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Bushings — Seismic qualification

National foreword

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

BUSHINGS – SEISMIC QUALIFICATION

FOREWORD

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- the required support cannot be obtained for the publication of an International Standard, despite repeated efforts, or
- The subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC 61463, which is a Technical Specification, has been prepared by subcommittee 36A: Insulated bushings, of IEC technical committee 36: Insulators.

This second edition cancels and replaces the first edition published in 1996 and Amendment 1:2000. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) the seismic spectrum profile has been substituted with the one of IEEE Std 693-2005, worldwide used as a reference;

b) the acceptance criteria have been reviewed and the maximum permissible stress for each main material has been harmonized with the relevant IEC Standard for that material;

c) a load on the head has been prescribed when the bushing is subject to the vibration test;

d) the sine sweep test has been added as a method of search of resonance frequency, worldwide used.

The text of this document is based on the following documents:

Enquiry draft	Report on voting
36A/178/DTS	36A/179/RVC

Full information on the voting for the approval of this document can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

As it is not always possible to define accurately the seismic severity at the bushing flange level, IEC TS 61463, which is a Technical Specification, presents three alternative methods of qualification. The three methods are equally acceptable. If the required response spectrum (RRS) at the bushing flange is not known, a severity (in terms of acceleration values) based on standard response spectra at the ground level may be used to carry out qualification through one of the three methods described in this document.

When the environmental characteristics are not sufficiently known, qualification by static calculation is acceptable. Where high safety reliability of equipment is required for a specific environment, precise data are used, therefore qualification by dynamic analysis or vibration test is recommended. The choice between vibration testing and dynamic analysis depends mainly on the capacity of the test facility for the mass and volume of the specimen, and, also if non-linearities are expected.

When qualification by dynamic analysis is foreseen, it is recommended that the numerical model be adjusted by using vibration data (see Clause 5).

This document was prepared with the intention of being applicable to bushings whatever their construction material and their internal configuration.The information contained, originally directed to porcelain bushings, has been partially updated to include also composite bushings.

BUSHINGS – SEISMIC QUALIFICATION

1 Scope

IEC TS 61463, which is a Technical Specification, is applicable to alternating current and direct current bushings for highest voltages above 52 kV (or with resonance frequencies placed inside the seismic response spectrum), mounted on transformers, other apparatus or buildings. For bushings with highest voltages less than or equal to 52 kV (or with resonance frequencies placed outside from the seismic response spectrum), due to their characteristics, seismic qualification is not used as far as construction practice and seismic construction practice comply with the state of the art.

This document presents acceptable seismic qualification methods and requirements to demonstrate that a bushing can maintain its mechanical properties, insulate and carry current during and after an earthquake.

The seismic qualification of a bushing is only performed upon request.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60068-2-47, *Environmental testing – Part 2-47: Test – Mounting of specimens for vibration, impact and similar dynamic tests*

IEC 60068-2-57, *Environmental testing – Part 2-57: Tests – Test Ff: Vibration – Time-history and sine-beat method*

IEC 60068-3-3:1991, *Environmental testing – Part 3-3: Guidance – Seismic test methods for equipments*

IEC 60137, *Insulated bushings for alternating voltages above 1 000 V*

IEC 61462, *Composite hollow insulators – Pressurized and unpressurized insulators for use in electrical equipment with rated voltage greater than 1 000 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 1 000 V*

IEC 62217*, Polymeric insulators for indoor and outdoor use – General definitions, test methods and acceptance criteria*

ISO 2041, *Mechanical vibration, shock and condition monitoring – Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60068-3-3, IEC 60137, IEC 61462, ISO 2041 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
critical cross-section
section of the bushing that is most likely to fail during an earthquake

3.2
response spectrum
plot of the maximum response to a defined input motion of a family of single-degree-of-freedom bodies at a specified damping ratio

[SOURCE: IEC 60068-2-57:2013, 3.18, modified — The words "as a function of their natural frequencies and at a specified damping ratio" has been replaced by "at a specified damping ratio".]

3.3
rigid equipment
equipment whose natural frequency is greater than 33 Hz is considered rigid for the purpose of this technical specification

3.4
standard frequency range
predominant frequencies of a typical earthquake

Note 1 to entry: This range is generally between 0,3 Hz and 33 Hz.

Note 2 to entry: This range is sufficient to determine the critical frequencies of the equipment and for its testing. In certain cases the test frequency range may be extended or reduced dependent on the critical frequencies present, but this shall be justified.

3.5
zero period acceleration
high frequency asymptotic value of acceleration of a response spectrum (above the cut-off frequency of 33 Hz)

Note 1 to entry: This acceleration corresponds to the maximum acceleration of the time history used to derive the spectrum.

4 Symbols and abbreviated terms

a_{bg}	equivalent maximum acceleration to the centre of gravity of the bushing during the seismic event
a_{f}	maximum acceleration of the bushing flange
a_{g}	maximum acceleration of the ground resulting from the motion of a given earthquake NOTE a_{g} is equal to the zero period acceleration (ZPA) of Figure 2.
d	damping of the bushing
d_{p}	distance between the centre of gravity of the part of the bushing which is under consideration and the critical cross-section
f_0	first natural frequency of the bushing

K	superelevation factor between ground and bushing flange: factor accounting for the change in the acceleration from the ground to the flange due to the amplification by foundation, buildings and structure
m_{p}	mass of the part of the bushing which is under consideration
M_{s}	bending moment at the critical cross-section of the part of the bushing considered, due to an earthquake
R	response factor derived from the required response spectrum (RRS) as the ratio between the response acceleration and the ZPA (see Figure 3)
RRS	required response spectrum: response spectrum specified by the user
S_{c}	coefficient established to take into account the effects of both multifrequency excitation and multimode response
S_{a}	spectral acceleration
ZPA	zero period acceleration (see a_{g})

5 Methods of seismic qualification

Seismic qualification should demonstrate the ability of a bushing to withstand seismic stresses and to maintain its required function without failure, during and after an earthquake of a specified severity (see Clause 6).

As bushings are mounted on apparatus or buildings, the seismic qualification of the bushing must consider the behaviour of the system on which the bushing is fixed. In the seismic qualification of a bushing, all parts should be included, which contribute to the stresses in the critical cross-sections during a seismic event, for example the conductor and inner spacer in gas insulated bushings.

Three methods and combinations thereof are described in this document:

- qualification by static calculation (Clause 7);
- qualification by dynamic analysis (Clause 8);
- qualification by vibration test (Clause 9).

A combination of the methods may be used

- to qualify a bushing which cannot be qualified by testing alone (e.g. because of size and/or complexity of the apparatus),
- to qualify a bushing already tested under different seismic conditions, and
- to qualify a bushing similar to a bushing already tested but which includes modifications influencing the dynamic behaviour (e.g. change in the length of insulators or in the mass).

Vibrational data (damping, critical frequencies, stresses of critical elements as a function of input acceleration) for analysis can be obtained by

a) a dynamic test on a similar bushing,
b) a dynamic test at reduced test level, and
c) determination of natural frequencies and damping by other tests such as free oscillation tests or sine sweep tests (see Annex B).

The methods result in the value of M_{s} which is determined for each part of the bushing on either side of the flange. The stress due to this moment should be combined with the other stresses acting in the bushing, and it should be demonstrated that the bushing withstands the combined stress (Clause 10).

The different methods of seismic qualification are illustrated in the flow chart given in Annex A.

6 Severities

6.1 At the ground

The ground acceleration depends upon the seismic conditions of the site where the apparatus is to be located. When it is known, it should be prescribed by the relevant specification. Otherwise, the severity level should be selected from Table 1.

Table 1 – Ground acceleration levels

Ground acceleration reference	Description of earthquake					
	General	*ZPA* = a_g m/s^2	Richter scale magnitude	UBC zone[a]	Intensity MSK[b]	RRS
AG2	Light to medium earthquakes	2 (0,2 g)	< 5,5	1 to 2	< VIII	Figure 1[c]
AG3	Medium to strong earthquakes	3 (0,3 g)	5,5 to 7,0	3	VIII to IX	Figure 1[c]
AG5	Strong to very strong earthquakes	5 (0,5 g)	> 7,0	4	> IX	Figure 1

[a] Approximate Uniform building code zone (International conference of building officials).

[b] MSK (Medvedev-Sponheuer-Karnik) corresponds to modified Mercalli intensity scale.

[c] Values for AG2 and AG3 are obtained by multiplying the values from Figure 2 by 2/5 and 3/5 respectively.

The selected qualification level should be in accordance with expected earthquakes of maximum ground motions for the site location, for which certain structures, systems and components are designed to remain functional. These structures are those essential to assure proper function, integrity and safety of the total system (S_2 type earthquakes, according to IEC 60068-3-3).

For qualification, it should be assumed that

– the horizontal movements as described in Table 1 act in any direction
– the severities of the vertical accelerations are 50 % of the horizontal (if a different value is used, a justification shall be provided), and
– both directions may reach their maximum values simultaneously.

The ground motion can be described by natural time histories when known, or by artificial time histories, which should comply with the RRS; this is used as input for dynamic analysis or vibration test on the complete apparatus.

NOTE Information on the correlation between seismic qualification levels, seismic zone and seismic scales is given in IEC 60721-2-6 [1][1] and IEC 60068-3-3.

6.2 At the bushing flange

The severity at the bushing flange (see Figure 5) may be available from the manufacturer of the apparatus and structures (i.e. transformers, gas insulated apparatuses (GIS), building) in terms of RRS or maximum acceleration (a_f). Where no information is available, the following simplified formula is used in order to establish an acceleration value at the flange of the bushing.

$$a_f = K \times a_g$$

The superelevation factor K can be

---

[1] Numbers in square brackets refer to the Bibliography.

- calculated by finite element analysis including soil interaction or any other careful modelling, or
- derived from results from calculations or tests on comparable apparatus or structures, or
- taken from typical values obtained from experience.

So far, very little experience is reported. Unless more background information is available, K should be assumed to be 1 for through-wall bushings, 1,5 for GIS bushings and for transformer bushings directly mounted on the transformer cover, and 2 for transformer bushings mounted on a turret. If the mounting configuration on the transformer is not known, K will be assumed as 1,5.

See also IEC 60068-3-3:1991, Table 4.

7 Qualification by static calculation

This method is valid for rigid equipment. It may be extended to flexible equipment, such as a bushing, taking into consideration the response factor R, as an alternative to the method by analysis. This allows simpler evaluation with increased conservatism.

Using the static calculation method, the bending moment in the critical cross-section of the part of the bushing under consideration is calculated from an equivalent acceleration of the centre of gravity of that part (a_{bg}):

$$M_{\mathrm{s}} = a_{\mathrm{bg}} \times d_{\mathrm{p}} \times m_{\mathrm{p}}$$

This acceleration, a_{bg}, is calculated from the flange acceleration a_{f} by multiplication with a coefficient S_{c} and the response factor R (see Annex C):

$$a_{\mathrm{bg}} = a_{\mathrm{f}} \times S_{\mathrm{c}} \times R$$

The value of S_{c} depends on the natural frequency f_0 of the mounted bushing:

$f_0 \leq 8$ Hz	$S_{\mathrm{c}} = 1{,}5$
$8 < f_0 < 33$ Hz	$S_{\mathrm{c}} = 1 + 0{,}5 \times (33 - f_0) / (33\text{-}8)$
$f_0 \geq 33$ Hz	$S_{\mathrm{c}} = 1{,}0$

If the natural frequency f_0 is not known, the conservative value $S_{\mathrm{c}} = 1{,}5$ should be used.

