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Edition 1.1 2019-05
CONSOLIDATED VERSION

TECHNICAL SPECIFICATION

colour
inside

High voltage direct current (HVDC) substation audible noise

IEC TS 61973:2012-04+AMD1:2019-05 CSV(en)

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High voltage direct current (HVDC) substation audible noise

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HIGH VOLTAGE DIRECT CURRENT (HVDC) SUBSTATION AUDIBLE NOISE

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IEC TS 61973 edition 1.1 contains the first edition (2012-04) [documents 22F/243/DTS and 22F/260/RVC] and its amendment 1 (2019-05) [documents 115/197/DTS and 115/207/RVDTS].

In this Redline version, a vertical line in the margin shows where the technical content is modified by amendment 1. Additions are in green text, deletions are in strikethrough red text. A separate Final version with all changes accepted is available in this publication.

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

IEC 61973, which is a technical specification, has been prepared by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment, with the participation of IEC technical committee 115: High voltage direct current (HVDC) transmission for DC voltages above 100 kV.

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

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

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HIGH VOLTAGE DIRECT CURRENT (HVDC) SUBSTATION AUDIBLE NOISE

1 Scope

This technical specification applies to the specification and evaluation of outdoor audible noise from high voltage direct current (HVDC) substations. It is intended to be primarily for the use of the utilities and consultants who are responsible for issuing technical specifications for new HVDC projects with and evaluating designs proposed by prospective contractors. It is primarily intended for HVDC projects with line-commutated converters. Part of this technical specification can also be used for the same purpose for HVDC projects using voltage sourced converters, and for flexible a.c. transmission systems (FACTS) devices such as static Var compensators (SVCs) and static synchronous compensators (STATCOMs).

2 Normative references

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

IEC 60076-10, *Power transformers – Part 10: Determination of sound levels*

IEC 60076-10-1*, Power transformers – Part-10-1: Determination of sound levels – Application guide*

IEC 61672-1, *Electroacoustics – Sound level meters – Part 1: Specifications*

IEC 61672-2, *Electroacoustics – Sound level meters – Part 2: Pattern evaluation tests*

ISO 1996-2, *Acoustics – Description, assessment and measurement of environmental noise – Part 2: Determination of environmental noise levels*

ISO 266:1997*, Acoustics – Preferred frequencies*

ISO 3740*, Acoustics – Determination of sound power levels of noise sources – Guidelines for the use of basic standards*

ISO 3743-2, *Acoustics – Determination of sound power levels of noise sources; engineering methods for small, movable sources in reverberant fields – Part 2: Methods for special reverberation test rooms*

ISO 3744, *Acoustics – Determination of sound power levels and sound energy levels of noise sources using sound pressure – Engineering methods for an essentially free field over a reflecting plane*

ISO 3745, *Acoustics – Determination of sound power levels of noise sources using sound pressure – Precision methods for anechoic and hemi-anechoic rooms*

ISO 3746, *Acoustics – Determination of sound power levels and sound energy levels of noise sources using sound pressure – Survey method using an enveloping measurement surface over a reflecting plane*

ISO 8297, *Acoustics – Determination of sound power levels of multisource industrial plants for evaluation of sound pressure levels in the environment – Engineering method*

ISO 9613-1, *Acoustics – Attenuation of sound during propagation outdoors – Part 1: Calculation of the absorption of sound by the atmosphere*

ISO 9613-2, *Acoustics – Attenuation of sound during propagation outdoors – Part 2: General method of calculation*

ISO 9614-1, *Acoustics – Determination of sound power levels of noise sources using sound intensity – Part 1: Measurement at discrete points*

ISO 9614-2, *Acoustics – Determination of sound power levels of noise sources using sound intensity – Part 2: Measurement by scanning*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1 Sound and noise terms

3.1.1
sound
any pressure variation in air, water or other elastic medium

Note 1 to entry: Sound is expressed as sound pressure, sound intensity or sound power (see 3.1.3).

Note 2 to entry: In this technical specification, the medium is assumed to be air.

3.1.2
sound waves in air
traveling sound pressure fluctuations

3.1.3
sound pressure
p
fluctuating pressure superimposed on the static pressure

Note 1 to entry: Sound pressure is expressed in pascal.

Note 2 to entry: Sound pressure is usually expressed through the use of a decibel scale, as sound pressure level (see 3.1.4).

3.1.4
sound pressure level
L_p
logarithm of the ratio of the r.m.s. value of a given sound pressure to the reference sound pressure

$$L_p = 10 \lg \left(\frac{(p)^2}{(p_0)^2} \right) = 20 \lg \left(\frac{p}{p_0} \right)$$

where:

p is the measured r.m.s. sound pressure in pascal;

p_0 is the reference r.m.s. pressure of 2×10^{-5} pascal, which corresponds to the 0 dB as threshold of audibility.

Note 1 to entry: lg(x) means the 10th logarithm of x; this convention is used throughout the document.

Note 2 to entry: The sound pressure level (L_p) is expressed in decibels (dB).

Note 3 to entry: Sound pressure level is measured with sound level meters, which normally incorporate a frequency-weighting filter. For further details see 3.2.3.

Note 4 to entry: Since the sound level distribution measured around sound emitting objects is usually non-uniform it is normally necessary to assess sound levels on spatial average figures gained from several measuring positions rather than on one single discrete position.

3.1.5
average sound pressure level

$\overline{L}_{p\mathrm{A}}$

$$\overline{L}_{p\mathrm{A}} = 10\ \mathrm{lg}\left(\frac{1}{N}\sum_{i=1}^{N} 10^{0{,}1 L_{p\mathrm{A}i}}\right)$$

where:

$\overline{L}_{p\mathrm{A}}$ is the average sound pressure level in dB(A);

$L_{p\mathrm{A}i}$ is the measured sound pressure level at location i in dB(A), if required corrected for the influence of background noise;

N is the total number of measurement locations.

Note 1 to entry: The summation of several frequency bands (1/1-octave, 1/3-octave etc.) is performed in a similar fashion:

~~$\overline{L}_{p\mathrm{A}} = 10\ \mathrm{lg}\left(\frac{1}{N}\sum_{i=1}^{N} 10^{0{,}1 L_{p(f\,j)}}\right)$~~

$$\overline{L}_{p\mathrm{A,TOT}} = 10\mathrm{lg}\left(\frac{1}{N}\sum_{i=1}^{N} 10^{0{,}1 L_{p(f_j)}}\right)$$

where:

$\overline{L}_{p\mathrm{A,TOT}}$ is the total sound pressure level in dB(A);

$L_P(f_j)$ is the sound pressure level in frequency band f_j in dB(A), if required, corrected for the influence of background noise;

N is the total number of frequency components.

Note 2 to entry: See 3.2.2 for more information on 1/3-octave and 1/1-octave bands.

3.1.6
sound intensity

I_I

for a plane propagating sound wave, the sound intensity, I_I at a given point is defined as

$$I_I = \frac{p^2}{\rho \times c}$$

where:

p is the r.m.s. value of the measured sound pressure in pascal;

ρ is the constant density of air in equilibrium in kg/m^3;

c is the speed of sound in air in m/s.

3.1.7
normal sound intensity

I_{In}

for a plane propagating sound wave, the sound intensity, I_I at a given point in the normal direction n is defined as

$$I_{In} = \frac{p^2}{\rho \times c}$$

where:

p is the r.m.s. value of the measured sound pressure in pascal;

ρ is the constant density of air in equilibrium in kg/m^3;

c is the speed of sound in air in m/s.

3.1.8
sound intensity level

L_I

expressed in decibels ratio of the sound intensity to the reference sound intensity

$$L_I = 10 \lg \left(\frac{|I|}{I_0} \right)$$

where, $I_0 = 1 \times 10^{-12} \text{Wm}^{-2}$

3.1.9
normal sound intensity level

L_{In}

ratio of the normal sound intensity to the reference sound intensity

$$L_{In} = 10 \lg \left(\frac{|I_n|}{I_0} \right)$$

where, $I_0 = 1 \times 10^{-12} \text{Wm}^{-2}$

Note 1 to entry: Normal sound intensity level is expressed in decibel.

Note 2 to entry: I_n may be negative if there is a sound wave into the enclosing surface, which may happen in the acoustical near-field. The level is then expressed as – “xx” dB. The equation in 3.1.6 however assumes a plane propagating wave in the far-field of a sound source, in the direction defined as positive.

3.1.10
sound power
W

rate at which sound energy is radiated by a source

Note 1 to entry: Sound power is a scalar quantity and is expressed in watt.

Note 2 to entry: The total sound power is defined as:

$$W = \oint_A \overline{I}\, d\overline{A}$$

where:

A is a closed surface of integration;

$\overline{I}$ is the vector of sound intensity on an elementary surface $d\overline{A}$.

3.1.11
sound power level
L_W

$$L_W = 10 \lg \left(\frac{W}{W_0} \right)$$

where:

W is the emitted sound power in watt;

W_0 is a reference sound power of 1×10^{-12} W and corresponding to 0 dB as the threshold of audibility.

Note 1 to entry: The sound power level is expressed in decibel.

Note 2 to entry: The A-weighted sound power level ($L_{W\text{A}}$) of an object may be determined from the surface sound pressure level ($L_{p\text{A}}$) according to ISO 3744.

$$L_{W\text{A}} = L_{p\text{A}} + 10 \lg \left(\frac{S}{S_0} \right)$$

where:

S is the area of the “measurement surface” enclosing the object (in m^2);

S_0 is a reference area of 1 m^2.

Note 3 to entry: The sound power within an enclosing surface is independent of the distance to the sound source, but the sound pressure depends on the distance, reflections etc.

3.1.12
sound propagation
for hemispherical propagation over a reflecting plane, the sound pressure level at a given point depends on the distance from the source, the source sound power and the geometry involved as expressed by the following equations

$$L_p = L_W - 10 \lg (2\pi r^2)$$

or alternatively

$$L_p = L_W - 10\ \lg(2\pi) - 20\ \lg(r)$$

Note 1 to entry: This expression is sometimes called “the law of distance” in acoustics, when dealing with sound propagation from stationary sources. The law of distance implies that the sound pressure level decreases by six decibels (6 dB) for each doubling of distance from the sound source, provided that the measurements are performed in the *far-field* of the sound source. The boundary of the far-field depends among other things on the size of the sound source, the spatial complexity of the sound field and on the radiated frequency. For example; for a large transformer, the far-field may begin at a distance of 30 m from the transformer. For a small reactor which radiates sound at e.g. 1 kHz, the far-field may begin at a distance of 5 m.

The law of distance is strictly speaking only valid for point sources. Many sources can however be treated as point sources at a sufficient distance from the source. Care must however be taken when applying the formula on real sources.

3.1.13
noise

unwanted sound

3.1.14
audible noise

unwanted sound with frequency range from 20 Hz to 20 kHz

3.2 Sound radiation terms

3.2.1
directivity of sound radiation

$$L_p = L_W - 10\ \lg \frac{4\pi r^2}{Q}$$

where:

L_p is the sound pressure level at distance r from the sound source;

L_W is the sound power of the sound source;

r is the distance between the source and the receiver;

Q is the directivity factor of the sound radiation, e.g.

Q = 1 for spherical sound propagation (see Figure 1);

Q = 2 for hemispherical sound propagation (see Figure 2);

Q = 4 for quarter spherical sound propagation (see Figure 3).

Note 1 to entry: The directivity of sound radiation may also be expressed in decibel and is then called directivity index (DI) which is defined by

$$DI = 10\ \lg Q$$

For example, for Q = 2 ⇒ DI = 3 dB, or for Q = 4 ⇒ DI = 6 dB.

Note 3 to entry: The directivity index is a correction index (dB-adder) which quantifies the deviation of the sound propagation from uniform spherical spreading. The sound pressure level may then be calculated from:

$$L_p = L_W + DI - 10\ \lg 4\pi r^2$$

3.2.2
sound measurement filters

standard filters used for sound measurement equipment and measuring the total level of sound pressure in a defined frequency band

Note 1 to entry: Usually “1/1-octave” or “1/3-octave” filters are used for these measurements. One 1/1-octave band contains three 1/3 octave bands. For example, the 31,5 Hz 1/1-octave band contains the 25 Hz, 31,5 Hz and 40 Hz 1/3-octave bands.

The top (f_1) and bottom (f_2) clause frequencies of the filter are related as follows:

$$f_2 = 2^a f_1$$

where:

a is 1 for the “octave” filter;

a is 1/3 for the “1/3 octave” filter.

The centre frequencies of the filters to be used should meet applicable standards (see ISO 266, [1[1]]).

3.2.3
A-weighting sound pressure level
A-weighted sound pressure level

incorporating the sound level measurement, is a frequency-weighting filter which differentiates between sounds of different frequency in a similar way to the human beings. It is expressed in dB (A)

A-weighted integrated sound pressure level, $L_{p\mathrm{A}}$ or L_{Aeq} is given by

$$L_{p\mathrm{A}} = L_{\mathrm{Aeq}} = 20\ \mathrm{lg}\frac{\left(\frac{1}{T}\cdot\int_{0}^{T} p_{\mathrm{A}}{}^{2}(t)d(t)\right)^{\frac{1}{2}}}{p_0}$$

where

T is the averaging time interval;

$p_{\mathrm{A}}(t)$ is the A-weighted instantaneous sound pressure;

p_0 is the reference sound pressure.

