identified in X.9.1.2.

#### **X.9.1.2 Exceptions to strength parameter**

The following are not addressed in this annex:

- Composite suspension insulators are not addressed in these requirements. Failure of suspended insulators is normally associated with tensile loading and is therefore not directly comparable to the cantilever performance criteria established in these requirements.
- Composite solid core surge arresters are addressed in a slightly different manner from the requirements of X.9.2 (see K.5.2.2).

### **X.9.2 Specified mechanical load (SML)**

#### **X.9.2.1 Determination of SML**

Determination of the SML shall be from a type test in conformance with the bending test given in IEC 61462 or IEC 62231-1, as applicable.

The sheds of the insulator need not be applied for the determination of the SML.

#### **X.9.2.2 Forms of expression of the SML**

The SML shall be expressed as a load applied upon the free end of the insulator normal to the axis of the insulator body.

### **X.9.3 Composite rating parameters-grouping**

Where SML tests have shown that the critical cross section corresponds to the interface between the composite tube and the end fitting, it will be permitted to group insulators provided that all insulators within a group have:

- a) A common end fitting,
- b) A common composite tube cross-section (OD/ID),
- c) A height variance of +/- 20% of the average height of all insulators in the group,
- d) The angle of fiber lay of the composite matrix (that is resin and fiber orientation) shall be the same.

### **X.9.4 Composite acceptance criteria**

#### **X.9.4.1 General**

Composite insulators shall meet the following criteria:

- a) Meet the appropriate subclauses of X.9.4,
- b) Pass the shed seal test in accordance with X.9.5.

#### **X.9.4.2 Design level qualifications**

The composite ASD acceptance criteria for design level qualifications shall be that the load upon the insulator shall not exceed 50% of the SML.

No composite insulator acceptance criteria have been established for load and resistance factor design (LRFD).

#### **X.9.4.3 Performance level qualifications**

The composite acceptance criteria for performance level qualifications shall be that the load upon the insulator shall not exceed 100% of the SML.

#### **X.9.4.4 Composite additional acceptance criteria**

##### **X.9.4.4.1 Other directions of loading**

Should a composite insulator loading not be dominated by bending loads, then it may be necessary to consider additional sufficiency criteria.

Additional sufficiency criteria shall be such that the seismic qualification objective (refer to 5.2) is maintained as follows:

- a) For performance level qualifications, the use of any additional sufficiency criteria shall be such that the projected value at the appropriate (either high or moderate) performance level of excitation does not exceed the established limit.

- b) For design level qualifications, the use of any additional sufficiency criteria shall be such that the projected value at the appropriate (either high or moderate) design level of excitation does not exceed 50% of the established limit.

Where additional sufficiency data is required, it is suggested that the composite insulator manufacturer be contacted for guidance (e.g., large tensile loads that may cause adhesive failure rather than tube failure).

#### **X.9.4.4.2 Other forms of loading**

Other forms of loading such as impact, thermal, hydraulic, and long-term vibration loading are not considered in these provisions and should be studied and accounted for if such loading is anticipated. Note that seismic loading is not considered to be a long-term vibration load nor an impact load.

#### **X.9.4.4.3 Deflection limitations**

Deflection limitations are not considered in this annex and should be studied and accounted for if such limitations are anticipated.

### **X.9.5 Shed seal type test**

#### **X.9.5.1 General**

The purpose of the shed seal test is to verify the resistance to moisture ingress at interface of the end fitting and the sheds under a bending load.

A shed seal test, as described herein, shall be conducted on all composite insulator designs but shall not be applicable to polymer surge arresters. The shed seal test for polymer surge arresters is described in K.4.6. The shed seal is intended to promote better seismic performance and shall not relieve the manufacturer of the obligation of perform other design tests should they be warranted.

- a) A shed seal test shall be conducted for each seal design used in equipment that is qualified by this recommended practice as follows: Only one test needs to be performed for each seal design method. The test applies to all equipment using the sealing method.
- b) The test need not be repeated for different equipment types or voltage classes where the same sealing method is used.

#### **X.9.5.2 Test procedure**

The shed seal test shall be performed using the following procedure:

- a) A tension line shall be connected to one end of the insulator or bushing with the other end of the insulator or bushing anchored rigidly to produce a moment connection, as shown in Figure X.1.
- b) The tension line shall be pulled to produce one half of the SML of the insulator or bushing.
- c) The tension shall be held for at least two minutes.
- d) While still under load, the interface of the end fittings and the sheds (at the moment end) shall be heavily coated with or immersed in dye-penetrant.
- e) The load shall be removed and the test specimen disassembled from the test apparatus.
- f) Longitudinally and transverse cuts are made at the highest stressed areas of the interface.
- g) The cut sections shall be examined for dye penetration.

### X.9.5.3 Acceptance criteria

The shed seal test will be considered acceptable if both of the following are satisfied:

- No dye has penetrated to within 2 mm of the outer surface of the fiberglass core via any leak path other than through the thickness of the sheath.
- No dye has penetrated through the thickness of the sheath to within 2 mm of the outer surface of the fiberglass core. For sheath thicknesses of 4 mm or less, dye shall not penetrate more than 50% of the sheath thickness.

### X.9.5.4 Additional requirements

The following shall be prepared after conclusion of the shed seal test:

- a) A test report shall be made which includes images of each step of testing, images of the cut pieces (including evidence of the dye) and a description of where the cut pieces were situated in the design tested unit.
- b) The shed seal test report must be signed and made available for insertion into equipment seismic qualification reports.

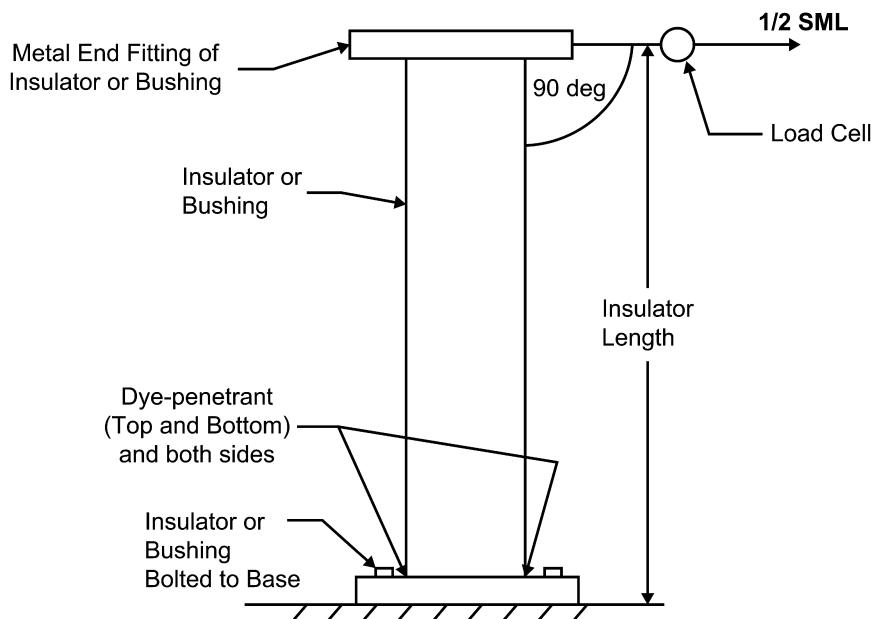


Figure X.1—Composite polymer shed seal test setup

## Annex Y

(informative)

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<sup>23</sup> ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

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<sup>26</sup> NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112, USA (<http://global.ihs.com/>).

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