The value R can be established by one of the following methods.

a) From the spectrum at the bushing flange (if available).

b) When the spectrum at the bushing flange is not known, the spectrum at the ground (Figure 2) may be used assuming that the levels at all frequencies are equally amplified (K factor) from the ground to the flange. For such cases, the values of R are summarized in Figure 3. The value of R is derived from the RRS (Figure 2 and Table 4) by dividing the spectrum values with the ZPA value of asymptotic acceleration.

   In order to correctly use the R values, it is necessary to know the first natural frequency f_0 and the damping d % of the bushing mounted on its supporting structure. The natural frequency can either be calculated as indicated for the superelevation factor or found by a free oscillation test as described in Annex B.

c) R may be assumed to be equal to 2,5 when information for frequency f_0 and damping d % of the bushing mounted on a transformer is not available. The value of 2,5 corresponds to the frequency range 1,1 Hz to 8 Hz and 5 % damping ratio (ref. to Figure 3 and Table 5).

d) R may be assumed to be equal to 2,9 when information for frequency f_0 and damping d % of the bushing mounted on a GIS structure is not available. The value of 2,9 corresponds to the frequency range 1,1 Hz to 8 Hz and 3 % damping ratio (ref. to Figure 3 and Table 5).

Different R values can be agreed between purchaser and manufacturer if justified.

Collected data show that the first natural frequency of a mounted bushing is lower than that of the bushing itself. Reported natural frequencies show a great variation, while the damping ratios lie within a limited range (see Table 2 and Table 3).

An example of the application of the method for bushings mounted on a transformer is given in Annex D.

Table 2 – Dynamic parameters obtained from experience on bushings with porcelain insulators (f_0 = natural frequency, d = damping)

Type of mounting	**Highest voltage of equipment**							
	123 kV to 170 kV		**245 kV to 362 kV**		**420 kV to 550 kV**		**800 kV to 1 200 kV**	
	f_0 [Hz]	d [%]	f_0 [Hz]	d [%]	f_0 [Hz]	d [%]	f_0 [Hz]	d [%]
Bushing alone (mounted on a rigid structure)	15 to 35	2 to 4	10 to 24	2 to 4	3 to10	2 to 5	1.5 to 5	2 to 6
Bushing mounted on a transformer tank	5 to 20	3 to 6	5 to 15	5	3 to 8	5	1 to 4	5
Bushing mounted on a GIS	4 to 12	3 to 5	4 to 10	–	3,5 to 10	–	4 to 5	1,5 to 3
Bushing mounted on a building	–	–	–	–	–	–	–	–

NOTE 1 In the case of special dissipating systems, higher damping ratios can be obtained.

NOTE 2 Additional data will be included in this table based on experience of the practical application of this technical specification.

Table 3 – Dynamic parameters obtained from experience on bushings with composite insulators (f_0= natural frequency, d = damping)

Type of mounting	**Highest voltage of equipment**							
	123 kV to 170 kV		**245 kV to 362 kV**		**420 kV to 550 kV**		**800 kV to 1 200 kV**	
	f_0 [Hz]	d [%]	f_0 [Hz]	d [%]	f_0 [Hz]	d [%]	f_0 [Hz]	d [%]
Bushing alone (mounted on a rigid structure)	14 to 18	1.5 to 2	5,5 to 13	1 to 3,5	3.5 to6,5	1 to 4		
Bushing mounted on a transformer tank								
Bushing mounted on a GIS			10		4 to 5,5	1 to 4		
Bushing mounted on a building								

NOTE 1 In the case of special dissipating systems, higher damping ratios can be obtained.

NOTE 2 An empty space means that data are not yet available. Additional data or ranges of values will be included in this table based on experience of the practical application of this technical specification.

8 Qualification by dynamic analysis

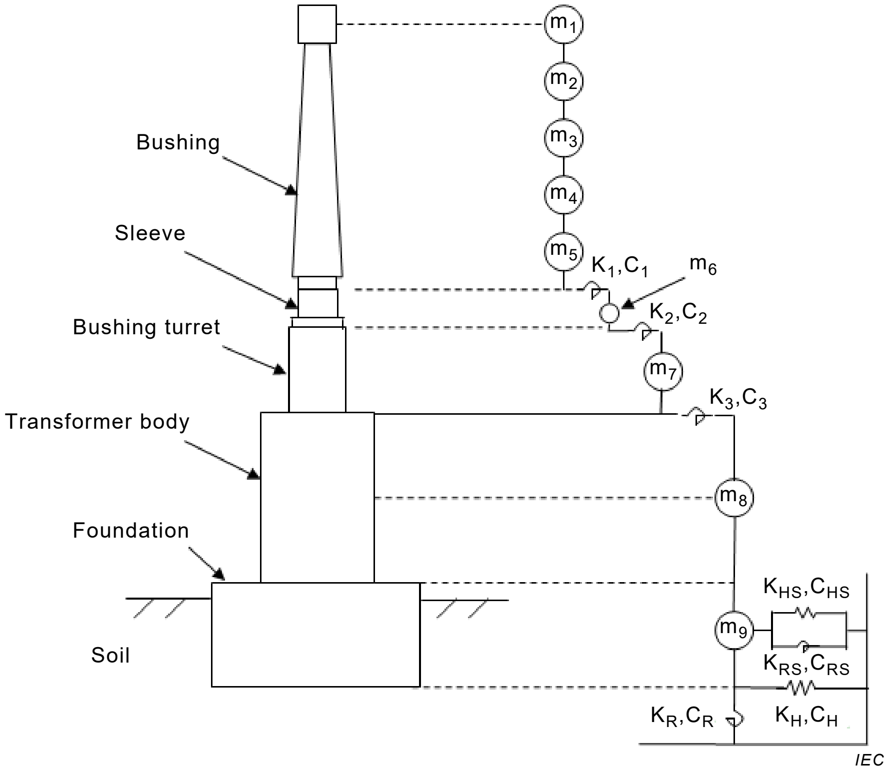
8.1 General

For dynamic analysis, the whole structure, the apparatus and the ground conditions including foundations, with the mounted bushing, should be modelled by finite elements or other mathematical modelling technique, taking into consideration the specific values of elasticity and damping of all elements as well as the relevant masses. The structure may be assumed to behave linearly and elastically except special seismic equipment (see 10.3, c)), which should be modelled with its actual properties. The linear values used should correspond to the values expected at the seismic load level.

Natural frequencies of the bushing, the rocking motion of the foundation and responses at the top of the bushing are influenced by the mass of the foundation, by the spring constant and by the damping coefficient of soil. When the natural frequency of the bushing and the one of the rocking motion are coincident, resonant phenomena occur and high response at the top of the bushing can be produced.

If then the condition of the soil is not good (soft), the modeling of the total transformer system (soil – foundation – transformer body – turret – bushing, refer to Figure 1) will be necessary.

The model in Figure 1 is an example of the whole system [3].



Symbols

m*i*:	mass
K_i,C_i:	Rotational spring constant and damping coefficient at joint
K_H,C_H:	Horizontal spring constant and damping coefficient at the bottom of foundation
K_R,C_R:	Rotational spring constant and damping coefficient at the bottom of foundation
K_{HS},C_{HS}:	Horizontal spring constant and damping coefficient at the side of foundation

K_{RS},C_{RS}: Rotational spring constant and damping coefficient at the side of foundation

Figure 1 – Example of model of the transformer system

From the calculation, the stresses in the critical cross-section of the bushing can be found.

A dynamic analysis may be performed on a bushing alone if the flange severity is already known.

The general procedure is to establish, using experimental data, a mathematical model as the previous shown of the structure in order to assess its dynamic characteristics and then to determine the response, using either of the methods described in 8.2 and 8.3. Other methods may be used if they can be justified.

8.2 Modal analysis using the time-history method

When the time-history method is used for seismic analysis, the ground motion acceleration time-histories shall comply with the RRS (see Figure 2). Two types of superimposition may generally be applied depending on the complexity of the problem:

- separate calculation of the maximum responses due to each of the three directions (x and y in the horizontal, and z in the vertical direction) of the earthquake motion. The effects of each single horizontal direction and the vertical direction shall be then combined by taking the square root of the sum of the squares, i.e. $(x_{\mathrm{max}}{}^2 + z_{\mathrm{max}}{}^2)^{1/2}$ and $(y_{\mathrm{max}}{}^2 + z_{\mathrm{max}}{}^2)^{1/2}$. The greater of these two values is used for the combination of the stresses of the bushing;
- simultaneous calculation of the maximum responses assuming one of the seismic horizontal directions and the vertical direction $(x \text{ with } z)_{\mathrm{max}}$ and, thereafter, calculation of the other horizontal direction and the vertical direction $(y \text{ with } z)_{\mathrm{max}}$. This means that, after each step of calculation, all values (force, stresses) are superimposed algebrically. The greater of these two values is used for the combination of the stresses of the bushing.

8.3 Modal analysis using the RRS

When the RRS method is used for seismic analysis, the procedure of combining the stresses is described for an orthogonal system of co-ordinates in the main axes of the bushing and with x and y in the horizontal and z in the vertical direction. The maximum values of stresses in the bushing for each of the three directions x, y and z are obtained by superimposing the stresses calculated for the various modal frequencies in each of these directions by taking the square root of the sum of the squares. The maximum values in the x and z direction — and in the y and z direction — are obtained by taking the square root of the sum of the squares $(x_{\mathrm{max}}{}^2 + z_{\mathrm{max}}{}^2)^{1/2}$ and $(y_{\mathrm{max}}{}^2 + z_{\mathrm{max}}{}^2)^{1/2}$. The greater value of these two cases (x, z) or (y, z) is used for the combination of the stresses of the bushing.

9 Qualification by vibration test

9.1 General

9.1.1 General

Three different approaches can be applied:

- test on the complete apparatus (bushing mounted on the real apparatus);
- test on the bushing mounted on a simulating support;
- test on the bushing alone.

The procedure for qualification by test shall be in accordance with IEC 60068-2-57 and IEC 60068-3-3. The tests shall be made at the ambient air temperature of the test location and this temperature shall be recorded in the test report. After the vibration test, the bushing shall pass a routine test according to IEC 60137.

9.1.2 Mounting

General mounting requirements are given in IEC 60068-2-47. The specimen should be mounted as in service including dampers (if any).

NOTE For more detailed guidance in the case of equipment normally used with vibration isolators, see A.5 of IEC 60068-2-6:2007 [2].

The orientation and mounting of the specimen during conditioning should be prescribed by the relevant standard. They are the only condition for which the specimen is considered as complying with the requirements of the standard, unless adequate justification can be given for extension to an untested condition (for instance, if it is proved that the effects of gravity do not influence the behaviour of the specimen).

9.1.3 External load

Generally, electrical and environmental service loads cannot be simulated during the seismic test. This applies also to possible internal pressure of the bushing due to safety requirements of the test laboratory.

During vibrational test, the following weight shall be added to the HV bushing terminal:

- For U_m greater than 420 kV: 11 kg
- For U_m less or equal to 420 kV: 7 kg

These weights represent the lower range of weight associated with conductor connections hardware and part of the weight of conductors connected to the bushing.