Note 1 to entry: There are other frequency weightings, for example ”C-weighting”, “D-weighting” etc. Measurements in dB (A) generally agree with people’s assessment of “loudness.” For more information about sound level meters and A-weighting see IEC 61672-1 and IEC 61672-2.

3.2.4
reflecting plane

any surface which fully reflects sound

3.2.5
principal radiating surface

hypothetical surface surrounding the test object, which is assumed to be the surface from which sound is radiated

3.2.6
prescribed contour

horizontal line on which the measuring positions are located and spaced at a defined horizontal distance (the "measurement distance") from the principal radiating surface

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[1] Numbers in brackets refer to the Bibliography.

3.2.7
measurement surface
hypothetical surface enveloping a sound source, on which the measurement points are located ,and terminating on one or more reflecting planes

3.2.8
measurement distance
X
horizontal distance between the principal radiating surface and the measurement surface

3.2.9
background noise
sound pressure level with the test object inoperative

Note 1 to entry: In this case, the test object can be the whole HVDC substation or a single component.

3.3 Acoustic fields

3.3.1
acoustic near field
region of space within a fraction of a wavelength away from a sound source

Note 1 to entry: According to this definition, the outer boundary of the near-field region varies inversely with frequency. In the near field, pressure fluctuations are typical and the sound pressure p and the particle velocity shows an arbitrary phase difference.

For the site location of and the frequencies emitted by an HVDC substation, the sound measurements are normally performed in the acoustic far field. Sound measurement in the near-field of structural sound sources is difficult in HVDC substations, since

- for safety reasons it is prohibited to access energized equipment like capacitor banks and air cored reactors; and
- it is also prohibited to access the top of the transformers while energized.

With regard to air-cored reactors considerations must be given to the influence of the magnetic field on the test equipment.

3.3.2
acoustic far field
region of space when, in the far field, the sound pressure and the particle velocity are almost in phase and show approximately plane sound wave propagation

Note 1 to entry: Since the plane sound wave propagation is a good approximation of spherical wave conditions in the far-field , it can be used as the best engineering approach for sound measurements. For further details, refer to ISO 9614-1 and ISO 9614-2.

4 Environmental influences

4.1 General

When sound is emitted from a source with a certain sound directivity, the surrounding environment influences how the sound propagates and is perceived over distance [2, 3]. This clause describes those environmental influences, namely "background noise", "topography" and "meteorological conditions". Above all, meteorological conditions have a significant influence on sound propagation over large distances (of order hundreds of meters).

4.2 Directivity of sound radiation

The simplest method to predict sound propagation (and one which is still frequently used) is to assume that the sound emitting source has a uniform pattern of sound radiation following the hemispherical spreading theory (see Figure 2).

However, some sound-emitting sources or groups thereof show a distinct directivity of sound radiation, which needs to be considered in the HVDC substation layout. Other effects, such as screening, reflection and absorption may also be included in sound propagation considerations.

The directivity of sound radiation may also be expressed in dB and is then called directivity index (DI) which is defined by:

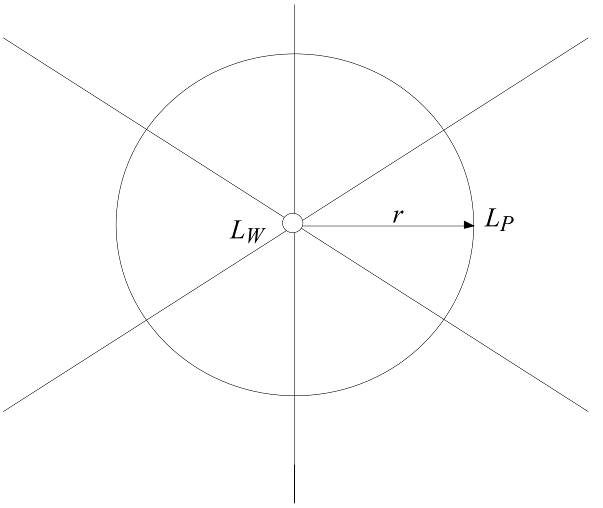
$$DI = 10 \lg Q \tag{1}$$

For example, for $Q = 2 \Rightarrow DI = 3$ dB, or

for $Q = 4 \Rightarrow DI = 6$ dB

The directivity index is a correction index (dB-adder) which quantifies the deviation of the sound propagation from uniform spherical spreading. The sound pressure level may then be calculated from:

$$L_p = L_W + DI - 10 \lg 4\pi r^2 \tag{2}$$



IEC 548/12

Key

$L_P = L_W - 10\lg(4\pi r^2)$

L_P is the sound pressure level (dB rel. 20 µPa);

L_W is the sound power level (dB rel. 1 pW);

$(4\pi r^2)$ is the surface area of sphere (m^2).

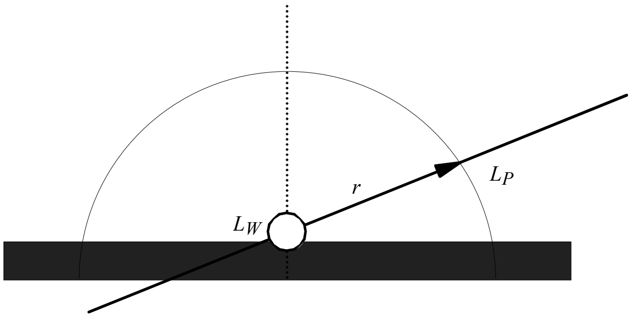
Figure 1 – Spherical spreading in a free-field from a point source

4.3 Background noise

In the situation where a specific noise is heard or measured at a given measuring point, background noise is the sound which is still heard at the point substation when the specific noise stops. As shown in Figure 4, the specific and background noise levels together give the total measured level.

At a proposed location for an HVDC, there background noise will always exist. Since background noise is a combination of man-made and natural sounds, each noise source may produce noise either during the day or night, or at some particular time. Therefore it is important to recognize the difference in the background noise at different times. Generally speaking, background noise levels are usually lowest when human activities are at a minimum, i.e. between midnight and 4 a.m.

It is most important to consider the background noise level when it is close to the regulatory maximum or is equal to the total measured sound level.



IEC 549/12

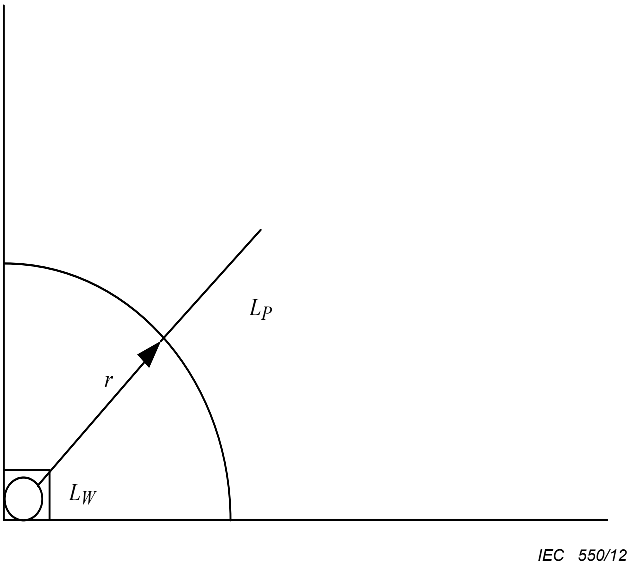
Key

$$L_P = L_W - 10\lg(4\pi r^2/2)$$

where;

L_P	is the sound pressure level (dB rel. 20 μPa);
L_W	is the sound power level (dB rel. 1 pW);
$(4\pi r^2/2)$	is the surface area of 1/2 sphere (m^2).

Figure 2 – Hemispherical spreading from a point source



Key

$$L_P = L_W - 10\lg(4\pi r^2/4)$$

where;

L_P	is the sound pressure level (dB rel. 20 µPa);
L_W	is the sound power level (dB rel. 1 pW);
$(4\pi r^2/4)$	is the surface area of 1/4 sphere (m^2).

Figure 3 – Quarter-spherical spreading from a point source

It is desirable to measure the background noise level for a predetermined HVDC site before its construction so as to confirm whether the level is close to the regulatory maximum or not. Once a substation has been built, and if the difference between the background noise level and the total measured level is less than 10 dB, it is important to consider the influence of the background noise when measuring. It might be impossible to determine the specific noise level accurately, even if the total measured level can be corrected.

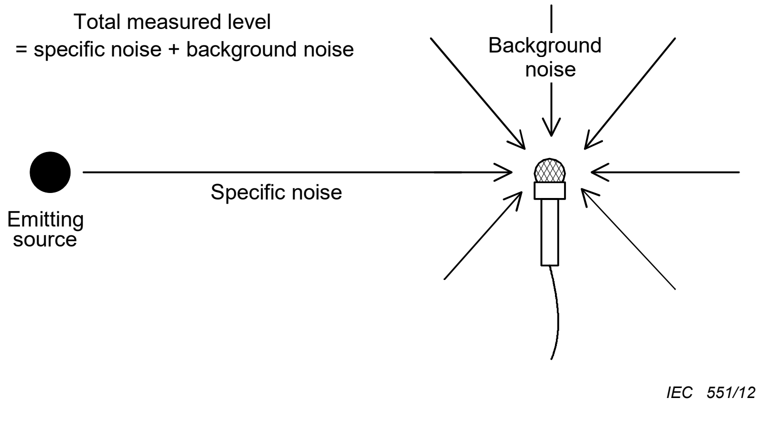


Figure 4 – Explanation of specific and background noise

NOTE See 10.3.3 for details on background noise.

4.4 Topography

The topography surrounding HVDC substation sites differs, e.g. some may be located close to the sea, some may be in the mountains or valleys and others may be in the plains. Topography influences sound propagation. Especially noticeable are the reflection, absorption, screening and attenuation of sound by land features, such as mountains, and the ground itself. In addition, when there is a difference in altitude between from the substation site and the chosen measuring point, the sound propagation will be different from the situation where they are at similar altitudes.

For instance, in Figure 5, there is a hill, which reflects sound, and low ground, which is in the shadow of the sound. Here sound attenuation will vary from place to place even if the distance from the source is the same. It is also important to be aware that the amount of surface reflection or absorption depends on the surface characteristics.

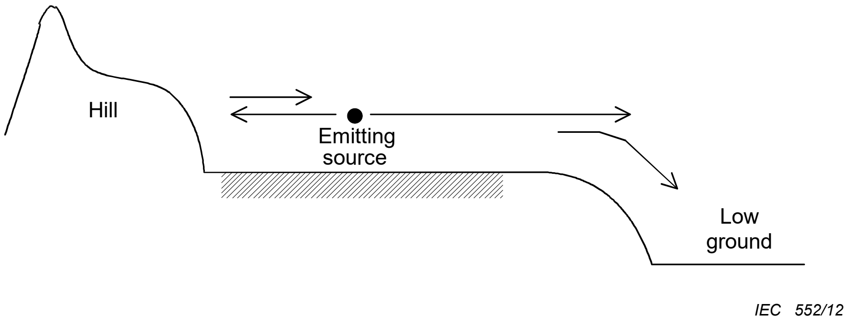


Figure 5 – Example of reflecting hill and low ground

As shown, low ground is a plane below the emitting source.

Therefore, when an accurate calculation of the sound emitted by a HVDC substation is required, it is important to take into account not only the topographical conditions, but also the ground-cover, such as forest, rocks, grassland etc.

However, when the land is basically flat and the groundcover is uniform and low-level, it is usually sufficient to calculate the attenuation over distance without detailed consideration of the sound propagation variation caused by topography.

4.5 Meteorological conditions

Over large distances, sound propagation through air can be influenced by meteorological conditions such as wind, temperature, rain, fog, and snow. In particular wind and temperature have a great impact on sound propagation. Therefore careful attention to meteorological conditions must be paid while measuring sound at the substation site.

a) Impact of wind speed and direction

   The wind velocity near the ground is usually lower than at higher altitude because of frictional resistance. The sound is refracted as shown in Figure 6 because the sound velocity is the vector summation of the wind velocity and the original sound velocity. Therefore there is a difference between the sound propagation on the downwind side and on the upwind side.

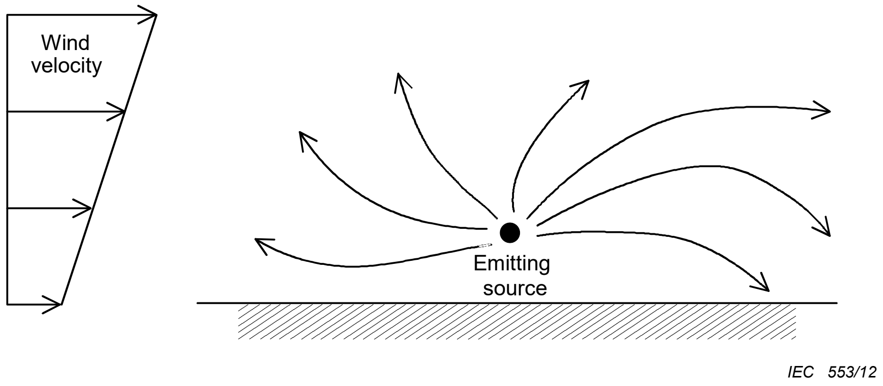


Figure 6 – Example of sound refraction with the shown wind gradient

For example, if there is a strong prevailing wind in the area selected for an HVDC substation, sound levels will be lower on the upwind side than on the downwind side. Careful consideration of this may enable optimization of the design of the substation layout and soundproofing equipment (N.B. If measurements are made on a windy day, it should be remembered that wind-induced noise on the microphone would produce so-called self-noise, which may be reduced by using a windscreen mounted on the microphone).

b) Impact of temperature gradients

Heated or cooled ground may cause vertical temperature gradients in the atmosphere, which may have a strong effect on sound propagation because sound travels faster in warm air than in cold (see Figures 7 and 8).

Consequently, sound attenuation for an observer at ground level is reduced for the condition shown in Figure 8. This phenomenon usually occurs at night.

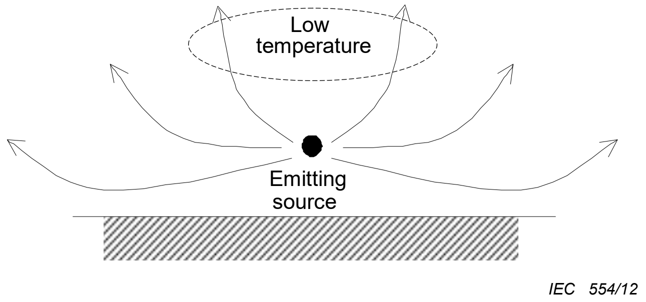


Figure 7 – Sound travels faster near the ground

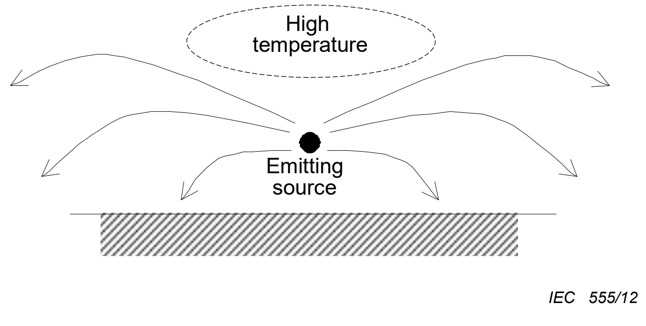


Figure 8 – Sound travels slower near the ground

c) Impact of atmospheric conditions (temperature, humidity, and pressure)

A sound wave propagating through air loses its intensity as the air absorbs its energy. The viscosity of the medium and the relaxation phenomenon of oxygen (O_2) and nitrogen (N_2) molecules mainly cause the absorption. On the whole attenuation is so small that it is negligible at lower frequencies, but it becomes quite large at higher frequencies (see 9.3.2.2 on atmospheric absorption).

d) Impact of rain, fog, and snow

Sound is sometimes carried further on a rainy or foggy day. The main reason is not the acoustic properties of rain or fog, but instead the effect of a temperature gradient or wind which accompanies this weather (see Figures 7 and 8). Experimental evidence has shown that the attenuation of sound by rain or fog is relatively small.

On the other hand, a surface covered with new-fallen snow has a high absorption coefficient for sound, and the attenuation is significant. Conversely, background noise levels are increased by the sound of falling raindrops on a rainy day.

e) Typical example data

Typical changes in sound attenuation caused by meteorological conditions are as follows:

- Up to 20 dB (A) lower sound levels when measured upwind as compared to measured when there is no wind.
- The effect of low or moderate wind velocities overrides the effect of even large temperature gradients.
- It is difficult to measure noise levels below 40 dB (A) correctly when wind velocity exceeds 3-4 m/s. This upper limit of wind velocity may be increased by the use of a windscreen, but the difference is normally only in the order of a few m/s.
- Large difference between dry and moist ground at low frequencies (10 dB (A) lower sound level on moist ground at 63 Hz).

Meteorological conditions may be different from one day to the next and from one area to another, so it is necessary to consider the influence of these conditions on sound propagation very carefully.

5 Noise level limits

5.1 General

No general international standards exist, such as ISO or IEC, which state noise emission level limits specific for substations. Different countries have local noise regulations. In general, these regulations are similar but for each case they may require separate consideration.

In almost all countries, there are however public regulations or recommendations for environmental sound. These sometimes include measurement methods to be used for verification. Such requirements or recommendations are established by federal or regional authorities and normally specify maximum allowable noise levels for various classifications of land use. There are also different frequency weightings of the sound such as A-weighting and C-weighting.

5.2 Regulations

5.2.1 Noise level limits

The only international noise standard on environmental noise descriptions and measurement methods in existence today is ISO 1996-2. However, standards for determining the sound level of specific equipment like power transformers (e.g. IEC 60076-10 and/or IEC 60076-10-1) and methods for determination of sound pressure and sound power levels (e.g. ISO 3746) do exist. IEC 61672-1 and IEC 61672-2 specify sound level meters.

From a regulatory point of view, environmental noise level limits are often related to land use classification and not to a specific distance from an audible noise source such as an HVDC substation. In cases where noise level limits are given at specific distances it is normally due to a more suitable verification procedure which is specified by the customer or the local planning authority. Furthermore, it may also be necessary to define more than one set of limits to cover different operating conditions.

Existing federal or regional regulations can be divided into two main approaches.

- Maximum allowed A-weighted sound pressure levels for different land-use classifications, including background noise.
- Maximum allowed increases over existing background noise.
- There may also be combinations of A-weighting and C-weighting, e.g. the C-weighted total sound level may not exceed the A-weighted total sound level by more than 15 dB.

Some of the regulations do not define a sound level limit for an entire area. For instance they give a limit at the border of properties. In areas with low background noise levels, the first approach is reasonable but in areas with high background noise levels the second approach would be more reasonable.

5.2.2 Noise level measurement

Existing regulations specify applicable conditions for an acceptable measurement. For further details, see 12.1.

5.3 Land-use classifications

Most human activities produce sound. This sound is emitted into the surroundings and may disturb human conversation or sleep. Therefore, most countries have legislation or guidelines on acceptable noise levels.

If the sound was suppressed at source, there would be no noise problem. The cost of suppression may however be disproportionately high for the benefit gained, and it is sometimes difficult to suppress the sound at its source, e.g. mobile sources such as airplanes.

Therefore land use is classified and, where possible, noisy sources are concentrated in one place away from residential and recreation areas. The site proposed for an HVDC substation and its surroundings may currently be in use for some other purpose, such as industry, recreation, farmland, or open-land. In each area, sound level limits are often specified in local legislation or regulations, which may be based on land-use classifications.

When the site for an HVDC substation is selected, it is necessary to examine the land use and sound level regulations in advance, so as not to encounter problems once construction is under way, or at any time in the future. In a residential area, it is especially necessary to understand the life and expectations of the future neighbors of the substation. It should also be recognized that the existing background noise level may be the result of land use regulations currently in effect.

5.4 Location of required performance limits

5.4.1 General

The boundary or location where the required noise performance limits shall be defined should follow the country’s regulation. The locations where the required noise limits shall be fulfilled as well as their advantages and disadvantages are described below.

5.4.2 At the fence surrounding the HVDC substation or at the border of the substation owner’s property

Advantages	Disadvantages
• Less affected by background noise.	• Verification at location where nuisance typically does not affect people.
• Less impact on measurement from weather conditions.	• May influence the substation layout unnecessarily.
• Less affected by surrounding topography and groundcover.	• More complicated and time consuming verification due to interference phenomena of the sound field.
	• Higher cost because the contractor may have to take actions to lower the radiated noise which, due to interference phenomena, has very pronounced maxima of the noise close to the substation.
	~~• Affected by background noise.~~

5.4.3 At the given contour away from the HVDC substation (e.g. on a circle perimeter or beyond a property border line)

Advantages	Disadvantages
• Simplified prediction of the noise levels compared to predictions close to the fence. The reason is that the substation may be treated as a point source (see 9.3).	• Verification at location where nuisance may not affect people. • Affected by background noise, weather conditions, topography and groundcover.

5.4.4 At the border of a nearby property

Advantages	Disadvantages
• Verification at locations where real nuisance can exist.	• Difficult to perform verification fulfilling all measurement conditions at the same time, i.e. the meteorological conditions.
• Corresponds to regulations for outdoor audible noise.	• Need access to private property.
• Simplified prediction of the noise levels.	• Affected by background noise.

Of course, in the future, houses may be built on previously uninhabited land. The local planning authority may be able to advise regarding known developments. Otherwise, future housing developments should take into account the existing noise climate, including the operational HVDC substation, when planning their development layout and considering landscape options.

5.5 Relationship of performance limits to time duration

In general, noise from an HVDC substation is continuous, but there are some noise sources of the substation, which produce impulsive noise, such as circuit breakers and disconnectors. Critical features of impulsive noise include:

- peak noise level;
- time duration;
- time of day;

- frequency of occurrence;
- regularity (the same tone every day may be worse than variable tones);
- single tones;
- time variation of noise impulse.

Equation (15) provides a method of evaluating impulsive noise as an equivalent continuous level. Many federal and regional authorities specify noise limits for daytime as well as night time.

In many cases, the limits dictated by safety regulations for the working staff are probably most significant for impulsive noise.

5.6 Typical noise performance limits

5.6.1 General

Before giving typical noise performance limits, it is important to recognize that the cost implication of changing the noise performance limits may be significant, even if the change is only a few dB (A).

As stated earlier in this clause, there are no international standards setting limits. However, a review of several national or regional regulations shows that there are two ways of specifying noise performance limits. These two ways are presented below.

5.6.2 Specific A-weighted sound pressure levels

Outdoor sound pressure levels are normally divided into a number of categories related to land use classification. Please note that local regulations in the same country may differ. Typically the following apply (only night time values are given):

- Working premises where industrial noise is not generated: < 50 dB (A) – 70 dB (A)
- Residential areas, education premises and hospitals: < 40 dB(A) – 55 dB (A)
- Recreation areas: < 35 dB (A) – 45 dB (A)

The requirements are typically more stringent if dominant single tones exist. A definition of a single tone is then given in each regulation. In case of dominant single tones, the levels given above may be decreased.

5.6.3 Maximum allowable increase over background noise levels

It is hard to give specific examples of maximum allowable increase over background noise levels because the span of required levels is quite wide. However, a range of allowable increases over existing noise levels appears to be 0 dB (A) to 7 dB (A). This form of specification is generally used at the boundary of a property considered sensitive to background noise. These allowable increases are also normally reduced if single tones are present.

A method for distinguishing the background noise from substation noise is proposed in Annex A.

6 Sound emitting sources

6.1 General

The purpose of sound requirements is to limit the level of noise emitted into the area surrounding an HVDC substation. This goal is accomplished by the contractor identifying the noise management required.

Efficient noise management requires an understanding of the acoustic behavior of each sound-emitting component, as well as knowledge of the relative acoustic strength of each of these sources. The target is to break down the audible noise requirement for the complete HVDC substation to the component level to allow the verification of the audible noise level in the laboratories of the component manufacturers. Once all the components have been installed, it is almost impossible to correctly determine the noise contribution of each individual component.

In this clause, the major sound emitting sources of an HVDC substation are introduced and the acoustic behavior of each source is discussed briefly. The most prominent components are:

- converter transformers;
- reactors;
- capacitors;
- cooling fans.

Other sources may contribute to the overall noise level, for instance:

- switching devices;
- cooling circuit pumps;
- synchronous compensators;
- outdoor valves;
- diesel generators;
- air conditioning plant;
- air compressors;
- corona discharge sources.

This clause describes the main parameters which affect each component's sound power. The correlation between sound power and sound pressure is explained in Clause 3 and Clause 10.

6.2 Converter transformer

6.2.1 Noise sources in a converter transformer

The converter transformer has the highest sound power of any single component in an HVDC substation and is therefore an important part of the audible noise considerations [4].

The noise from an HVDC converter transformer is generated by three sources:

- magnetic core (noise generated by magnetostriction and joints);
- electromagnetic forces in windings, tank walls and magnetic shields;
- fans/pumps of the cooling system of the transformer.

Fans and pumps are not strictly part of the transformer, and may be supplied by different manufacturers (see 6.5 and 6.6.5)

6.2.2 Comparison with a.c. power transformers

More is known about the mechanism of sound generation for a.c. power transformers, and this is discussed in the following paragraphs. International standards on the determination of sound levels in power transformers are available (see [5, 6]).

In the past, the core vibrations had been identified as the main source of transformer noise. The noise emission was primarily dependent on the rated power of the transformer and the magnetic flux density in the iron core, but not on the loading.

Technological advances in the core design, such as the use of high quality core sheets to reduce the magnetostriction and the use of improved core-joint technologies (e.g. step-lap cores), have reduced the core noise such that the load-dependent winding noise, generated by electromagnetic forces, has become increasingly significant.