Other masses could be agreed between parts.

NOTE For combination of seismic and service loads to be taken into account during static or dynamic analysis, see Clause 10.

9.1.4 Measurements

Measurements shall be performed in accordance with 5.2 of IEC 60068-3-3:1991, and should include

- acceleration at both ends of the bushing and at the centre of gravity,
- displacement of the top of the bushing, and
- strains on critical cross-sections.

9.1.5 Standard frequency range

The frequency range shall be 0,3 Hz to 33 Hz.

9.1.6 Test methods

9.1.6.1 General

The following test methods with their waveforms shall be used to comply with RRS:

- time-history; or
- sine-beat; or
- other waveforms, for example sine wave (requiring justification).

9.1.6.2 Parameters for time-history

9.1.6.2.1 General

The total duration of the time-history should be about 30 s of which the strong part not less than 20 s. The test method shall be in accordance with IEC 60068-2-57.

9.1.6.2.2 Test severity

The test severity shall be chosen in accordance with 6.1.

The recommended response spectra are given in Figure 2 for the different qualification levels. The curves are related to 2 %, 3 %, 5 %, 10 % of the bushing damping. If damping is unknown, 5 % damping will be applied for transformer bushings and 3 % damping will be applied for GIS bushings, in accordance with 7c) and 7d).

Spectra for different damping values may be obtained by linear interpolation.

9.1.6.2.3 Spectrum definition

The following expressions give the RRS spectrum values: depending on the level (high, medium, low), the right RRS will be given in function of the frequency.

$S_a = 1{,}144 \cdot \alpha \cdot \beta \cdot f$ for $0{,}3 \leq f < 1{,}1$

$S_a = 1{,}25 \cdot \alpha \cdot \beta$ for $1{,}1 \leq f \leq 8{,}0$

$S_a = \alpha \cdot [(13{,}2 \cdot \beta - 5{,}28)/f - 0{,}4 \cdot \beta + 0{,}66]$ for $8{,}0 < f < 33$

$S_a = 0{,}5 \cdot \alpha$ for $f \geq 33$

$\beta = (3{,}21 - 0{,}68 \cdot \ln(d))/2{,}1156$

where

d is the percent damping (2, 3, 5, 10, etc. with $d < 20$ %),

α = 1 for AG5 level (5 m/s^2, 0,5g), α = 0,6 for AG3 level (3 m/s^2, 0,3g) α = 0,4 for AG2 level (2 m/s^2, 0,2g)

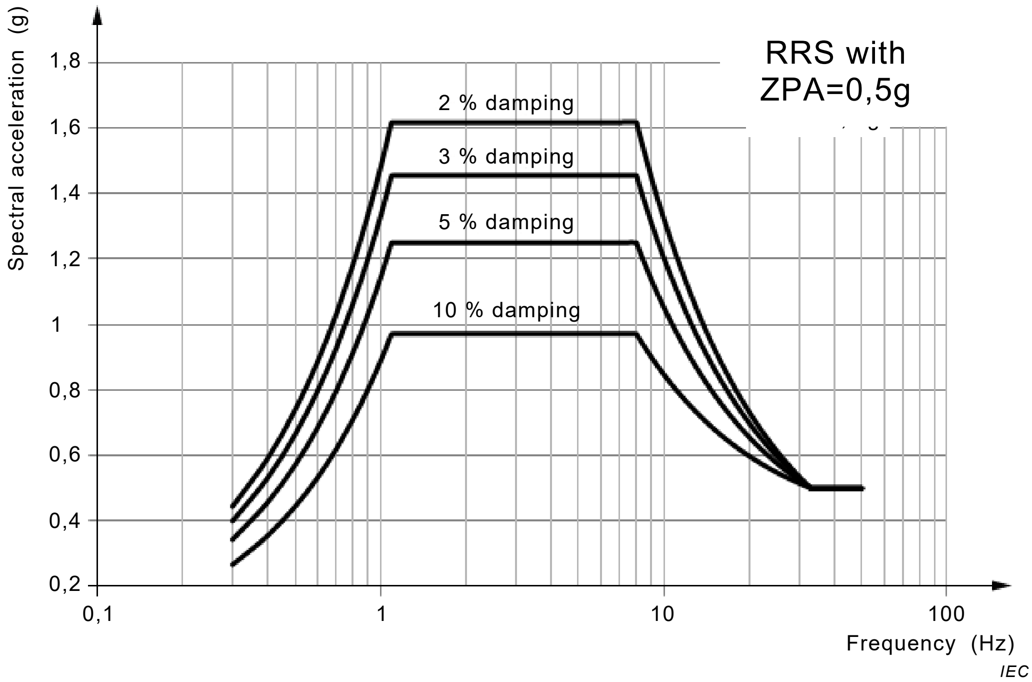


Figure 2 – RRS for ground mounted equipment – ZPA = 0,5 g [1] [2]

The other spectra related to medium level (ZPA = 0,3 *g*) and low (ZPA = 0,2 g) level can be easily obtained by the above expressions.

Table 4 – Example of qualification level: AG5: ZPA = 0,5 g

Frequency Hz	**Response acceleration** m/s^2			
	Damping ratio 2 %	**Damping ratio 3 %**	**Damping ratio 5 %**	**Damping ratio 10 % and more**
0,3	4,4	4,0	3,4	2,7
1,1	16,2	14,6	12,5	9,7
8	16,2	14,6	12,5	9,7
33	5,0	5,0	5,0	5,0

NOTE According to IEC 60068-3-3, the value of g is rounded up to the nearest unit, that is 10 m/s^2.

9.1.6.3 Parameters for sine-beat

Test frequencies should cover the frequency range stated in 9.1.5 with half octave spacing, and should include the resonance frequencies of the specimen. The test method should be in accordance with IEC 60068-2-57.

9.1.7 Testing

9.1.7.1 Test axes

The test axes should be chosen according to 3.19 of IEC 60068-3-3:1991. In some cases, the effect of the vertical acceleration results in negligible stresses, and the vertical excitation may be omitted.

Single axis or biaxial excitation may be accepted if suitably justified.

9.1.7.2 Test sequence

The test sequence should be as follows.

a) Vibration response investigation

   The vibration response investigation should be carried out according to 10.1 and 14.2 of IEC 60068-3-3:1991 over the frequency range stated in 9.1.5.

b) Seismic qualification test

   The test should be performed by applying one of the procedures stated in flow chart A.3 (except test Fc) or flow chart A.4 of IEC 60068-3-3:1991 depending on the test facilities.

The test should be performed once at the level chosen in Clause 6.

During the seismic test, the measurements as stated in 9.1.4 should be recorded.

9.2 Test on complete apparatus

When the size and/or complexity of the apparatus allow assembly on the shaker table, a test on the complete apparatus is recommended.

The test severity should be chosen in accordance with 6.1. The time-history method is recommended since it more closely simulates the actual conditions, particularly if the behaviour of the specimen under test is not linear.

9.3 Test on the bushing mounted on a simulating support

The bushing is mounted on a simulating support which is fastened to a shaker table (see Figure 4). The simulating support has to dynamically reproduce (stiffness and damping) the actual apparatus.

The severity and test method should be as described in 9.2.

9.4 Test on the bushing alone

If the size and/or complexity of the apparatus (transformer, GIS apparatus, building) does not allow the test to be performed as described in 9.2 or 9.3, the test should be performed on the bushing alone, rigidly connected to the shaker table. In this case, the severity should be the RRS or the peak acceleration value at the flange of the bushing (see 6.2 and Figure 5).

The sine-beat test method is recommended. In case the RRS at the flange is not available, coefficients K and R should be either obtained by calculation or taken from the values given in Clauses 6 and 7.

10 Evaluation of the seismic qualification

10.1 Combination of stresses

The seismic stresses determined as described in Clauses 7, 8 or 9 should be combined with other service stresses to evaluate the total stress induced by all the combined loads on the bushing.

The probability of an earthquake of the recommended seismic qualification level occurring during the lifetime of the bushing is low, as the maximum seismic load in a natural earthquake would only occur if the bushing were excited at its critical frequencies with maximum acceleration. As this would last only a few seconds, a combination of extreme electrical and environmental service loads would lead to unrealistic conservatism.

Consequently, the following stresses are considered to occur simultaneously, if not otherwise specified (see IEC 62155):

- the stress of an operating load equal to 70 % of the cantilever operating load specified for the bushing (cantilever is a force applied perpendicularly to the bushing axis in the middle part of the bushing HV terminal; make reference to the cantilever table of IEC 60137, operating loads);
- the stress of wind pressure of 70 Pa;
- the stress determined by the components of the mass of the bushing which acts perpendicular to the bushing axis;
- the stress of the average internal pressure at normal service conditions;
- the stress induced by the seismic event (Clauses 7, 8 or 9).

These stresses can either be included in the test or analysis model, or separately added.

NOTE 1 This combination of stresses assumes that connection lines do not limit the motion of the terminal of the bushing during the seismic event.

NOTE 2 As this load combination is based on a reasonable conservatism, it is possible that it does not apply to each installation.

NOTE 2 This combination of stresses will not be used during the vibrational tests, which are referred to in 9.1.2 (external load), but only for static and dynamic analysis.

10.2 Cantilever test

A cantilever test can be used to find the highest permissible stress of the bushing to be determined.

A cantilever test can be performed on a complete bushing or on parts of it. When testing a separate insulator, the clamping arrangement shall be equal to that of the complete bushing. The test procedure shall be in agreement with IEC 60137.

10.3 Acceptance criteria

The bushing shall insulate and carry current during and after the earthquake. No crack, leakage, permanent deflection or relative movement of parts is permitted.

The bushing is considered to be qualified for the seismic requirement if

a) – its components made by cast epoxy resins, ceramic materials or glasses are not stressed over the 100 % of their type test withstand bending moment, in accordance with IEC 62217 and IEC 62155,

b) – its components made by composite material are not stressed over 1,5 times their maximum mechanical load (MML), which corresponds normally to the elasticity limit of the material, in accordance with IEC 61462, and

NOTE Different acceptance criteria can be agreed between purchaser and manufacturer, in accordance to other Standards or Specifications.

c) – metallic parts are not stressed above the yielding point by the combined stresses. Assembly fittings, specially designed for seismic purpose (e.g. to reduce the natural frequency or increase the damping) may however use friction and ductility in a controlled way.

By considering the actual stress-strain relationship and stress redistribution, the stress limit in metallic parts need not be satisfied at a specific location if the stress is a self-limiting secondary stress or if it is caused by a local structural discontinuity which affects a relatively small volume of material and does not have a significant effect on the overall stress or strain pattern.

11 Necessary exchange of information

11.1 Information supplied by the apparatus manufacturer

When specifying, the purchaser should provide as much of the following information as necessary, as well as any additional information needed to determine clearly the required characteristics.

a) Severity

It should be clearly stated if the severity is to be applied to the bushing flange or to the apparatus base. Severity at the bushing flange is recommended.

b) Details of mounting

Position and angle of mounting.

c) Apparatus stiffness

For qualification by calculation, the stiffness of the bushing support (e.g. angle of deflection vs bending moment) and the damping of the structure shall be stated. If the stiffness of the support is so high and the natural frequency of the bushing can be expected to be above 8 Hz, it should also be stated that the rest of the structure down to the base is equally stiff, otherwise the lower accelerations at high frequencies may not be utilized.

d) Dynamic analysis

Qualification by dynamic analysis is to be made by the manufacturer of the apparatus (e.g. a transformer) because of the great amount of structural data required. The apparatus manufacturer requests the necessary data from the bushing manufacturer.

11.2 Information supplied by the bushing manufacturer

a) Design data

In case of dynamic analysis of the complete apparatus, the bushing manufacturer should provide

- the geometrical parameters (i.e. dimensions, centre of gravity, moment of inertia) and masses of the complete bushing, and
- the mechanical properties (i.e. Young and Poissons ratio or shear modulus, flexural/compressive/tensile strength) of the porcelain and the damping ratio of the bushing, unless standard values can be used.

The apparatus manufacturer will perform the dynamic analysis and inform the bushing manufacturer of the results to be used in the evaluation according to Clause 10.

b) Seismic qualification report

A report showing the result of the evaluation performed according to clause 10. The report should contain a description of the bushing, the assumptions adopted and the results obtained. In the report the maximum displacement of the bushing terminal during the earthquake should be provided.

NOTE A specification may limit the maximum permissible deflection of the bushing head under the specified earthquake conditions. However, a limitation of the deflection leads to a construction with higher stiffness and possibly lower damping. That can cause higher stresses and, consequently, lower resistance against seismic loads. This is especially important for bushings with composite insulators.

c) Test record

If tests are performed, the report should contain identification of test object, test location, test equipment, description of the test, results (resonance frequencies and damping) and significant conclusions.

When qualification is performed according to 9.4, information should be given in order to justify that the adequacy of the bushing for a certain ground acceleration level is related to particular apparatus dynamic parameter.

When reference is made to tests on apparatus similar to the actual, the following information should be given: description of both with details of their differences, test results and their extrapolation to the actual apparatus.

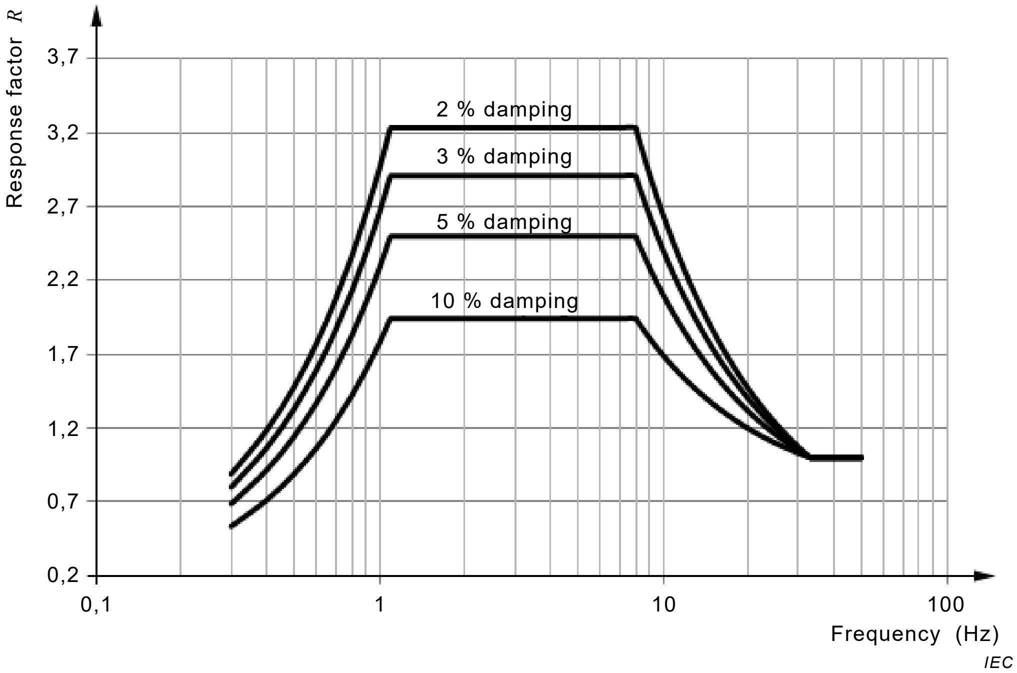


Figure 3 – Response factor *R*

R is the ratio of RRS and ZPA.

Table 5 – Response factor *R*

Frequency Hz	**Response factor *R***			
	Damping ratio 2 %	**Damping ratio 3 %**	**Damping ratio 5 %**	**Damping ratio 10 % and more**
0,3	0,9	0,8	0,7	0,5
1,1	3,2	2,9	2,5	1,9
8	3,2	2,9	2,5	1,9
33	1,0	1,0	1,0	1,0

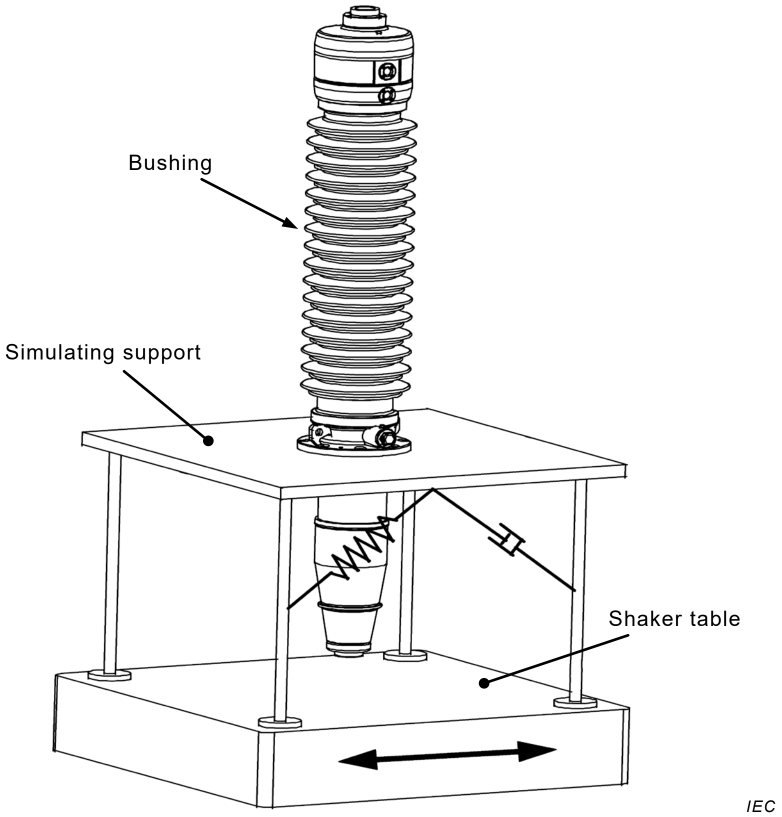
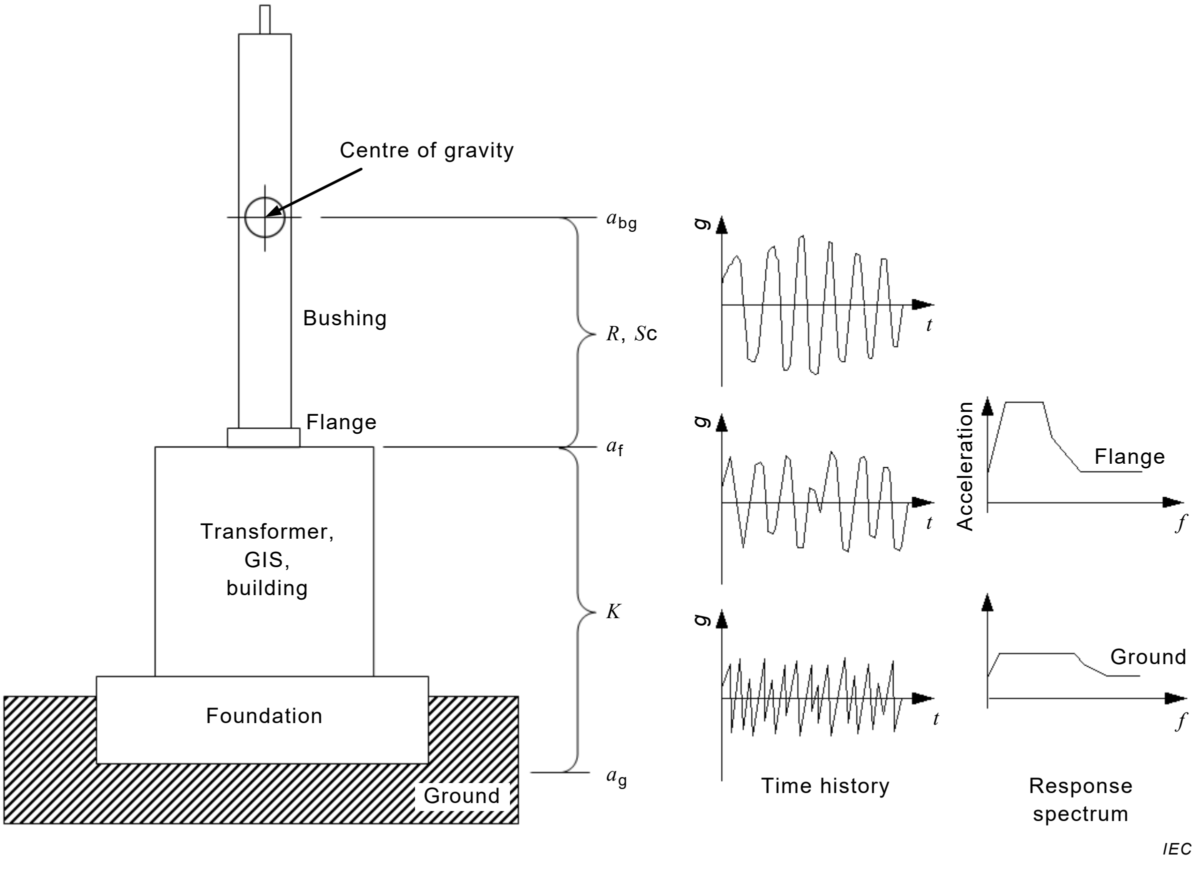