The sound power of the winding noise of modern a.c. power transformers could be equal to the core noise, and may even exceed it, if the core induction level at rated voltage is reduced to approximately 1,4 T or lower. The sound power level of the winding noise can be roughly estimated from:

$$\cancel{L_{WA,W} \approx 39 + 10\lg\left(\frac{S_r}{S_p}\right) \text{dB(A)}} \qquad \cancel{(3)}$$

~~where~~

~~$L_{WA,W}$ is A-weighted sound power level from the winding at rated current, rated frequency and impedance voltage~~

~~S_r is rated power in MVA;~~

~~S_p is reference power of 1 MVA.~~

$$L_{\mathrm{WA,Ir}} \approx 39 + 18\lg\left(\frac{S_{\mathrm{r}}}{S_{\mathrm{p}}}\right) \text{ for 50 Hz power frequency} \qquad (31)$$

$$L_{\mathrm{WA,Ir}} \approx 44 + 18\lg\left(\frac{S_{\mathrm{r}}}{S_{\mathrm{p}}}\right) \text{ for 60 Hz power frequency} \qquad (32)$$

where

$L_{\mathrm{WA,Ir}}$ is the estimated A-weighted sound power level of the transformer at rated current and rated frequency at the short-circuit condition;

S_{r} is the rated power in MVA;

S_{p} is the reference power of 1 MVA.

The normal a.c. operation of a transformer generates a noise spectrum containing frequencies, which are typically below 1 kHz. The winding noise at sinusoidal load current contains almost exclusively double the power frequency (power frequency is fundamental electrical frequency). The core noise frequency spectrum additionally contains large components of the 2nd to 5th harmonics of double the power frequency, depending on the flux density level. Therefore the noise of a loaded a.c. transformer is essentially dominated by a 100 Hz tone or 120 Hz tone (according to whether the power frequency is 50 Hz or 60 Hz) superimposed on the no-load spectrum.

6.2.3 Special features of HVDC converter transformers

HVDC converter transformers normally have a higher sound power level than a.c. transformers of the same rated power. There are two factors, which increase the noise level:

- Load current of a converter transformer has a high harmonic content.
- Converter transformer will experience a small d.c. bias current in the valve – and temporarily in the network – side windings.

These factors are capable of generating a sound power level increase of more than 10 dB over normal a.c. operation.

The sound spectrum generated by converter transformers contains frequencies of up to several kHz and in therefore more audible to humans (as demonstrated by A-weighting of the sound level). As the dominating frequencies are above 300 Hz for converter transformers, external sound reduction measures (such as screening and absorption arrangements) are more effective.

The noise generated by the d.c. magnetization is not directly dependent on the load level, as the small d.c. current is governed by:

- Asymmetry in the firing of the thyristor valves, which in turn depends upon the accuracy of the firing control system
- Impedance differences in the converter transformers
- Potential difference between the ground electrode and substation ground for monopole ground-return operation.
- Positive sequence 2nd harmonic voltage.

DC magnetization of a transformer core will increase the transformer audible noise also at moderate levels of d.c. content. The reason is that the d.c. magnetization will add a 50 Hz or 60 Hz tone (dependent on power frequency) and harmonics at the odd multiples of 50 Hz or 60 Hz. In addition the audible sound at normal even harmonics (100 Hz or 120 Hz, 200 Hz or 240Hz, 300 Hz or 360 Hz, etc.) will be increased by the d.c. magnetization.

For an HVDC converter transformer, the winding is generally the dominant audible noise source and thus the audible noise level increases with transformer load.

In this context, reference is made to [4], which described the difference between the actual noise level in service and the values recorded during the standard factory substation tests under no-load conditions. One of the conclusions presented in this paper is that the sound power levels of the converter transformers – estimated from sound pressure measurements in various HVDC systems – operated up to their nominal loads-generally increase with the transformer load. However, there is hardly any correlation between the levels of this noise increase and the assigned power ratings of the transformers subjected to this investigation. The difference between no-load sound power level and sound power level at nominal load may be anything between a few dB up to more than 20 dB.

The additional sound power generated by the cooling equipment needs to be considered, especially for transformers employing a low-noise design. Some aspects of the acoustic performance of cooling fans are discussed in 6.5.

6.2.4 Transformer winding noise

Electromagnetic forces in the transformer windings generate winding noise when the current carrying winding conductors are exposed to the stray magnetic flux of the winding. The forces in the winding are proportional to the current multiplied by the magnetic flux in the winding. The magnetic flux is, however, proportional to the current during normal operation range, thus giving:

$$F \sim B \times I \sim I^2 \tag{4}$$

where:

F is the vibration winding force in N;

B is the magnetic flux density in the winding in T;

I is the winding current in A.

The vibration amplitude and velocity are directly proportional to the force. As the sound power is proportional to the square of the vibration velocity, it can be derived that the sound power is proportional to the fourth power of the load current:

$$W \sim v^2 \sim (\omega \times x)^2 \sim F^2 \sim I^4 \tag{5}$$

where:

W is the radiated sound power;

v is the vibration velocity;

x is the vibration amplitude;

$\omega = 2\pi f$ is the angular acoustical frequency.

6.3 Reactors

6.3.1 Type and design of HVDC reactors

In an HVDC system, reactors are used for various functions:

- HVDC smoothing reactors connected in series with the HVDC transmission line and/or cable or inserted in the intermediate d.c. circuit of a back-to-back link to reduce voltage/current pulsations and the harmonics on the d.c. side, to reduce the current rise caused by failures in the d.c. system and to improve the dynamic stability in the HVDC system;
- filter reactors installed for harmonic filtering on the a.c. and on the d.c. side;
- power line carrier- and radio interference filter reactors employed on the a.c. and/or d.c. side of the HVDC substation to reduce high frequency noise propagation on the lines;
- shunt reactors may form part of an HVDC substation to provide inductive compensation for a.c. harmonic filters, especially under light load conditions, where a certain minimum number of harmonic filters is required to satisfy harmonic filters performance requirements;
- ELIS (Electrode Line Impedance Supervision) reactors which together with capacitors and resistors will form an electrode line supervision system.

When considering the impact of audible noise emanating from an HVDC substation, the a.c. filter reactors and the HVDC smoothing reactor are the main types of reactors which need to be considered.

It is common practice to employ air-core dry-type reactor technology for all the above applications, unless special circumstances require the use of tanked oil-type HVDC smoothing reactors (e.g. at sites with extreme pollution and climatic conditions).

The following descriptions of reactor design and mechanisms of sound generation are essentially confined to the air-core dry-type technology. For tanked oil-type reactors, see also 6.2 which deals with converter transformers as the sound generation mechanisms and sound reduction measures are similar, apart from the additional noise source created by the gaps in the magnetic core.

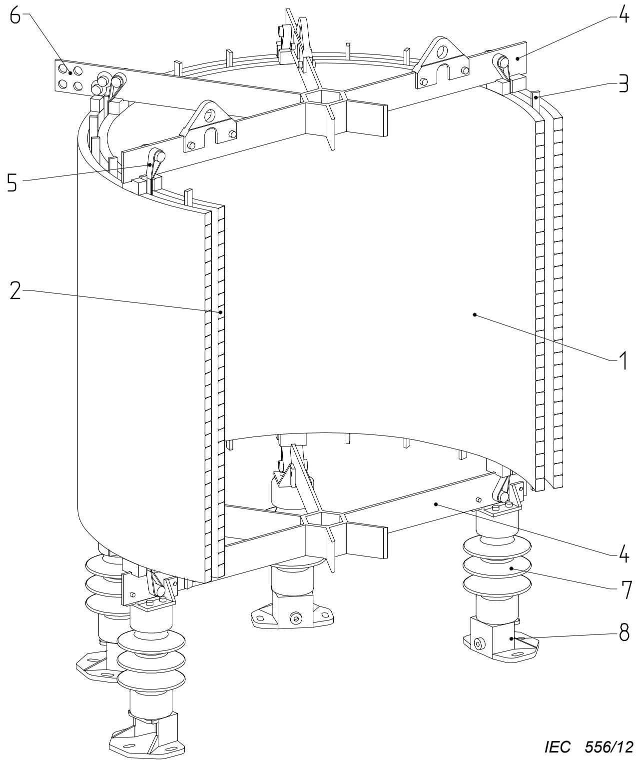
The major construction features of an air-core dry-type reactor are illustrated in Figure 9.

The winding of the reactor consists of one or multiple resin-impregnated and encapsulated winding layer(s) made of insulated aluminum conductors. The concentric layers are connected in parallel by welding their ends to metallic beam structures (spiders). Both the top and bottom spider are clamped together by several sets of fiberglass ties located along the winding. The packages are radially spaced by circumferentially arranged fiberglass-reinforced sticks, which form vertical air ducts for natural convective cooling of the windings.

6.3.2 Mechanism of sound generation

The noise generated by air-core reactors mainly results from vibration winding forces caused by the interaction of the current flowing through the winding and its magnetic flux.

In case of iron-core reactors, forces acting in the magnetic circuit induce further vibrations of the apparatus. If gapped iron-cores are used, the noise contribution by the forces in the air gaps needs to be considered. This noise contribution is generally higher than the noise caused by magnetostriction.



Key

1 – Winding	5 – Fiberglass tie
2 – Conductor	6 – Electrical terminal
3 – Duct stick	7 – Support insulator
4 – Spider	8 – Mounting fitting

Figure 9 – Dry-type air-core reactor

Any current-carrying conductor experiences forces when it is exposed to a magnetic field. Consequently, the magnetic field crossing the winding area generates electromagnetic winding forces. As an example, Figure 10 shows the distribution of the magnetic field of an air-core reactor of 30 MVAr power rating.

As already outlined under 6.2.4, the forces in the winding are proportional to the current multiplied by the magnetic field in the winding, and thus they are proportional to the square of the current.

When calculating the winding forces, it can be shown that the frequency spectrum of the forces differs from the electrical frequency spectrum. In case of single frequency a.c. current, the forces are oscillating with twice the frequency of the current. If, however, the reactor is simultaneously loaded by several currents of different frequencies, in addition to vibration modes at double the electrical frequencies there are also additional vibration frequencies (see 6.3.3).

The oscillatory forces on the winding cause the reactor to vibrate in the axial and in the radial direction. While the oscillating forces can be clearly determined, the analysis of the vibration response of the winding structure is rather complex. As with any mechanical structure, the dynamic behavior of the reactor may be described in terms of vibration modes. Since the oscillating forces are of almost rotational symmetry, it would be expected that only symmetrical modes of the structure coinciding with the shape of the force distribution would be excited. However, the finite number of duct sticks between concentric winding layers, the spiders attached at the winding ends and manufacturing tolerances result in the excitation of modes other than those of rotational symmetry. The fundamental modes of the cylindrical reactor structure are:

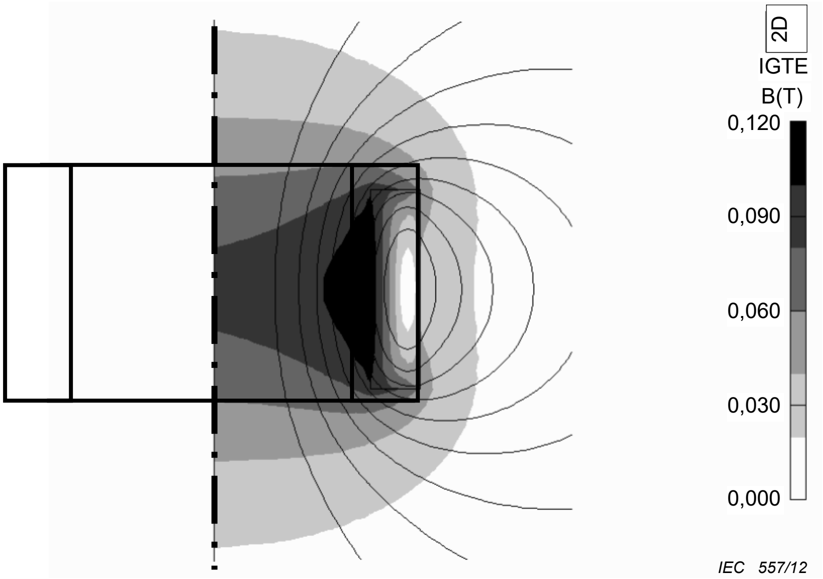


Figure 10 – Magnetic field of an air-core reactor winding

- So-called "breathing mode" where the reactor winding is deformed like a cylindrical pressure vessel. This modal frequency essentially depends on the material parameters of the winding and is inversely proportional to the winding diameter. Typically the breathing mode frequency is between several hundreds of Hz and 1 kHz. The breathing mode is fully symmetrical (see Figure 11) and its shape coincides with the distributed exciting electromagnetic force resulting from the axial magnetic field component.
- "Compression modes" in the axial direction where the reactor is symmetrically compressed towards the reactor midplane. This mode is excited by the radial magnetic field component.
- "Flexural modes" (bending modes) of the winding layers, characterized by the number of nodes in circumferential and axial direction. The frequencies of interest for these modes are usually lower than the breathing mode frequency. Although the flexural modes are not of rotational symmetry they become excited by the electromagnetic forces (see Figure 12).