Figure 4 – Test with simulating support according to 9.3



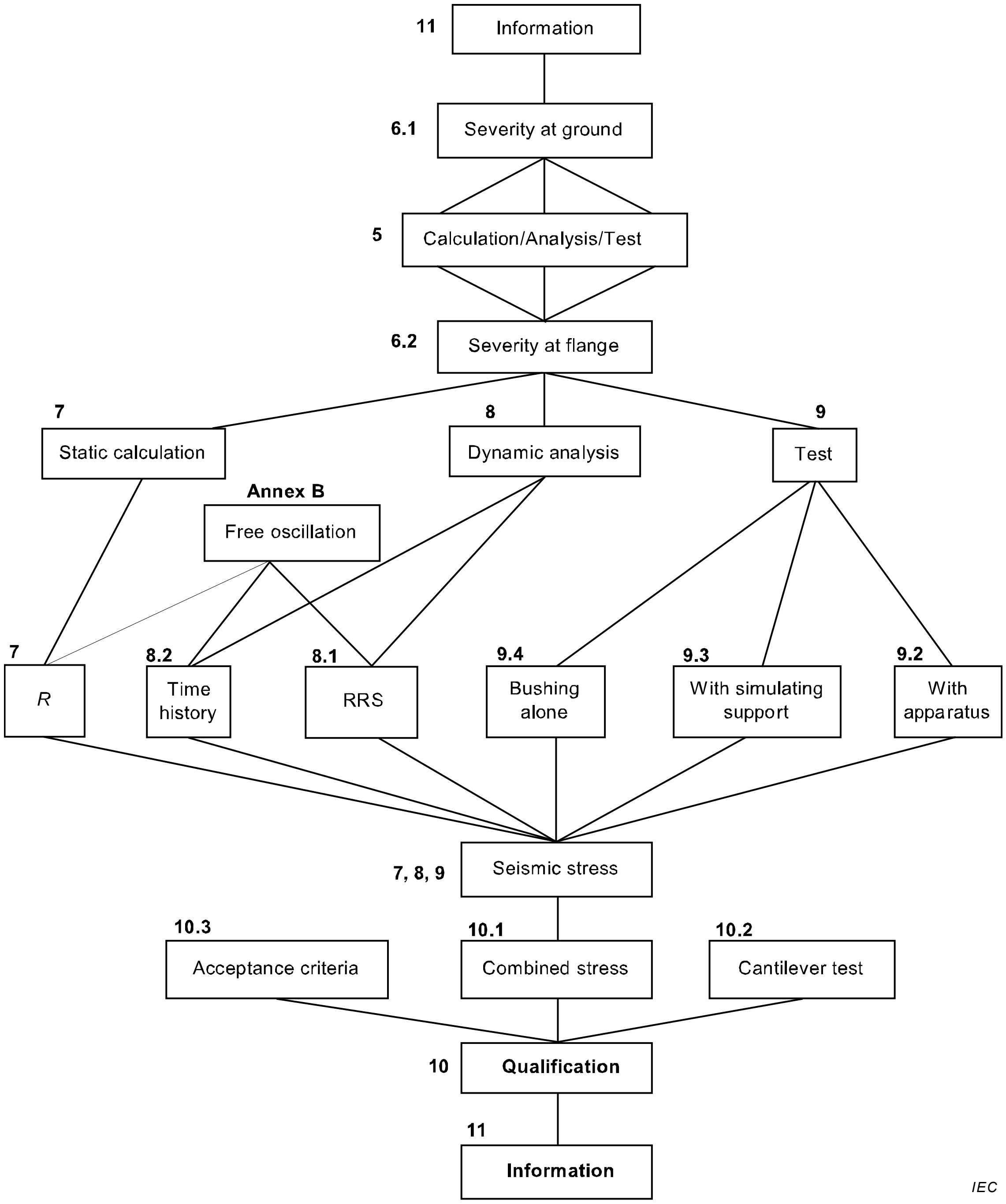
NOTE Time histories and relevant response spectra are given as examples only.

Figure 5 – Determination of the severity

Annex A
(informative)

Flow chart for seismic qualification

Figure A.1 shows a flow chart for seismic qualification.



NOTE Numbers at the blocks refer to clauses and subclauses of this technical specification

Figure A.1 – Flow chart for seismic qualification

Annex B
(informative)

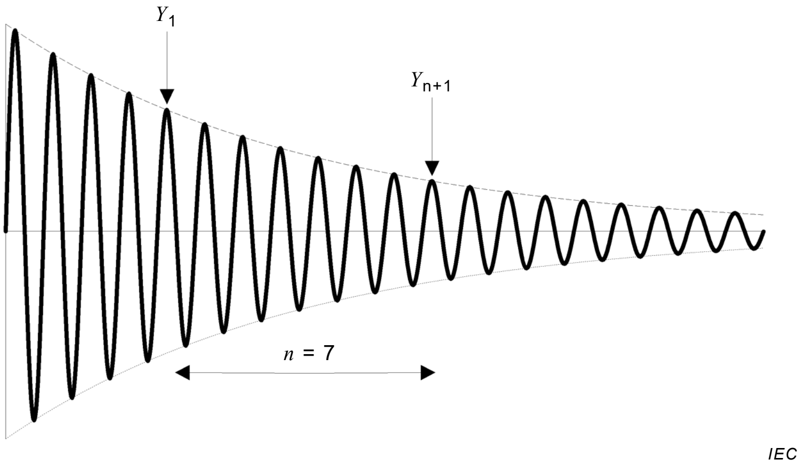
Natural frequency and damping determination: Free oscillation test

B.1 Free oscillation test

The natural frequency and damping can be obtained by a free oscillation test. Great care should be taken to distinguish between the data of the bushing and the data of the test frame. The test can be performed on the bushing when it is mounted upon the apparatus to obtain data for the actual application. Due to non-linear dynamic behaviour of the bushing, in order to obtain correct values on both frequency and damping, the test should preferably be performed with amplitude levels similar to those expected during an earthquake, but low enough to avoid damaging the apparatus under test.

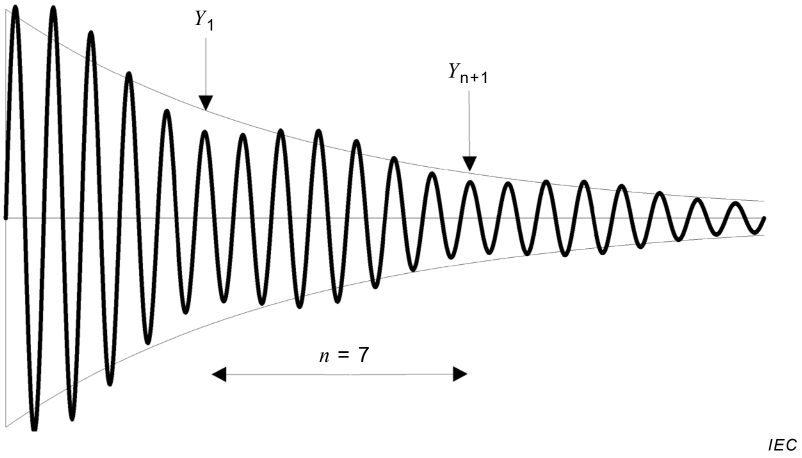
The bushing should be mounted as in service condition to the test frame or apparatus. A string should be connected to the terminal, pulled with a force corresponding to the expected earthquake stresses and then suddenly released.

Measurement transducers attached to the insulator and the bushing flange record the free oscillation of the bushing. If the flange also oscillates, this movement is subtracted if frequency and damping of the bushing itself are the sought values.



NOTE n represents the number of cycles.

Figure B.1 – Typical case of free oscillations



NOTE n represents the number of cycles.

Figure B.2 – Case of free oscillations with beats

The exponential curve in Figure B.1 is the envelope of the peak values. The exponential curve in Figure B.2 is obtained by using the least square roots of the peak values.

The damping ratio can be calculated by means of the following approximated formula:

$$d(\%) = \frac{1}{2\pi n} \times \ln\left(\frac{Y_1}{Y_{n+1}}\right) \times 100$$

The natural frequency and damping should be measured after a few periods, and before the amplitude has been significantly attenuated as shown in Figures B.1 and B.2.

The method described is commonly used to measure natural frequency and damping. Other methods can also be used.

B.2 Sine sweep frequency search

Sine sweep test is an equivalent method to determine the natural frequencies and dampings of an equipment.

The sine sweep 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 in the vertical one to determine the resonant frequencies and dampings.

The amplitude shall not be less than 0,05 g (an amplitude of 0,1 g is suggested).

A frequency 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.

Annex C
(informative)

Static calculation method – Additional considerations

C.1 General

The vibration at the centre of gravity of the bushing is of importance for the qualification by static calculation (see Clause 7).

As explained below, there is no simple relationship between the vibration occurring at the centre of gravity of the bushing during an earthquake and the equivalent acceleration a_{bg} used in Clause 7. The value of a_{bg} is taken in order to obtain $M_{\mathrm{s}} = a_{\mathrm{bg}} \times d_{\mathrm{p}} \times m_{\mathrm{p}}$ that gives a bending moment at the critical cross-section equivalent to that occurring during an earthquake. The explanation of the relation $a_{\mathrm{bg}} = a_{\mathrm{f}} \times S_{\mathrm{c}} \times R$ is given in C.2 to C.6.

C.2 Effect of the first bending mode

It is assumed that the bushing is equivalent to a clamped free beam and that the seismic wave excites only the first bending mode. By computation of this model for the first bending mode, and for a seismic excitation, the following can be determined:

- the bending moment at the base;
- the acceleration of the centre of gravity of the bushing (a_{bg}).

C.3 Determination of S_{c}

The coefficient S_{c} aims to take into account the effects of both multifrequency excitation and multimode response (see definition of S_{c} in Clause 4).

In the case of a bushing, the first bending mode, and possibly the second bending mode, is excited. An increase in stress of 45 % maximum over that of the first bending mode is obtained by the effect of the second bending mode (refer to Table C.1). As a consequence, a value of S_{c} between 1,0 and 1,5 without any additional safety margin is recommended.

C.4 Value of a_{bg}

From the above (with S_{c} = 1,5),

$$a_{\mathrm{bg}} = a_{\mathrm{f}} \times S_{\mathrm{c}} \times R = a_{\mathrm{f}} \times 1{,}5 \times R$$

As explained below, a_{bg} is different from the actual acceleration at the centre of gravity due to the seismic excitation.

a_{bg} differs from the value measured at the centre of gravity of the bushing excited on the shaker table with the RRS at the flange level: on the shaker table the absolute acceleration resulting from the dynamic behaviour of a continuous beam (all modes are involved) is measured, sometimes with the effect of coupling axes.

Consider a single degree of freedom system, as per Figure C.1:

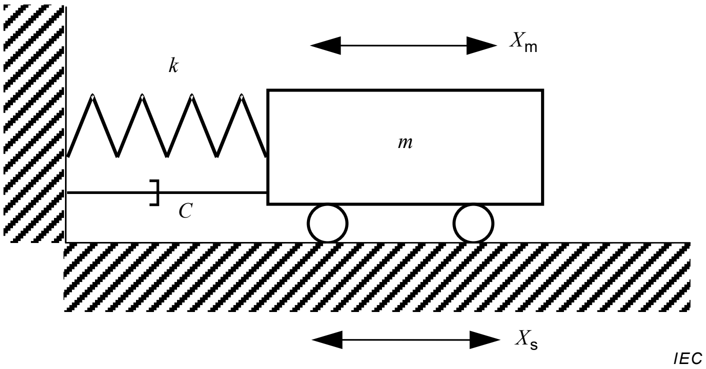


Figure C.1 – Single degree of freedom system

The equation of motion is

$$m(Xm''+Xs'') + CXm' + KXm = 0 \quad \text{or} \quad mXm'' = -mXs'' - CXm' - KXm$$

where

Xm is the relative displacement of the mass;

Xm' is the relative velocity of the mass;

Xm'' is the relative acceleration of the mass;

Xs'' is the input acceleration of the base.

The bending moment (and stress at the critical cross-section) is proportional to the absolute acceleration and to the relative displacement of the mass.

The flexibility of the system “turret plus base flange” and of the dampers (if any) will induce a rotation of the bushing around the base which will sum up to the bending deformations; the effects are analysed in Table C.1.

C.5 Typical seismic response of cantilever type structures

Many types of electrical apparatus may be considered as a cantilever type of structure only connected to the foundation at the base. Examples of such apparatus are bushings, measurement transformers and surge arresters. The seismic response of this type of structure can be predicted using well-known formulae for the dynamic behaviour of structures.