The vibrations of the surface of the apparatus radiate to the surroundings as airborne acoustic noise. The radiated sound power in defined by

$$W = \rho_0 c A_W \sigma v^2 \tag{6}$$

by introducing:

$$v = \omega x \tag{7}$$

The radiated sound power at a certain acoustic frequency is defined by:

$$W = \rho_0 c A_W \sigma \omega^2 x^2 \tag{8}$$

where:

W is the radiated sound power;

ρ_0 is the air density in kg/m^3;

c is the speed of sound in air in m/s;

A_W is the sound radiating surface in m^2;

σ is the radiation efficiency (no unit);

ω the is angular acoustical frequency (= $2\pi f$);

χ is the vibration amplitude in m.

The vibration amplitude and the size of the sound radiating surface of the apparatus essentially determine the sound power. Therefore the sound emission of a dry-type air core reactor is governed by the magnitude of the winding vibration on the radial direction, since the winding represents the main part of the radiating surface. The contribution of axial winding vibrations and that of other components to the total sound emitted is relatively low.

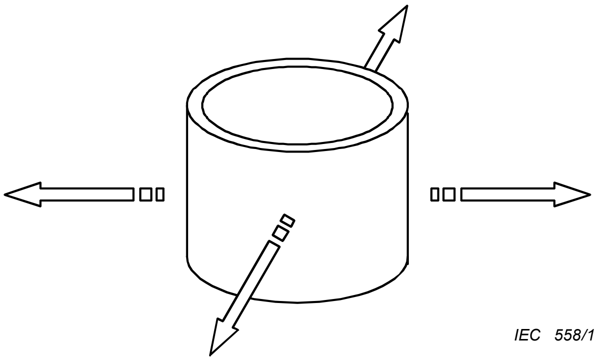
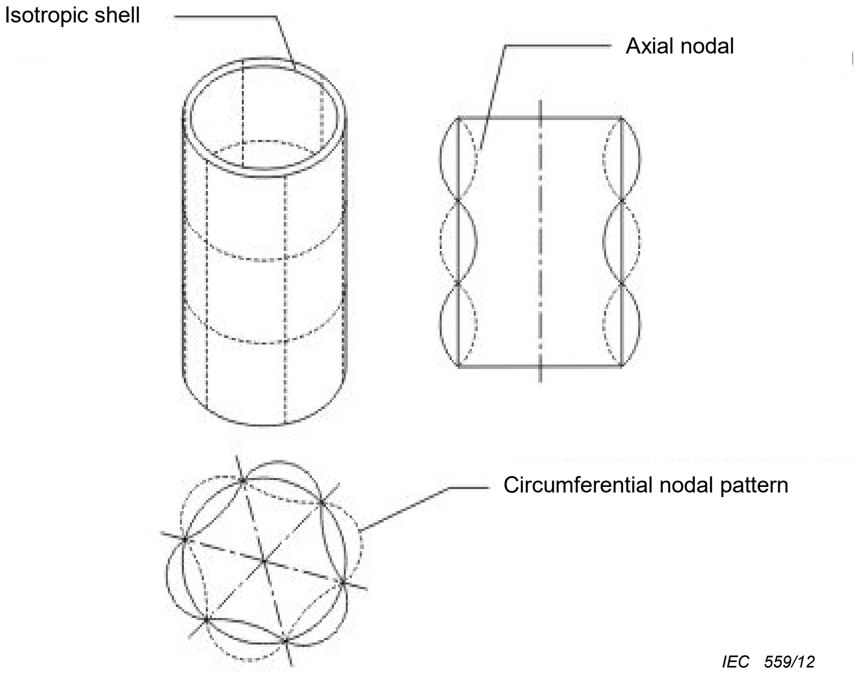


Figure 11 – Simplified shape of the symmetrical breathing mode of a reactor winding



NOTE I is the number of circumferential wavelengths = 3 and j is number of axial half wavelengths = 3..

Figure 12 – Example of flexural modes (bending modes) for a simply supported winding layer without axial constraint

To avoid dynamic resonance amplification of the vibration amplitude, the forcing frequencies (which are governed by the electrical frequency spectrum), should not coincide with the structural resonance frequencies.

As the vibration amplitude is directly proportional to the vibration force, it can be derived that the sound power of the reactor is proportional to the fourth power of the load current (see 6.2.1). For specifying sound criteria, it is therefore necessary to clearly specify the substation's operating conditions. The specified current ratings for the thermal design of the reactor may not necessarily be the same as the ratings specified for the acoustic design.

The radiation efficiency σ depends on the frequency and the geometrical and structural properties of the component. For example, if a surface vibrates at a frequency at which the structural wavelength is considerably greater than the acoustic wavelength in the ambient medium, e.g. air, then the air cannot move out laterally to cancel out pressure differences, and the particle velocity of the air will be equal to the velocity of surface, even outside the immediate vicinity of the surface. Thus σ=1. If the situation is the opposite, then $\sigma < 1$. At frequencies where the wavelength of the vibrating structure is about the same as the wavelength in air, σ can become greater than 1. See 10.2.4.

As explained above, the sound power increases with the fourth power of the load current. This allows direct scaling of test load results, which is useful to achieve because operational currents are often hard to achieve in laboratories. Assuming linearity, the sound power level L_{W1} measured at current I_1 can be scaled to another current I_2 as follows:

$$L_{W2} = L_{W1} + 40 \lg\left(\frac{I_2}{I_1}\right) \tag{9}$$

where:

L_{W1} is the sound power level in dB at current load I_1;

L_{W2} is the sound power level in dB at current load I_2.

The total sound power level, including all acoustic frequencies, is derived by logarithmic summation (see Clause 3). The acoustic frequency spectrum depends on the load current spectrum of the reactor, and is thus very much dependent on the reactor application, as outlined below.

6.3.3 AC filter reactors

As an example, Figure 13 shows the simplified current spectrum of an a.c. filter reactor. It is assumed that the current consists of a component with fundamental frequency f and one harmonic component with harmonic number, h. In reality, the current always consists of more than one harmonic component.

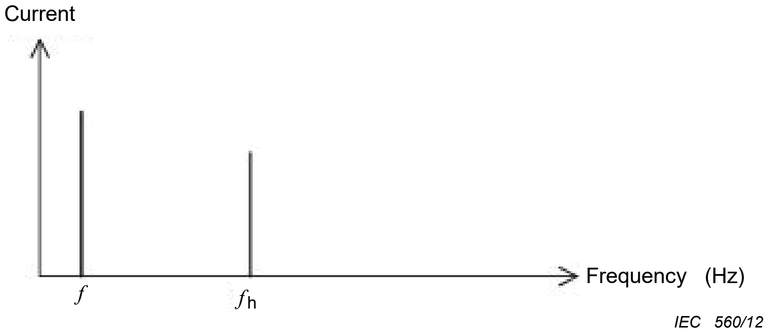


Figure 13 – Example of spectrum of currents through a.c. filter reactor

Figure 14 below depicts the force components acting on the winding of the reactor. The force consists of a static pre-load and components with frequencies $2f$, $f_{(h-1)}$, $f_{(h+1)}$ and $2f_h$. Only the vibration force components are generating noise; the static pre-load does not affect the sound power.

When going from electrical load to electrical force, a frequency shift occurs and the number of force components is equal to or less than the squared number of load components. The acoustic frequency spectrum will therefore increase significantly if the reactor's current spectrum includes several harmonics.

Like any mechanical structure, a reactor with distributed mass and structural properties has an infinite number of structural resonances. Amplification of the equipment vibrations, and thus increased sound generation, may occur if one or several frequencies of the force spectrum coincide with these structural frequencies. For proper consideration of the acoustic behavior of the filter reactors, it is therefore necessary to include both the fundamental and the harmonic content of the current.

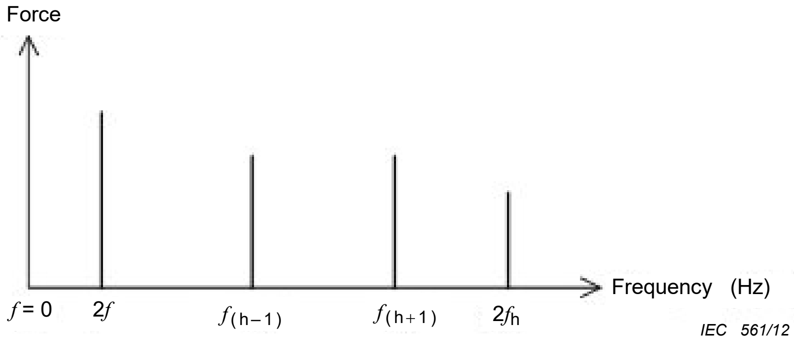


Figure 14 – Example of spectrum of forces acting on the reactor winding

6.3.4 HVDC smoothing reactors

The most significant components of the noise radiated from an air-core dry-type smoothing reactor winding are caused by the vibration of the winding due to the interaction of the d.c. current with the harmonic currents. Since modern converter substations generally operate with 12-pulse bridges, the main harmonics are the 12^{th} and the 24^{th}. Therefore for 60 Hz a.c. systems, the corresponding frequencies are 720 Hz and 1 440 Hz.

As an example, Figure 15 shows the simplified current spectrum of an HVDC smoothing reactor. It is assumed that the current consists of a d.c. component and one harmonic of the power frequency with harmonic number h. In reality, the current always consists of more than one harmonic component.

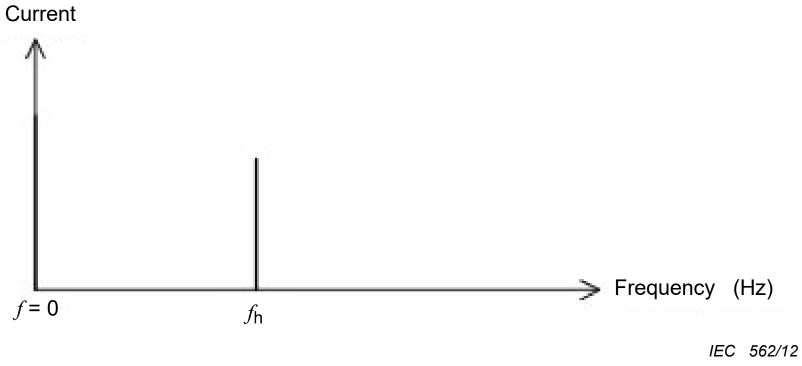


Figure 15 – Example of a spectrum of currents through an HVDC smoothing reactor

Figure 16 depicts the force components acting on the winding of the reactor. The force consists of a static pre-load and vibration components with frequencies f_h and $2f_h$.

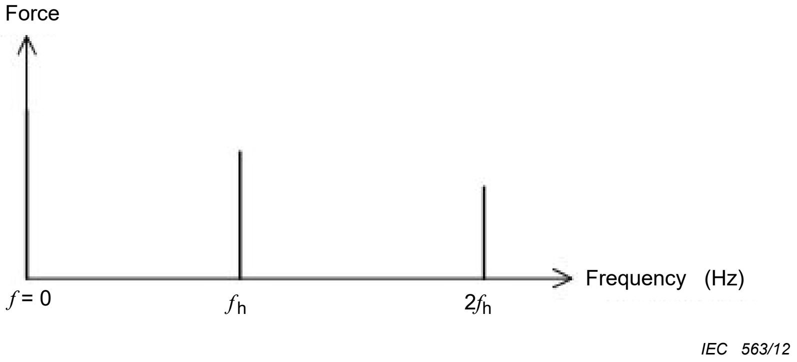


Figure 16 – Example of spectrum of forces acting on the reactor winding

The static pre-load (force with frequency $f = 0$) does not in practice affect the total noise.

6.3.5 Self-tuned filter reactors

AC filters need to have a certain bandwidth to limit the consequences of filter detuning. Self-tuned filter reactors can be adjusted to follow frequency excursions and component variations. These reactors have an iron core with a control winding, see Figure 17. A d.c. current in the control winding affects the permeability of the core and changes the inductance of the reactor. Further harmonic components can appear due to unsymmetrical magnetic saturation. The a.c. cable is wound on a fiberglass cylinder, which surrounds the iron core. A sound screen encloses the whole reactor.

Sound measurements have shown that the reactor essentially behaves as a conventional air-cored reactor as a function of the a.c. current. The d.c. current in combination with the a.c. current creates forces at the a.c. frequency as shown in Figure 16. A change of the d.c. current thus only affects the sound at the a.c. frequency (and e.g. not double the a.c. frequency). There will be no sound radiation at the frequency 0 Hz.

Radial vibrations of the fiberglass cylinder seem to determine the radiated sound power, and not as has been found on air-cored reactors, the radial vibrations of the a.c. winding. See also Clauses 9 and 10.

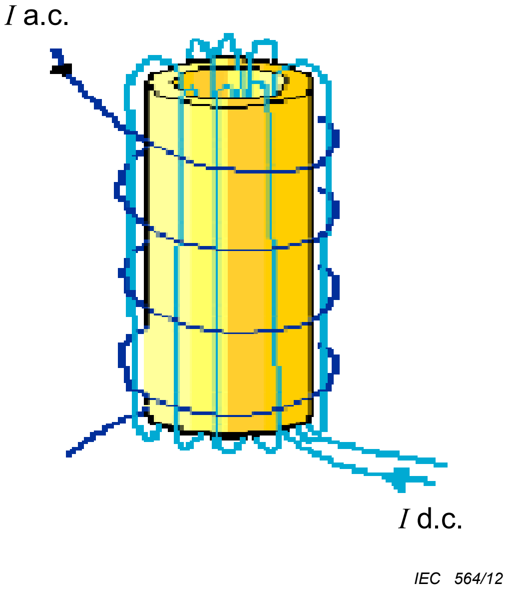


Figure 17 – Reactor for self-tuned filter applications

6.4 Capacitors

6.4.1 Type and design of capacitors

After transformers and reactors, capacitors are the main noise sources in an HVDC substation. Capacitors are used for various functions in an HVDC scheme, such as for a.c. and d.c. filters, reactive power compensation, for power line carrier (PLC) circuits and as capacitive voltage transformers (CVTs).