The elastic characteristics of apparatus will be inside a range given by the behaviour of an elastic beam deformed by bending and that of a hinged elastic rod with angular flexibility at the base.

The seismic response is usually dominated by the lowest mode of the structure (exceptions may be very flexible structures with lowest natural frequency below 1 Hz). SRSS procedure (square root of the sum of squares) may be used for combining modal response to resultant design value.

To assess the bending moment (M_s) at the critical cross-section, the commonly used simplified procedure of applying a seismic acceleration (given by estimated natural frequency and damping of lowest mode) at the centre of gravity yields a good approximation. See the examples given in Table C.1.

The actual seismic acceleration at the middle of the structure is, however, for cases of distributed mass, clamped and elastic base, not equal to the acceleration of the response spectrum but lower, typically in the range 0,5 to 0,8 of that acceleration level, depending on the shape of the lowest eigenmode. For the acceleration at the tip of the structure, a value of about 1,6 times the response acceleration is appropriate (see the examples given in Table C1).

The model of concentrated mass and elastic base needs a definition of the spring stiffness (rotational spring constant) (Table C.1). This value however generally can not be easily estimated from the dimensions and weight of the bushing. An experimental formula is reported below.

The lower portion of a bushing with cemented flange is composed by the porcelain, by the cement and by the metal flange (Figure C.2).

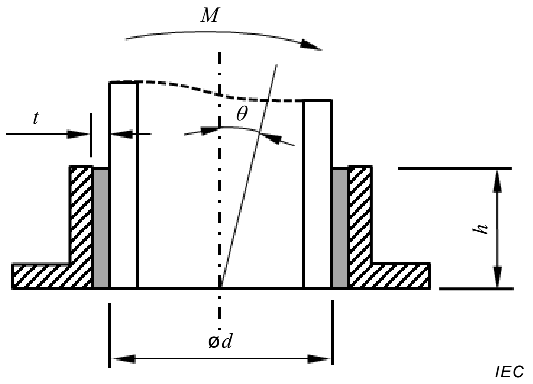


Figure C.2 – Structure at the flange of a bushing with cemented porcelain [5] [7]

This system is not rigid at it could appear, but the cement allows a certain elasticity if the bushing is subjected to a moment M.

As a consequence it is possible to define a spring stiffness C due to cementation (see for reference Figure C.2), by means of the following experimental formula:

$$C = 66{,}7 \times \frac{d \times h^2}{t}$$

where

C is the spring stiffness, in MNm/rad;

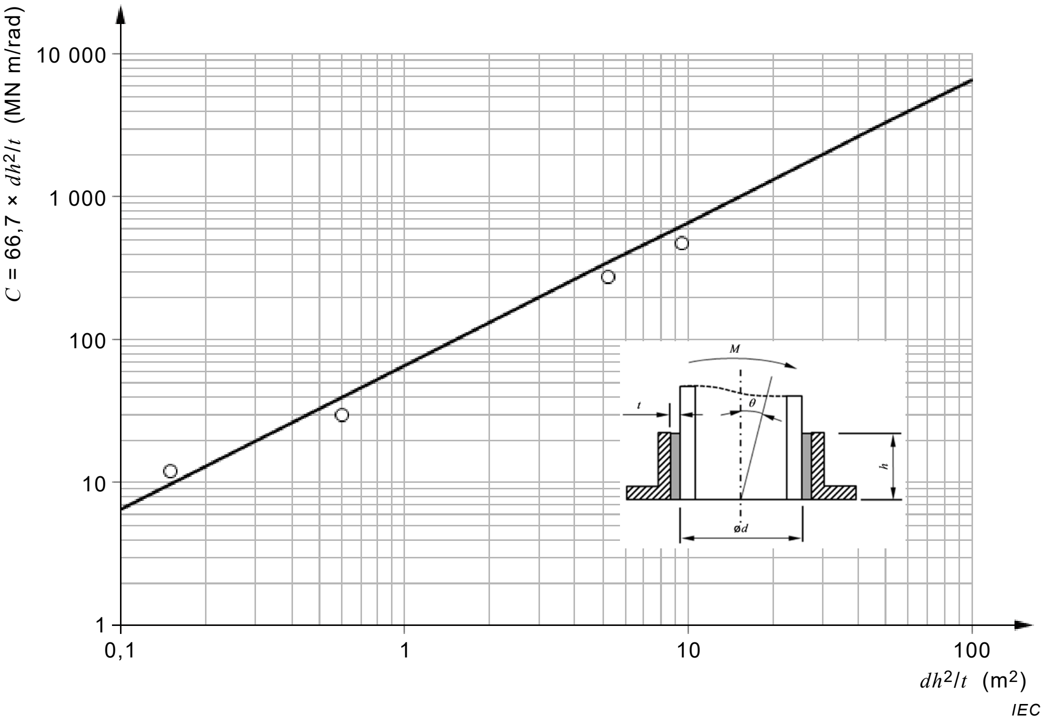
d is the external diameter of the porcelain, in m;

h is the height of the metallic flange, in m;

t is the thickness of the cement, in m.

For a visual check, a diagram can be built with C as ordinate and the ratio dh^2/t as abscissa (Figure C.3).

When this elastic phenomenon is not considered, generally the calculated natural frequency of the bushing shows a value slightly higher than real frequency. Validity of this equation has been confirmed by a campaign of measurements carried out in Japan [5] [7].



NOTE The circles are real cases.

Figure C.3 – Spring stiffness C in function of cemented part geometry [5] [7]

C.6 Superelevation factor K

The amplification factor at the top of the transformer body, were the bushing is fixed, depends on the existence of the transformer body itself and of its foundation (ref. to 6.2 and Figure 4).

When f_1 is the natural frequency of bushing-bushing turret system, f_0 is the natural frequency of soil-foundation-transformer body system, the relation between the ratio f_1/f_0 and the amplification or superelevation factor is presented as shown in Figure C.4.

These data come from Japanese measurements carried out on different transformers [5] [7].

According to these results, the superelevation factor given by the system transformer body and foundation is of the order of 1,5 to 2, as stated in 6.2.

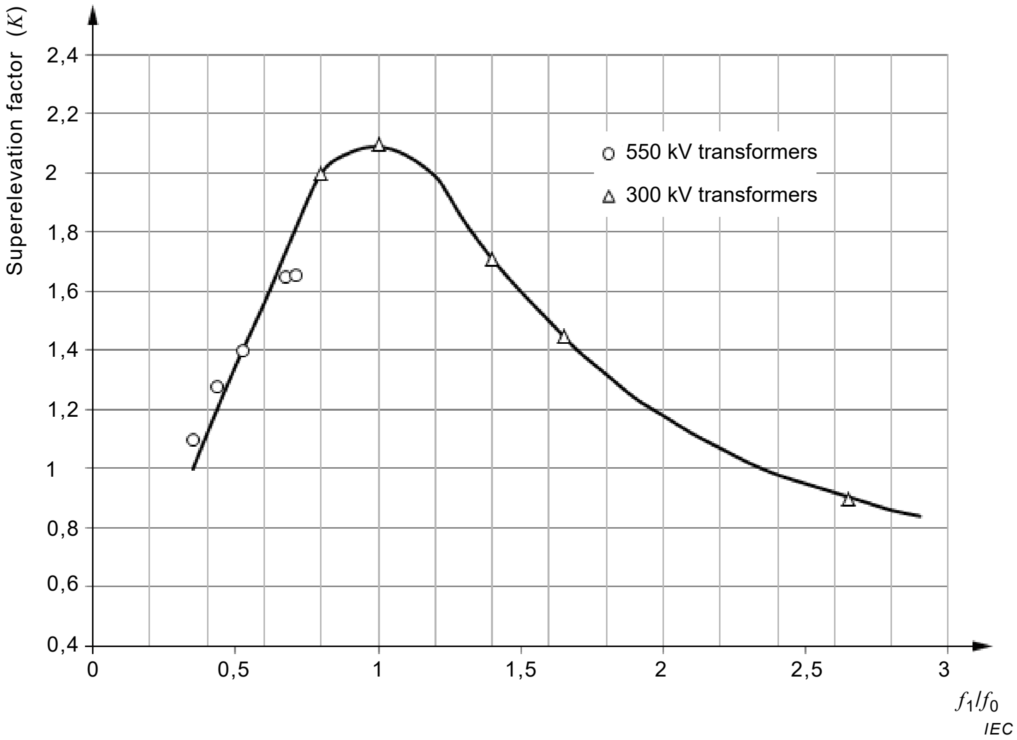
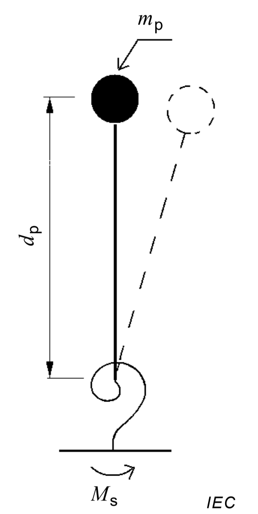
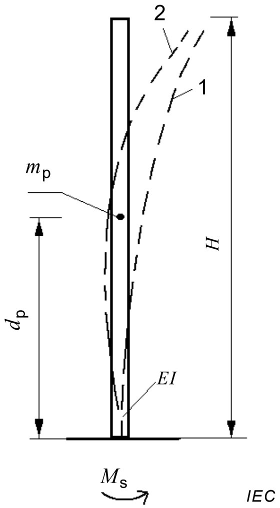
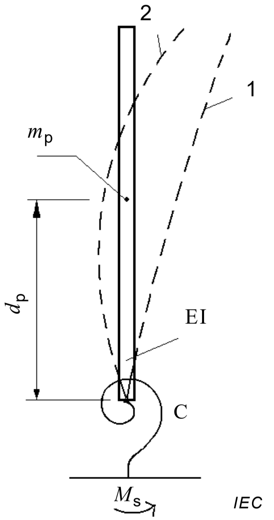


Figure C.4 – Superelevation factor due to the existence of transformer body and foundation [5]

Table C.1 – Examples of typical seismic responses

Characteristic		Type of structure									
Generic	**Example**	**Concentrated mass, elastic base**		**Distributed mass, clamped base**				**Distributed mass, elastic base [EI / (CH) = 1,53]**			
Total height H Centre of gravity height d_p Total mass m_p Bending stiffness EI Damping ratio x % Spring stiffness C	5 m 2,5 m 1 250 kg 32,8 MNmm^2 2 % 4,3 MNm/rad										
		Mode 1	**Example**	**Mode 1**	**Example**	**Mode 2**	**Example**	**Mode 1**	**Example**	**Mode 2**	**Example**
Natural frequency (f_i) [Hz]		$\frac{1}{2\pi}\sqrt{\frac{C}{(m_p\,x\,d_p^2)}}$	3,7	$\frac{0{,}56}{H}\sqrt{\frac{EI}{H\,m_p}}$	8,1	$\frac{3{,}51}{H}\sqrt{\frac{EI}{H\,m_p}}$	50,8	$\frac{0.208}{H}\sqrt{\frac{EI}{H\,m_p}}$	3.0	$\frac{2{,}544}{H}\sqrt{\frac{EI}{H\,m_p}}$	36,9
Ground response spectrum (spectral response acceleration, see Figure 2, with f_i and x %)		$S_A(\xi_1, f_1)$	16,2	$S_A(\xi_1, f_1)$	16,2	$S_A(\xi_2, f_2)$	5	$S_A(\xi_1, f_1)$	16,2	$S_A(\xi_2, f_2)$	5
Flange response spectrum = ground response spectrum × K (where K = 1,5) [m/s^2]		$K \times S_A$	24,3	$K \times S_{A1}$	24,3	$K \times S_{A2}$	7,5	$K \times S_{A1}$	24,3	$K \times S_{A2}$	7,5
Centre of gravity acceleration ($d_p = H/2$), a_{bg} [m/s^2]		$K \times S_A$	24,3	0,53 $K \times S_{A1}$	12,9	0,62 $K \times S_{A2}$	4,65	0,73 $K \times S_{A1}$	17,7	0,46 $K \times S_{A2}$	3,45

Characteristic		Type of structure									
Generic	**Example**	**Concentrated mass, elastic base**		**Distributed mass, clamped base**				**Distributed mass, elastic base [EI / (CH) = 1,53]**			
Top of the beam acceleration [m/s^2]		–	–	1,6 $K \times S_{A1}$	38,9	0,87 $K \times S_{A2}$	6,53	1,51 $K \times S_{A1}$	36,7	0,76 $K \times S_{A2}$	5,7
Bending moment at the base (critical cross-section), M_s [Nm]		0,5 $K\ S_A\ m_p\ H$	75 938	0,45 $K\ S_{A1}\ m_p\ H$	68 344	0,04 $K\ S_{A2}\ m_p\ H$	1 875	0,5 $K\ S_{A1}\ m_p\ H$	75 938	0,005 $K\ S_{A2}\ m_p\ H$	234

NOTE 1 Formulae obtained by rigorous mathematical analysis.