Capacitors used in filters and for reactive power compensation are typically stacks of power capacitor cans. Other capacitor types, which employ insulator housings, are coupling capacitors in PLC circuits and capacitive voltage transformers for measurement and protection. For sites subject to space restrictions, polluted environment and/or frequent earthquakes, tanked capacitors may be used.

In general, it is the can-type capacitor, which needs to be considered for noise limits. Therefore the following description of the capacitor design mainly refers to can-type capacitors.

In order to explain the mechanism of sound generation, the design of a capacitor and some terms need to be explained. A capacitor stack consists of a number of capacitor cans. The capacitor can is the steel covered capacitor including bushings. Each capacitor can is filled with oil and contains a capacitor element package that is built up by a number of capacitor elements (see Figure 18), which are connected in series or parallel. The capacitor element is made by winding two aluminum foils and a number of plastic or paper films of a specific length.

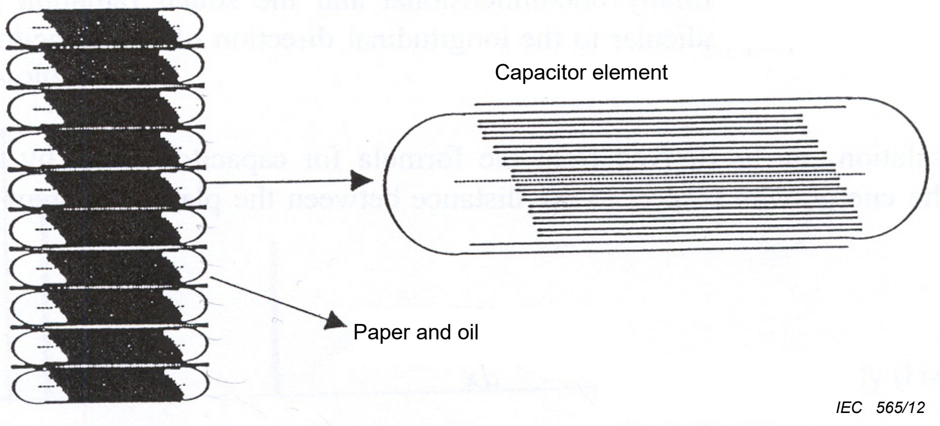


Figure 18 – Capacitor element package with capacitor elements

The design of the capacitor elements and the capacitor element packages of capacitors in porcelain housings, such as coupling capacitors and capacitive voltage transformers, is basically the same. Therefore the mechanism of sound generation described below refers to all types of capacitors.

6.4.2 Mechanism of sound generation

The section across an energized capacitor element (see Figure 19) shows that most of the charge-carrying aluminum foils are in force equilibrium because they have an attracting foil on each side. The only foils that are not in equilibrium are those on the edges (force F_1) and in the middle of the capacitor element (force F_2). As the stiffness of the thin oil layer in the middle of the capacitor element is quite high, the middle forces cancel each other with a very small displacement. The net forces on the capacitor element are then the forces on the edges.

Therefore, the parts contributing most to the generation of audible noise are the top and the bottom of the capacitor element. This is also valid for the capacitor element packages; the mechanical response is therefore governed by the first longitudinal resonance in the package. The sound generation is essentially one-dimensional and the sound radiation is mainly confined to the surfaces perpendicular to the longitudinal direction of the capacitor element package.

The force calculation can be derived from the formula for capacitor plates by taking the derivative of the energy with respect to the distance between the plates (theorem of virtual displacement):

$$F = \frac{dW}{dx} \tag{10}$$

where:

W is energy stored in the capacitor in W;

x is distance between the capacitor plates in m.

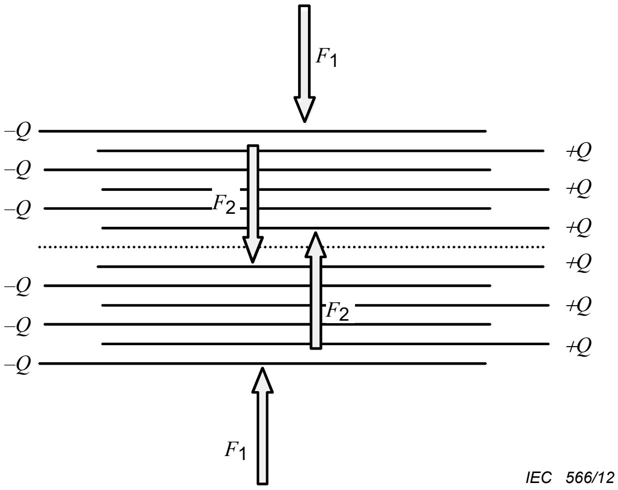


Figure 19 – Forces in a capacitor element

By introducing the formula for the energy stored in a capacitor

$$W = \frac{U^2 C}{2} \tag{11}$$

where:

U is r.m.s voltage across the capacitor in V;

C is capacitance in F.

The force can then be calculated by:

$$F = -\frac{U^2 C}{2x} \tag{12}$$

If U is a sinusoidal voltage

$$U(t) = \sqrt{2}\, U \sin(\omega t) \qquad (13)$$

The force will be composed of one static and one oscillating (harmonic) force. It must also be remembered that the acoustic frequency spectrum will increase significantly if the voltage spectrum includes several harmonics.

As an example, Figure 20 shows the simplified voltage spectrum of an a.c. filter capacitor. It is assumed that the voltage spectrum consists of a component with fundamental frequency f and one harmonic component with harmonic number h. In reality, the voltage always consists of more than one harmonic component.

Going from voltage stress to force, a frequency shift occurs and the number of force components equals the number of voltage components squared. The forces in the capacitor element packages finally cause vibrations of the steel enclosure of the capacitor unit and thus generate acoustic noise, which is radiated as airborne sound.

To calculate the sound power and the sound power level at a certain acoustic frequency, the same formulae mentioned in 6.3 can be used. If all equations are considered, it can also be derived that the sound power is proportional to the fourth power of the dielectric stress in the capacitor.

Figure 20 shows the voltage of the basic frequency, f, and the harmonic frequency, f_h, for the filter.

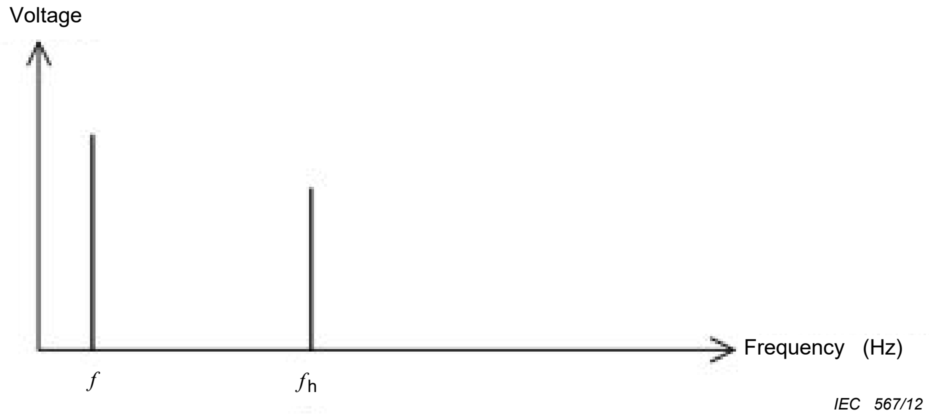


Figure 20 – Example of spectrum of voltages across the capacitor

Figure 21 depicts the vibration force components acting on the winding of the capacitor. The force consists of components with frequencies $2f$, $f_{(h-1)}$, $f_{(h+1)}$ and $2f_h$.

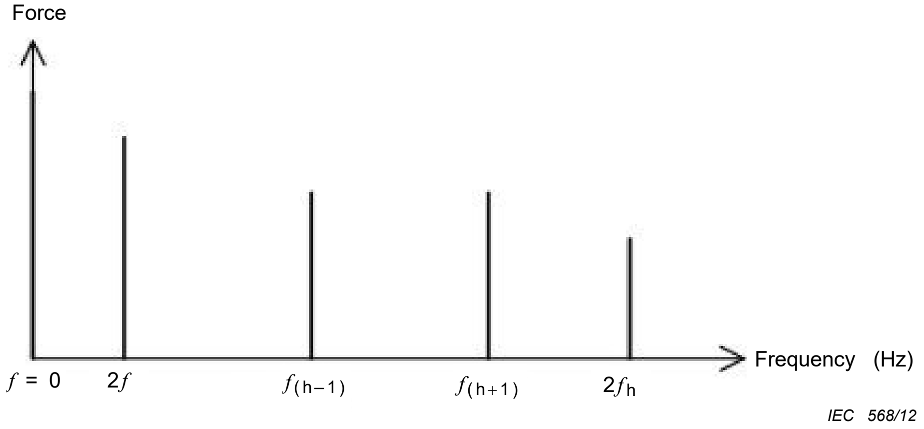


Figure 21 – Example of spectrum of electrostatic forces in a capacitor

In order to determine the sound power level of the complete capacitor stack, the sound power level of all capacitor units can be added as uncorrelated sound sources:

$$L_W^{\text{stack}} = L_W^{\text{unit}} + 10\,\lg(n) \tag{14}$$

where

L_W^{stack} is the sound power level of the complete capacitor stack in dB;

L_W^{unit} is the sound power level of a capacitor unit in dB;

n is the number of capacitor units.

The sound power radiation from a stack of capacitors is essentially dependent on:

- fundamental and harmonic a.c. voltage across the capacitors;
- mechanical stiffness;
- mechanical resonance frequencies (of capacitor element packages, housing and rack);
- number of capacitor units;
- position/location of the units/racks.

The above formulae for the radiated sound power, as well as for the sound power level, are considering a single acoustic frequency only.

The total sound power level considering all acoustic frequencies is derived by logarithmic summation (see Clause 3). The acoustic frequency spectrum depends on the frequency spectrum of the voltages across the capacitor.

6.5 Cooling fans

Forced air coolers are normally used for thyristor valve cooling; these consist of heat exchangers (with cooling media of water/ethylene glycol and air) and axial flow fans. Usually several fans are used per cooler module. The fans are separated from one another by a partition. This enables stepwise controlling of the cooler capacity (kW-capacity) by successively switching each fan on and off according to the cooling demand.

By selecting the optimum cooler size for a specific application, the optimum fan speed (typically between several hundred and 1 000 rpm) and the number of fans, the noise level can be kept to a minimum. Low-noise axial flow fans, with large diameters and operating at low rotational speeds, may reduce noise emission. Two-speed motors or motors with frequency control for speed regulation may be employed. The manufacturers are able to optimize the acoustic design of the coolers by combining adequate standardized cooler modules for which acoustic ratings is available.

For un-enclosed converter transformers of normal acoustic design, the noise of the cooling equipment is insignificant. For enclosed or low-noise converter transformers, the additional sound power generated by the cooling fans needs to be considered.

Cooling of transformers with very high rated powers may require separate radiator banks. Such free-standing coolers are also advantageous as they allow enclosure of the transformers themselves.

6.6 Other sound-emitting sources

6.6.1 Switching devices

In contrast to the components described above, switching devices such as circuit breakers and disconnectors only generate audible noise when operated. This noise is short-term, but may significantly exceed the background noise. The audible noise produced by the opening and/or closing of a circuit breaker is classified as impulsive noise. The duration of a single acoustic impulse is usually less than one second.

One approach to evaluate impulsive noise is to express it as an equivalent continuous noise level. The equivalent continuous A-weighted sound power level of a noise over a time interval T, can be derived from the A-weighted sound power levels during the periods T_i by using Equation (15). There is however no standard values for T_i. The values of T_i should be chosen to give an appropriate description of the impulsive event, e.g. 10 seconds for air-break connectors or earth switches (see 7.3.7).

$$L_{W\text{Aeq}} = 10\ \text{lg}\left[\left(\frac{1}{T}\right)\sum T_i 10^{0{,}1 L_{W\text{Aeq},T_i}}\right] \qquad (15)$$

where:

$L_{W\text{Aeq}}$ is the equivalent continuous A-weighted sound power level in dB over time interval T (rel. 1 pW);

T is the total time interval ($T = \sum T_i$) in s;

$L_{W\text{Aeq},T_i}$ is the equivalent continuous A-weighted sound power level in dB during period T_i (rel. 1 pW);

T_i is the time period in s during which the noise occurs at the level (L_{WAeq}, T_i).

Depending on the definition of the total time interval T, different A-weighted quantities may be used to evaluate the effects on the environment, such as

- equivalent continuous sound level;
- daytime average sound level;
- night time average sound level;
- day-night averaged sound level with a dB-adder for the night sound level;
- hourly average sound level.

Normally the noise generated by switching devices does not have a significant impact on the overall noise level of an HVDC substation since the accumulated noise dose is relatively low compared to sources continuously producing noise. In many cases, circuit breakers are operated just a few times per year, except filter bank circuit breakers, which may be operated several times daily. However, the accumulated noise dose during a working day has to be within the sound level limits established to limit the risk of causing hearing damage for staff on site. These limits, which may be taken from local safety directives, are dependent upon the accumulated sound exposure duration, and are usually getting lower for higher frequency sound.

The acoustic impulse generated during a switching operation depends upon the type of switch (e.g. air-blast circuit breakers, vacuum or SF_6 circuit breakers) as well as on the breaker operating mechanism (e.g. spring-operated, hydraulic-operated). The level of sound is highest for air-blast circuit breakers, whereas modern vacuum or SF_6 circuit breakers produce a relatively low level of sound.

Air break disconnectors and earth switches can produce significant sound levels for up to 10 s, during a switching operation.

6.6.2 Synchronous compensators

Synchronous compensators tend to run continuously and are enclosed in a building or a prefabricated acoustic and weatherproof housing. There will be some residual noise from the equipment inside the enclosure, such as exciters, slip ring/brush assembly and auxiliary transformers. However, the most significant noise from the enclosed synchronous compensator will be noise produced by the cooling plant. Thus, the sound aspects listed for cooling fans apply in this case also.

6.6.3 Diesel generators

A diesel generator is almost always enclosed in a building, but the level of sound outside the building due to the exhaust vent can be substantial. However, diesel generators only operate occasionally, either for routine testing of under emergency conditions. Routine testing can be confined to the daytime in the normal working week, and hence noise sensitive periods will – on the whole – be avoided.

6.6.4 Air conditioning plant

Whilst the direct noise of an air-handling plant is generally contained in a building, there may still be a substantial residual sound emanating from the inlet and outlet air vents. The sound emanating from these sources includes airflow and louver noises and residual noise from the air-handling plant, although acoustic louvers are available. With regard to the fan noise generated by air-conditioning systems, the factors described in 6.5 apply.

6.6.5 Cooling circuit pumps

If cooling system pumps are installed outdoors, they may have to be included in noise management considerations.

6.6.6 Converter valves

As this clause only describes those components emitting sound into the area surrounding an HVDC substation, the acoustic behavior of the thyristor valves is not discussed as they are almost always installed indoors. The noise of the valves themselves is mainly generated by the magnetic components such as the valve reactors. The coolers of the thyristor valves, however, are generally installed outdoors and are discussed under 6.5.

In the rare case of tanked valves installed outdoors, valve reactors and the fans of the cooling equipment may be dominant sound-emitting source.

6.6.7 Air compressors

If air compressors are installed outdoors, they may be one of the major noise sources.

6.6.8 Corona sources

Practically all high voltage connections emit a certain level of corona. For reasons other than just sound (e.g. radio interference requirements and the risk of flashover), corona should be limited to low levels and low levels of corona should trigger remedial actions.

In particularly sensitive sites it may be necessary to suppress corona levels by methods described in 7.2.9.

6.7 Typical sound power levels of sound emitting sources

The figures stated below in Table 1 for component sound power are based on a "standard design" of each component. A modern standard design includes the use of common practices for internal noise reduction, for instance avoidance of critical mechanical resonances. The stated sound power figures, however, do not include the use of external noise reduction measures, such as sound shields, enclosures, etc.

Table 1 – Examples of component sound power level

Sound emitting source	**Component sound power** L_{WA} in dB (A)
HVDC converter transformer	
– nominal load	90 to 125
– no load	85 to 110
HVDC smoothing reactor	85 to 100
Self-tuned filter reactors	90 to 100
AC and d.c. filter reactor	65 to 90
AC and d.c. filter capacitor bank (can-type capacitors)	55 to 105
Cooling fans (forced air coolers for valve cooling)	
– fan speed approx. 300 rpm	
Cooling capacity 30 kW / 300 kW	approx. 55/85
– fan speed approx. 900 rpm	
Cooling capacity 500 kW / 1 300 kW	approx. 90/105
Switching device	(Impulsive noise)
– air blast circuit-breaker	150 to 160
– oil and SF_6 circuit-breaker	105 to 130

7 Sound reduction measures

7.1 General

Where there are components, which generate significant levels of sound so that noise limits, are exceeded, it is necessary to use sound reduction measures. This is generally the case for HVDC substations.

Ideally sound reduction should be part of the original design and is a combination of substation layout techniques and component design measures. The aim is to use two techniques in conjunction to produce an effective and cost-efficient design.

Very often encapsulation and screening are required to contain sound in an area where high sound levels are not permitted. Retrofitted sound reduction measures may be required when measurements are made after installation of the equipment. These may include more screens, further encapsulation and even active noise reduction techniques.

Additional information concerning sound reduction methods is given in other publications [7, 8].

7.2 Substation layout

7.2.1 General

The maximum possible separation between the area designated for sound-emitting components and the sound-sensitive area should be chosen. This can be done by arranging significant sound-producing components so as to hinder the propagation of sound waves in sound-critical directions by making use of the natural topography of the area, or by using the screening effects of the converter equipment and other buildings.

Some of the major sound sources notably pumps and thyristor valves are indoor equipment and the noise considerations here are related to the effects on workers and visitors to the converter substation. In general, the level of sound emitted outside the rooms by these components is not considered a nuisance and, where access is required for inspection whilst in service, ear defenders are considered acceptable. Specific information can be found in the local health and safety guidelines.

General sound reduction measures, which can prove very effective for the whole site, include:

- surrounding the site with either a wall or a substantial earth mound;
- building the site in a hollow or locating the site in a suitable valley, preferably without steep rock sides.

The typical twelve-pulse and dual twelve-pulse HVDC substation layouts are shown in Annex B.

7.2.2 Transformers and tanked reactors

In terms of layout, the sound suppression measures to be adopted for transformers and tanked reactors is based on the concept of constraining the sound to an enclosure (absorbing sound energy in the process, e.g. with a special lining such as “Rock-wool”). An alternative would be radiating it in a particular direction where it will cause an acceptable level of disturbance.

Thus it is possible in some instances to consider orienting the converter building and converter transformers, and even the entire converter substation, to shield a sound-sensitive area from transformer noise.

For converter transformers and tanked d.c. reactors, it is often the case in a modern HVDC scheme that the connections to the converters are via bushings directly through the valve hall wall. Consequently, there is a highly effective barrier to sound transmission in one direction, provided the valve hall is significantly taller than the transformer or reactor.

Very often it is a requirement to provide fire barriers between transformers or even around transformers and these can also provide useful sound attenuation – again provided they are high enough compared to the transformer/reactor. Where a complete enclosure is not provided, one must be aware that the part enclosure provided may result in a magnification of noise in a particular unprotected direction due to resonance and/or reflection effects.

7.2.3 Air-cored reactors

Air cored reactors can be significant sound producers, particularly those in filters. Air cored reactors can be enclosed, if care is taken to consider in- and outlet air and electric insulation distances.

From a site layout point of view, there are two possibilities for air-cored reactors:

- Locate them at the maximum practical distance from sound-sensitive areas. Since many reactors are in harmonic filters, there is some flexibility in terms of relocation.
- Locate them in a location which uses the converter buildings (and other site buildings) to shield sound-sensitive areas from unacceptable levels of sound.

7.2.4 Capacitors

In some cases, capacitors can be significant sound generators and they can be treated in the same way as air-cored reactors for layout-based sound reduction techniques.

The capacitor stacks in HVDC filters have large dimensions and a complex radiation pattern. Capacitor stacks may have a very pronounced directivity and thus the location, orientation, height and screening technique can be optimized with respect to the acoustic layout of the HVDC substation.

7.2.5 Cooling fans

In many respects the same considerations as for air-cored reactors apply on cooling fans. There is the significant point that some fans are strongly directional from a sound emission point of view. This gives the added opportunity to orient the fans in a direction in which the sound levels are less of a nuisance.

7.2.6 Diesel generators

For a diesel generator, the main noise source is usually the exhaust vent (as described in 6.6.3). In this case further sound reduction in terms of site layout is as for air-cored reactors and dependant on site size and location of buildings.

7.2.7 Switching devices

Whilst switchgear produces a significant level of sound in its occasional operation, this is generally acceptable and is no different from a conventional substation. For particularly sensitive locations consideration may need to be given to locating the switchgear in a building.

7.2.8 Air conditioning plant

Whilst the direct noise of air-handling plants is generally contained in a building, there is still the substantial residual sound from the inlet and outlet air vents. Although the sound emanating from these sources includes not just airflow but also louver noises (remembering that "acoustic louvers" are available) and residual noise from the air handling plant, the same concepts that apply to fans are generally suitable.

7.2.9 Corona sources

In particularly sensitive sites it may be necessary to suppress even normally acceptable levels of corona and a number of methods may be used to achieve this:

- use of adequate electrode configurations for the outline design of the components;
- increased clearances between phases and between busbars;
- use of cables or gas insulated busbars.

7.2.10 Synchronous compensators

As described in 6.2.2, the most significant noise from an enclosed synchronous compensator will be noise produced by the cooling plant. Thus the considerations that apply to cooling fans also apply in this case.

7.3 Component design

7.3.1 General

Low-noise designs of equipment normally seek to minimize the vibration amplitudes of the component's sound radiating surface. For this purpose, it is essential to design the equipment so that the natural frequencies of the component do not coincide with the frequencies of the major excitation forces.

The sound producing process is described in more detail in Clause 6; this clause highlights the design features that lead to a component that produces less sound.

One technique, which reduces sound for many types of equipment, is the use of resilient mountings. By providing vibration isolation, that limits the spread of low frequency sound.

7.3.2 Transformers and tanked reactors

Many of the sound reducing design issues are standard aspects of transformer and reactor design; for example:

- modern core materials;
- lower magnetic flux operation;
- utilizing modern core-joint technologies;
- avoiding critical mechanical resonances;
- provision of mechanical damping both in the tank and in the installation;
- better control of manufacturing tolerances;
- use of low noise fans (see 7.3.5 below);
- use of separate cooler banks may reduce the requirement for forced cooling and ease the enclosure of the transformer.

7.3.3 Air-cored reactors

The key issue for controlling reactor noise is to limit vibration of the windings. Typical techniques used for this include:

- adjustment of physical dimensions, spacers and mechanical supports to move resonance frequencies away from critical frequencies;
- use of larger conductors (to increase inertia and thus reduce vibration amplitude). However, this is usually not an economic approach to reduce the generation of reactor noise. A doubling of the cross-section, and thus doubling the winding weight, gives a noise reduction of maximum 6 dB.

7.3.4 Capacitors

The sound reduction techniques applicable to capacitors aim to reduce the vibration of the surface of the capacitor units.

The following are internal sound reduction measures, which are applicable to capacitors with steel cases, as well as to those with porcelain housings:

- by increasing the number of series connected capacitor elements, the dielectric stresses in the capacitor can be reduced and thus the vibration forces;

- stiffness of the capacitor element packages may be increased by compacting the stacked capacitor elements through improved mechanical damping;
- considering resonance frequencies in the capacitor design.

7.3.5 Cooling fans

The technology for low-noise fans is well established. A number of techniques have a significant effect on the sound produced:

- axial flow fans with large diameters and low rotational speeds;
- silencers and air baffles.

Such measures for transformer coolers may dictate the need for freestanding coolers.

7.3.6 Pumps and diesel generators

Since in normal operation pumps and diesel generators produce a large amount of sound, this can be greatly increased and damage may occur if some basic precautions are not observed. It is recommended to ensure that the alignment of the rotating parts is correct. This needs to be performed very accurately.

7.3.7 Switching devices

The level of sound emitted by switchgear is dependent on the switchgear technology in use.

The level of sound is highest for air-blast circuit breakers, whereas modem SF6 circuit breakers produce a relatively low level of sound. Additionally the breaker operating mechanism (spring, hydraulic) may have an effect on the noise produced. Given a particular type of circuit breaker, there is little to be done with the sound level that is produced by operation.

Methods for limiting the noise produced include:

- reconsidering the switching sequence of such switches, but this must be secondary to safety considerations;
- restricting switching operations to daytime, where possible.

7.3.8 Air-conditioning plant

The same considerations than those for fans apply to air-conditioning plant.

7.3.9 High voltage connections

If it is necessary to reduce corona levels, then the solution is to use higher voltage class connectors and larger conductors or conductor bundles. Corona rings and fittings should also be considered.

7.4 Sound enclosures

7.4.1 General

Sound enclosures include buildings, screens, encapsulation, and other methods of containing and absorbing sound. Enclosures or sound barriers are more practical for higher frequency noise (above 300 Hz). For a barrier to be effective, the receiver location must be in the acoustic shadow zone of the wall. There are formulas for determining the shadow zone and hence the wall height necessary to protect the receiver location [9].

A number of considerations should be made when using enclosures, for example their availability, reliability, and cost.