NOTE 2 K = Superelevation factor.

NOTE 3 f_1 and f_2 for the elastic beam with elastic base are, generally speaking, lower than the corresponding natural frequencies of the elastic beam with clamped base: the higher the ratio EI/(CH) is, the lower are the two frequencies f_1 and f_2 (high-base flexibility means low values of C). The lowest value of f_1, corresponding to C = 0, is zero: the beam is rigidly rotating about its base; the lowest value of f_2 is obtained by substituting 2,55 with 2,45 (about 70 % of the clamped base natural frequency).

NOTE 4 S_A = Spectral acceleration [m/s^2]

NOTE 5 Eigen value equation of the model with distributed mass and elastic base is the following:

$$\frac{EI}{CH} = \frac{1 + \cos \lambda H \cosh \lambda H}{\lambda H \left(\sin \lambda H \cosh \lambda H - \sinh \lambda H \cos \lambda H \right)}$$

With $\lambda^4 = \dfrac{\omega^2 \rho A}{EI}$ $\quad \rho$: *mass density*

A : *cross area*

When as solutions of this equation it is put $\lambda_N H$ with N = 1, 2, 3... natural frequencies are expressed as follows.

$$f_N = \frac{1}{2\pi} \left(\lambda_N H \right)^2 \frac{1}{H} \sqrt{\frac{EI}{H m_P}}$$

Following the example in this table, it is obtained *EI/CH* = 1,53, that gives $\lambda_1 H$ = 1,142, $\lambda_2 H$ = 3,998, $\lambda_3 H$ = 7,113, and consequently $f_1 = \dfrac{0.208}{H} \sqrt{\dfrac{EI}{H m_p}}$ $\quad f_2 = \dfrac{2,544}{H} \sqrt{\dfrac{EI}{H m_p}}$,

etc.

Annex D
(informative)

Qualification by static calculation – Example on transformer bushing

D.1 Seismic ground motion

In all calculations of earthquakes affecting bushings, the vertical acceleration shall be applied downwards in the direction of the acceleration due to gravity. This gives the greatest load on the bushing:

- horizontal ground acceleration, a_{gh}, (ZPA): 5 m/s^2
- vertical ground acceleration, a_{gv}: 2,5 m/s^2

D.2 Critical part of the bushing

When a cantilever test is performed or during an earthquake, the most critical part of the bushing is at the insulator base. The two major critical factors are the risk of oil leakage (see Figure D.1) and the bending stress at the insulator base. For this reason, the bending moments are calculated at the insulator base.

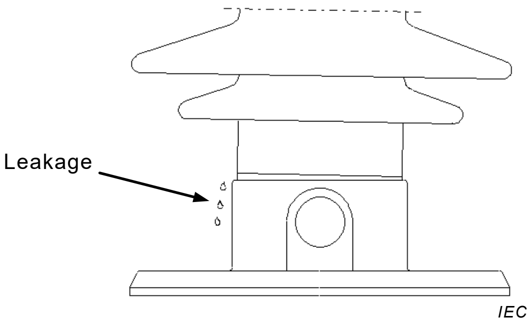


Figure D.1 – Critical part of the bushing

D.3 Static calculation

D.3.1 General

The transformer tank is very heavy compared to the bushings, but finite element (FEM) analysis shows that the transformer tank cannot be considered as rigid. The ground acceleration is amplified through the transformer tank to the transformer tank cover with an amplification factor K. Without background information, the amplification factor K is assumed to be 1,5 (see 6.2). If the bushing is mounted on a turret, this can be considered rigid. Therefore, the transformer tank cover and the turret are subjected to the same acceleration:

- horizontal acceleration at the transformer tank cover/turret ($K \times a_{gh} = K \times$ ZPA): 7,5 m/s^2
- vertical acceleration at the transformer tank cover/turret ($K \times a_{gv}$): 3,75 m/s^2

The acceleration of the transformer tank cover will be amplified to the bushing with the response factor R. The response factor depends on the natural frequency and the damping of the bushing mounted on the transformer tank cover. The value of the response factor R is taken from Figure 3.

If the response factor R cannot be estimated, the conservative value of the response factor at a certain value of damping is used. For a bushing mounted on a transformer tank cover, a damping ratio of 5 % can be assumed:

– natural frequency for bushing mounted on the transformer tank cover (Hz):	unknown
– damping ratio for bushing mounted on the transformer tank cover:	5 %
– response factor R, taken from Figure 3 (conservative value):	2,5

The response is then multiplied by a coefficient, S_c, which takes into account both multifrequency excitation and multimode response. The conservative value of the coefficient is 1,5.

The acceleration of the transformer tank cover, the response factor of the bushing mounted on the transformer tank cover, the static coefficient and the air side mass, m_p, of the bushing give rise to a force that affects the bushing at the air side centre of gravity (see D.3.1). If the bushing is mounted at angles to the vertical plane, both the vertical and the horizontal parts of the earthquake will affect the bushing.

D.3.2 Seismic load

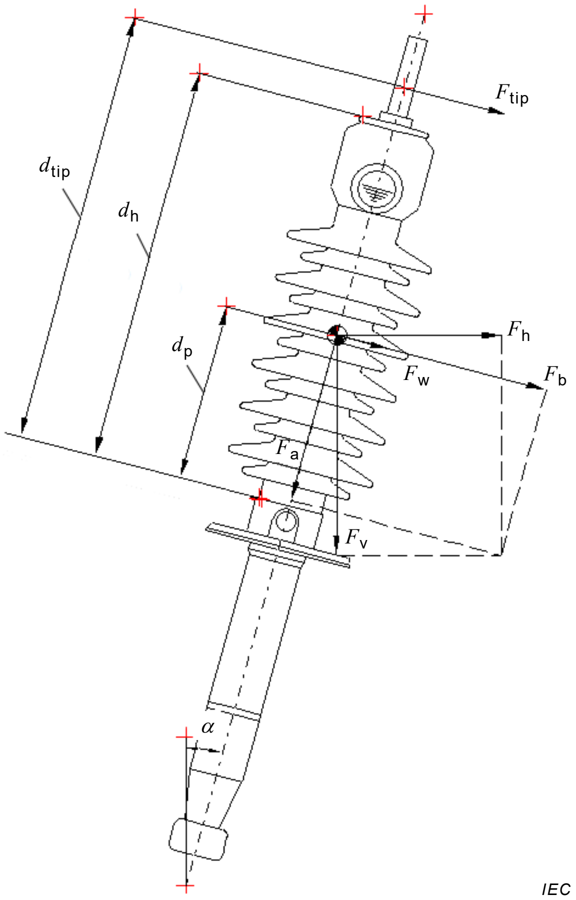


Figure D.2 – Forces affecting the bushing

In these seismic calculations, the vertical acceleration is applied downwards, in the same direction as the acceleration due to gravity. This produces the greatest load on the bushing.

The air side mass of the bushing, m_p, is the mass of all the parts of the bushing above the bushing flange.

d_p is the distance from the critical part of the bushing flange to the air side centre of gravity (see Figure D.2):

- air side mass, m_p: 63 kg
- d_p: 590 mm
- mounting angle to the vertical plane, α: 20°
- horizontal force, F_h, $(m_p \times K \times a_{gh} \times R \times S_c)$: 1772 N
- vertical force, F_v, $(m_p \times K \times a_{gv} \times R \times S_c + m_p \times g)$: 1516 N
- compressive force, F_a, $(-F_h \times \sin \alpha + F_v \times \cos \alpha)$: 819 N
- bending force, F_b, $(F_h \times \cos \alpha + F_v \times \sin \alpha)$: 2184 N
- bending moment due to the seismic event and gravity, M_{bs}, $(F_b \times d_p)$: 1,29 kNm

D.3.3 Wind load

Wind loads are considered as static loads. As a combination of the extreme values of all electrical and environmental service loads would lead to unrealistic conservatism, a wind pressure of 70 Pa acting at the same time as an earthquake should be assumed.

The resulting wind force (F_w) affects the bushing in its air side centre of gravity (see Figure D.3):

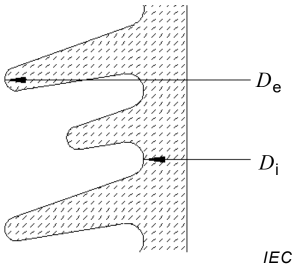


Figure D.3 – Porcelain diameters

- wind pressure, p: 70 Pa
- outer diameter of the porcelain sheds, D_e, see Figure D.3: 280 mm
- outer diameter of the porcelain core, D_i, see Figure D.3: 150 mm
- distance from the critical cross-section to the top of the bushing, d_h, see Figure D.2: 1 205 mm
- wind force, F_w, see Figure D.2, $(p \times (D_e + D_i)/2 \times d_h)$: 18,14 N
- bending moment due to the wind, M_{bw}, $(F_w \times d_p)$: 0,01 kN·m

D.3.4 Terminal load

The tip load at an earthquake event is equal to 70 % of the cantilever operating load specified for the bushing according to 10.1:

- cantilever operating load, taken from IEC 60137 (U_r = 170 kV, I_r = 1250 A, Class I), F_{op}: 800 N
- tip load at the terminal, F_{tip}, see Figure D.2, $(F_{op} \times 0,7)$: 560 N
- distance from the critical cross-section to the terminal, d_{tip}, see Figure D.2: 1 325 mm
- bending moment due to the tip load, M_{btip}, $(F_{tip} \times d_{tip})$: 0,74 kNm

D.4 Guaranteed bending strength

The bushing must withstand a cantilever test load in accordance with IEC 60137 without leakage or damage. The bending moment occurring during this test should be compared with the total bending moment occurring at the critical cross-section due to the seismic, wind, terminal loads and the effect of gravity:

– cantilever withstand load, F_{test}:		1 600 N
– bending moment occurring under cantilever test:	$(F_{\text{test}} \times d_{\text{tip}})$	2.12 kNm
– total bending moment occurring during the seismic event:	$(M_{\text{bs}} + M_{\text{bw}} + M_{\text{btip}})$	2,04 kNm

Result of qualification:

The bending strength is greater than the stress during the specified seismic event. The bushing is therefore qualified.

As an alternative, it can be compared the mechanical stress (moment due to cantilever) at which the insulator mounted on the bushing has been subjected during its type tests with the one above found, which must be lower.

Annex E
(informative)

Center clamped bushings

The external insulator of a traditional oil-to-air bushing for transformer can be of four types: composite, porcelain cemented to the flange, porcelain mechanically clamped to the flange and porcelain center clamped.

Figure E.1 shows the typical structure of a center clamped bushing.

The porcelain is compressed by the axial clamping force of the springs placed in the bushing head that act on the pre-tensioned central tube or rod of the bushing. The lower end of the insulator is not fixed to the flange, as for the other types, and generally a gasket is inserted between the lower end of the porcelain and the flange.

When a lateral increasing force is applied, the bending moment increases up to a value that exceeds the opposite resistance moment given by the axial compression force of the springs, and the porcelain starts to uplift from its end fitting. When this opening process is only small, in case of an oil impregnated paper bushing, some oil starts to exit and when the bending force decreases the bushing recloses without damages (the nonmetallic gasket normally placed between porcelain and end fitting protects in this case from ruptures), but when the opening process is more evident the bushing remains damaged (gasket extrusion or even worse porcelain breaking).

The failure process of a center clamped bushing is typical of this type of bushing and can be schematized in the following steps (make reference to Figure E.1 and to the following flow chart of Figure E.2), depending on the lateral force entity:

d) opening starts and in presence of oil there is a slight spilling;
e) slippage of porcelain and extrusion of the gasket;
f) increase of tensile stress at the lower end of porcelain;
g) cracking of the edge of the porcelain.

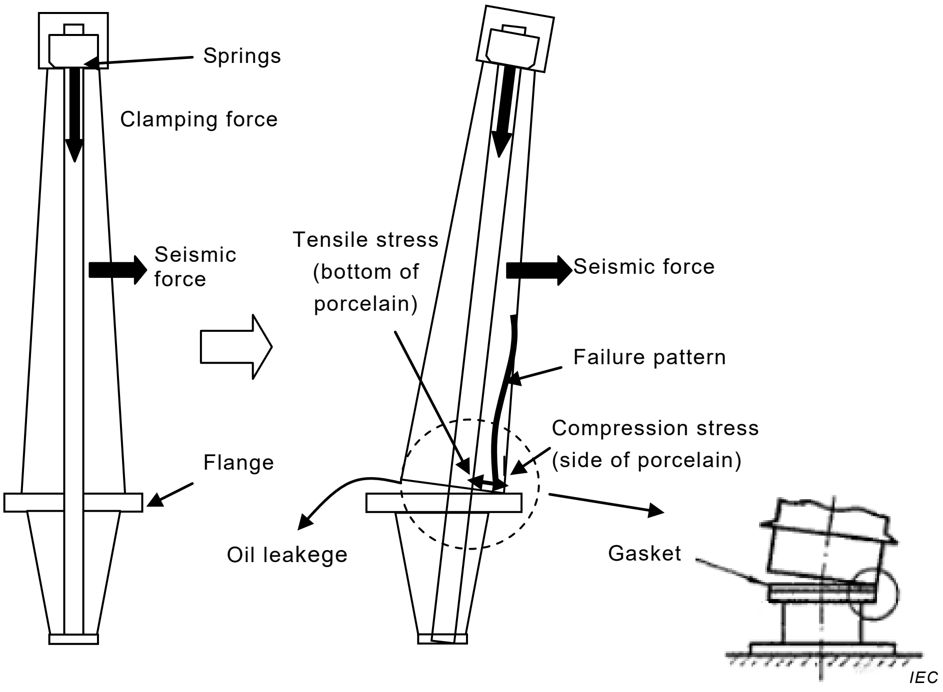


Figure E.1 – Failure process [6]

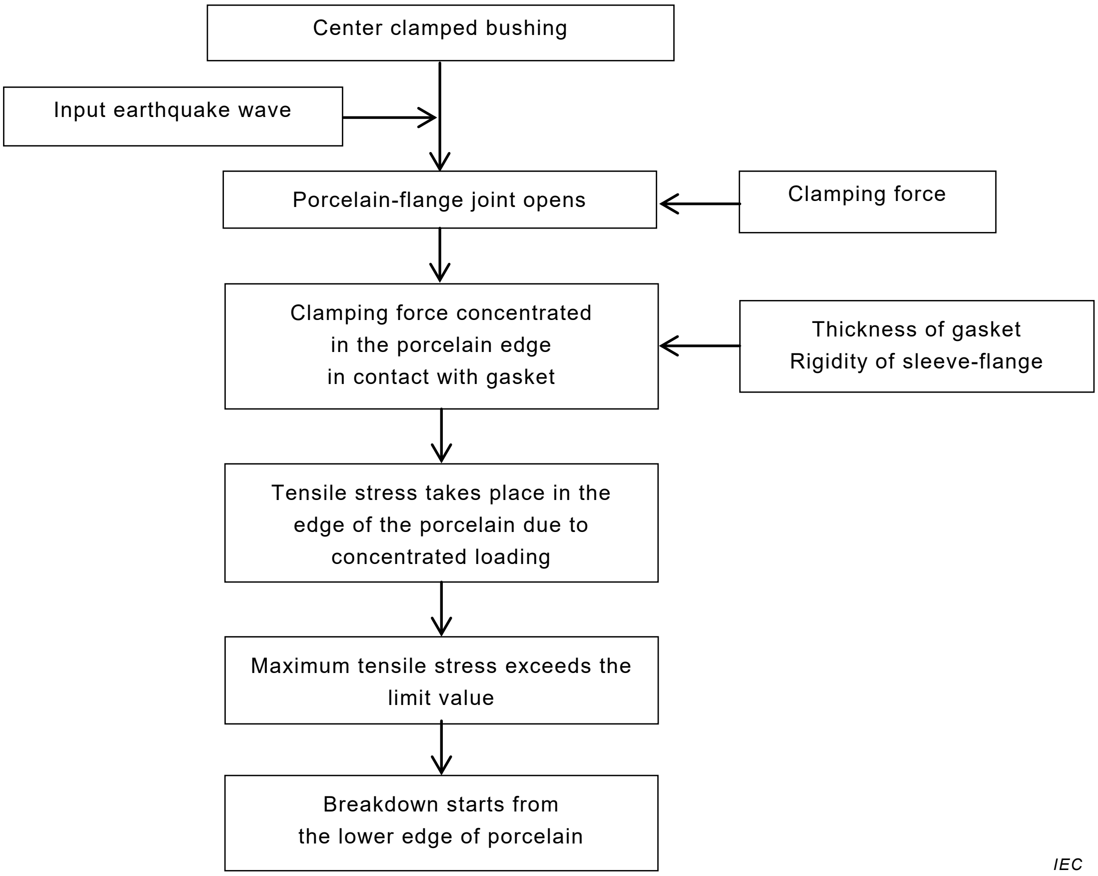


Figure E.2 – Failure process, flow chart [5] [6]

The profile of the stresses, compression stress (σc) and tensile stress (σt), during the opening phase of the insulator is qualitatively indicated in Figure E.3.

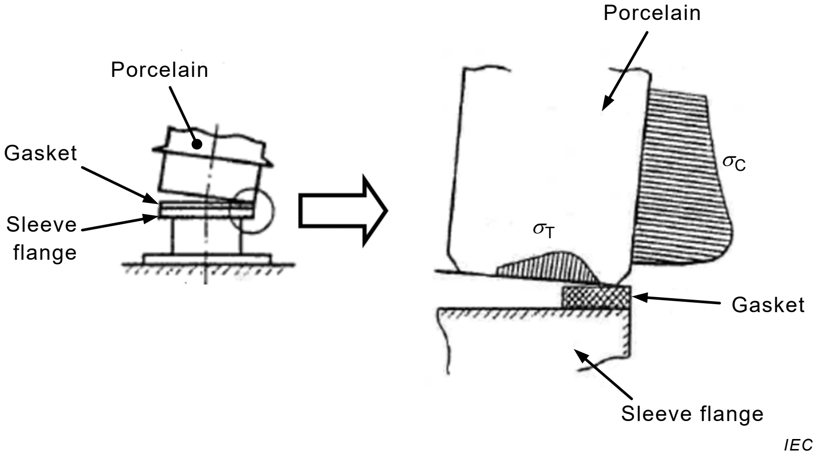


Figure E.3 – Stress profile during the opening process [6]

Following to some experimental and FEM studies, it has been found a dependence between the compression stress and the tensile stress in the edge of the porcelain part due to the concentrated loding.

A diagram is shown in Figure E.4 [6].

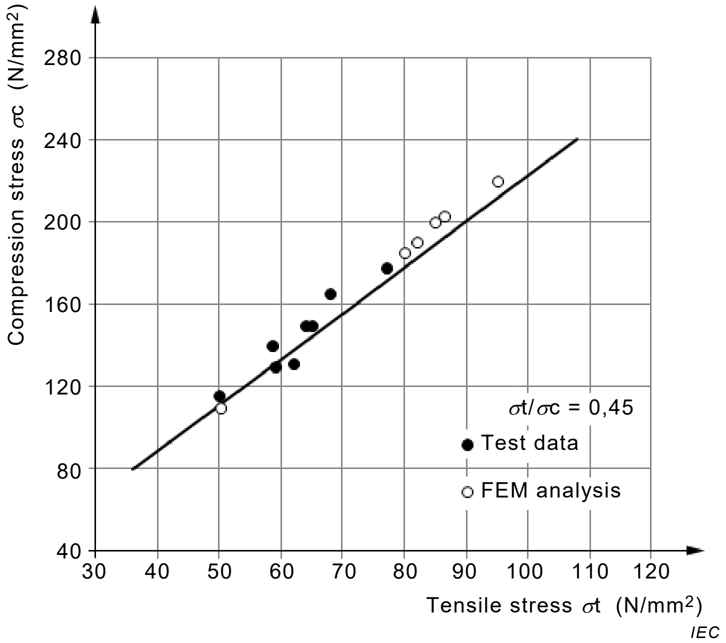


Figure E.4 – Relation between compression and tensile stress in the bottom edge of the porcelain due to the opening process [6]

This relation can be useful because is possible to measure the compression stress with strain gauges, and calculate consequently the tensile stress.

Special consideration shall be paid for the seismic evaluation of this kind of bushings, because due to their structure they show typical non-linear phenomena, to be taken into account during the vibrational tests.

The following three types of non-linear phenomena are observed.

1) Natural frequency shifts to low frequencies when increasing the input level.

   As a consequence, when a sinusoidal wave as sine-beat with natural frequency is used, an accurate searching of maximum response will be necessary in order to calibrate the exciting frequency.

2) Vibration mode changes from simply bending to a rotation+bending. The rotation is consequence of the opening phenomenon of the porcelain. This leads to a behavior no more axisymmetric.

3) The response of the bushing shows non-linear characteristic when the input level is increased.

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