7.4.2 Transformers and tanked-reactors

Enclosure of transformers and tanked reactors is well established as a noise-reduction technology. Screening and absorption arrangements are very efficient due to the frequency spectrum of the sound (dominating frequencies are above 300 Hz). Indeed, it is standard practice in some utilities to enclose all transformers and tanked-reactors.

One common element of such enclosures is that the enclosure design is greatly simplified by having freestanding coolers, which can be placed outside the enclosure.

The most basic form of enclosure is a brick-built one or an extension to the fire/blast enclosure. This completely encloses the transformer/reactor and contains no sound absorbing material. Depending on the nature of the enclosure, this will give a sound reduction of up to 14 dB (A) without a roof, of 20-35 dB (A) with a roof. However this is strongly dependent on the construction and surface finish of the enclosure walls, and also the relative dimensions of the transformer and the enclosure. It should be noted that a badly designed enclosure of this type might actually amplify sound.

An alternative to the complete enclosure, particularly where blast and fire-containment walls are provided, is the use of sound-absorbing cladding on these walls. This is particularly relevant for converter transformers as these are usually placed against the valve hall wall and so there is a significant amount of sound reflected unless there is some sound absorbent material installed.

Where very significant noise reduction is required, a complete enclosure (possibly with two layers) with sound absorbing material on the inside will be needed to both contain and absorb the sound from the transformer. Such an enclosure might provide attenuation of up to 40 dB (A). A detailed summary of noise abatement methods is given in [8].

7.4.3 Air-cored reactors

These pose a much more significant noise reduction problem. There is a need to ensure that the airflow is not interrupted such that the reactor does not overheat and that electrical clearances are not infringed. Clearly any noise enclosure must be designed in conjunction with the reactor designer. Noise enclosures come in two basic varieties – buildings and reactor-mounted. Buildings must allow substantial heat removal and are often fitted with roof-mounted fans. The same comments concerning the effectiveness of sound reduction provided by the building apply as for the transformer enclosures. Care must also be taken not to create any magnetic loops around the reactors, which may overheat due to the reactor's magnetic field.

Reactor mounted sound enclosures are an integral part of the reactor design. These may vary from a simple extra package on the outside of a reactor to complex fiberglass housing with an independent support structure and lined with sound absorbing material. Such housings may give an attenuation of up to 15 dB (A), but possibly at a cost exceeding the cost of the reactors. However, with regard to the voltage strength of the reactor winding, there might be restrictions on providing sound shields or enclosures, especially for high-LIWL reactors in wet and polluted conditions. Typical maximum attenuation ranges are:

– screening	(3 to 5) dB (A)
– partial enclosures	(5 to 10) dB (A)
– total enclosures	(10 to 25) dB (A)

7.4.4 Capacitors

To limit sound from capacitors, encapsulation can be used. The complication for capacitors is that they are often high voltage equipment with graded insulation. Therefore the encapsulation must either observe the maximum clearance requirement or alternatively be applied in separate sections throughout the capacitor structure. For tanked capacitors, no such complication exists and standard transformer enclosure techniques can be used.

As is the case with all enclosures, they can be simple non-absorbing barriers or complex (and expensive) sound-absorbing enclosures depending on the noise requirements and economic considerations. With partial screening of each rack level in a capacitor stack, reductions of up to 10 dB can be achieved. Higher reductions may be achieved by complete enclosures.

7.5 Retrofitable techniques

7.5.1 Enclosures

Subject to layout, thermal and electrical considerations, it may be possible to erect noise barriers around equipment, which proves to be much noisier in operation than expected. This is nearly always significantly more expensive than building the equivalent enclosure at the construction stage and also involves interruption to the operation of the HVDC link.

7.5.2 Damping

It is sometimes possible to add additional damping to some components, and this may provide some sound reduction where it can be shown that the noise is due to an interaction between the equipment and the foundation or a support structure.

This may either involve modifications to the support structure or the equipment itself such as by adding mass. For example, filling the transformer ribs with sand can help control radiated noise.

7.5.3 Active noise and vibration mitigation

There are methods of sound cancellation, which use microphones installed at the sound radiating surface or installation of loudspeakers close to a sound-radiating component. Such a technique requires a very detailed noise study with precise modeling of all structures.

Active noise and vibration control (ANVC) is most practical for low frequency noise. Effective installations in operation today on power transformers use a combination of vibration actuators mounted directly on the tank and acoustic (speaker-like) actuators that are mounted close to the tank. Error-sensing microphones are placed in the far-field to measure the noise levels and provide input to the controller. On a new transformer, it is possible to use near-field microphones or vibration sensors that are mounted on the transformer tank. An electronic controller takes the inputs from the microphones and minimizes the noise at multiple locations by driving actuators.

If the installation is successful, ANVC can give better noise cancellation at low frequencies than can be achieved with a sound barrier. However, active control is more difficult for sound and vibration problems in three dimensions than it is for problems with one dimension. The successful implementation of ANVC is in general easier and cheaper for small noise sources than for large sources, such as transformer tanks.

8 Operating conditions

8.1 General

This clause deals with the specification of the operating conditions under which the noise requirements shall be fulfilled.

There are many operational factors affecting the acoustic noise from an HVDC substation. These factors include:

a) HVDC substation operating parameters such as:
  - power
  - power direction

  - poles in service
  - firing angle
  - filters/shunt capacitors/shunt reactors in service
  - usage or not usage of redundant equipment e.g. coolers

b) External a.c. parameters influences such as:

  - a.c. system voltage and frequency
  - background harmonics
  - other converters and SVCs

c) Environmental influences such as (see also Clause 4):

  - time of day
  - ambient temperature
  - wind and other meteorological factors
  - external noise sources

Operating conditions affect the acoustic noise level because the load on the equipment (e.g. coolers and fans), the production of harmonics from the converter and to some extent the amount of equipment in operation (e.g. coolers and a.c. harmonic filters) is dependent on the operating conditions.

When looking at the operating conditions for a complete HVDC substation, it is necessary to split up the noise into an "internal part" and an "external part". The HVDC equipment itself produces the internal part while the external part is generated by a.c.-related equipment and harmonics related to the a.c. network.

The a.c. harmonics on the a.c. network will contribute to the total noise level of an HVDC substation. These harmonics are an external contribution, and the customer has to include data on harmonics on the a.c. network in the technical specification, so that the contractor can take it into account when making calculations for the complete substation (see Figure 22).

In practice, it is of most interest to the customer to look at the total substation noise level, but when specifying it is important for the customer to know the different noise sources if, at a later stage, it should be necessary to take further noise reduction measures.

The customer has to specify the requirements in such a way that it is possible for the contractor in a reasonable way to verify that the requirements are fulfilled. On the other hand it is also important that the customer get qualified verification of the noise level of the HVDC substation which can be used as documentation for the authorities.

When specifying noise requirements in the technical specification and subsequently verifying the noise level, it is important to know how the operating conditions will influence the noise level.

Operating conditions can be split up into the following categories:

- normal operating conditions;
- exceptional operating conditions;
- operating conditions specified for verification.

8.2 Normal operating conditions

Normal operating conditions are conditions that are achievable for extended periods of time, or are likely to be repeated regularly. The normal operating conditions include:

Table 2 – Normal operating conditions

Power range	From minimum to nominal
d.c. voltage range	nominal (for long distance transmission systems)
a.c. voltage & frequency	normal continuous
filter configuration	corresponding to power levels
control strategy	normal
redundancy	operation without redundant equipment

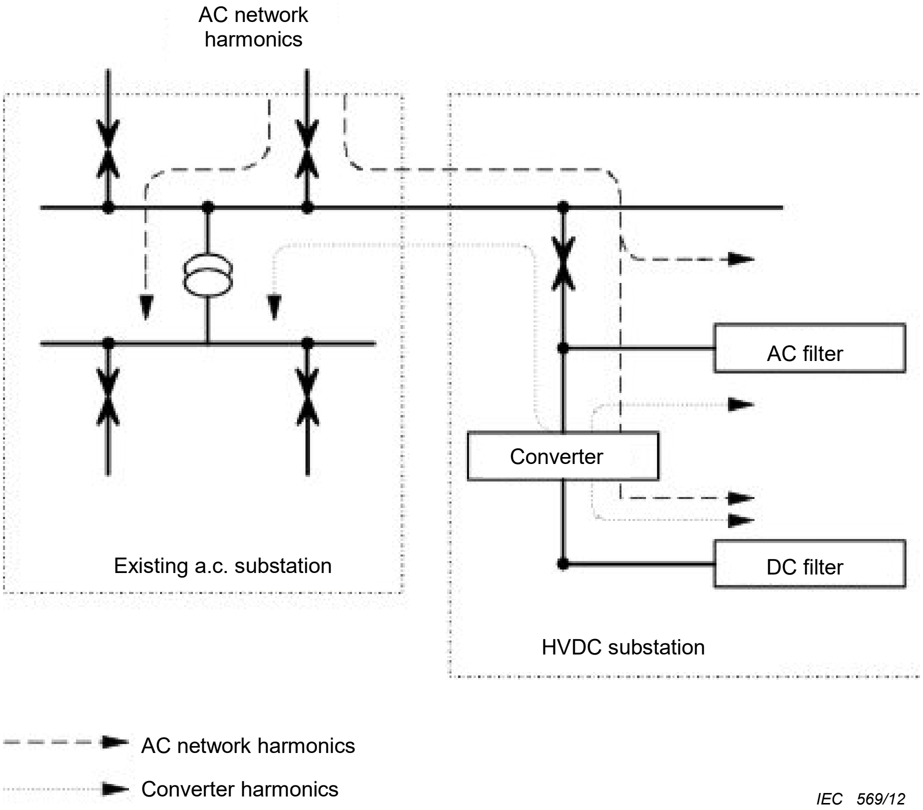


Figure 22 – Explanation of a.c. network harmonics and converter harmonics

8.3 Exceptional operating conditions

Exceptional operating conditions are defined as the occasions when special control functions are used or during temporary (short time) operation such as switching of a.c. filters and frequency or voltage deviations of the a.c. network. Exceptional operating conditions are listed in Table 3.

If the sound levels are to be within the specified requirement limits under all operating conditions, it is recommended that these limits are specified separately, one for normal conditions and one for exceptional conditions.

Table 3 – Exceptional operating conditions

Power range	From minimum power to maximum possible power
d.c. voltage range	full operating range (for long distance transmission systems)
a.c. voltage & frequency	normal continuous
filter configuration	corresponding to power levels
control strategy	for example, using increased firing angles and/or reduced d.c. voltage
redundancy	all redundant equipment in operation (e.g. thyristor and transformer cooling)

8.4 Operating conditions specified for verification

For verification of sound level limits, it is recommended to use the normal operating conditions or a specifically agreed condition. Due to practical on-site measurement constraints, verification will often be via a combination of measurement and calculation. The measurements will be a "verification" of the calculations for a particular operating condition, with the calculations predicting the worst case for normal and – if specified – exceptional conditions. Thus, the preconstruction studies should list the following cases if applicable:

– worst normal operation;

– worst exceptional operation;

– a few typical cases which one may reasonably expect to be measured.

9 Sound level prediction

9.1 General

Prediction of noise emission is important when planning a new installation, an expansion of an existing site, a change in operating conditions of existing plant or noise reduction measures for plant.

Calculation of expected environmental noise resulting from a new development, or when modifying existing installations, is important and often necessary for obtaining the necessary permits. Evaluating alternative design plans for a site is another case where sound level prediction is important. Finally, the calculated predicted sound levels can be compared to the specified levels at the points of interest (see Clause 4 for further details).

The prediction of sound levels in the vicinity of an HVDC substation is based on the sound generated by equipment at site. Thus, such predictions only include the contribution from the HVDC substation to the sound level at a point of interest. A predicted sound level does not include existing background noise level. The background noise level varies with the time of day depending on weather conditions, road traffic noise, railway or air traffic, and operation of other industrial installations or construction work. The background noise level does not therefore influence the contribution from the HVDC substation; however it has a significant influence on measurements of the sound level.

The accuracy of predicting sound levels in or around a converter substation is dependent on reliable acoustic data for the different sound sources at the site. Further, large buildings or other obstacles acting as sound screens must be accounted for in the prediction, as these may obstruct or reflect the sound in different directions. Also, the landscape in the vicinity of the substation affects the sound propagation.

9.2 Modelling of plant

9.2.1 General

Modeling of the plant requires selection of the important components and structures, and use of these as input data for a model for calculation purposes. This is done by the contractor; normally both in the tender and contract stage. In practice, such calculations are most often performed using an engineering tool, such as a computer program, especially when a large number of sound sources and frequencies are included. These computer programs should be commercially available.

An HVDC substation normally consists of a.c. and d.c. filters, transformers, smoothing reactors, thyristor valves and cooling fans. Buildings included in a normal installation consist of a service building and the valve hall. The model of the plant, for calculating the predicted sound levels in and around the substation, should include the dominant sound sources, and also the most important buildings. In addition, the substation layout and the transmission paths should be considered.

9.2.2 Layout

The converter substation layout defines the location and orientation of all equipment at site. Buildings and the site area are also included in the model of the substation. Further, there may be different types of ground surfaces at site, e.g. asphalt pavement, gravel or cultivated grass. The ground at site may therefore range from acoustically hard (asphalt) to soft (grass). This influences the reflection of sound and thus also the propagation.

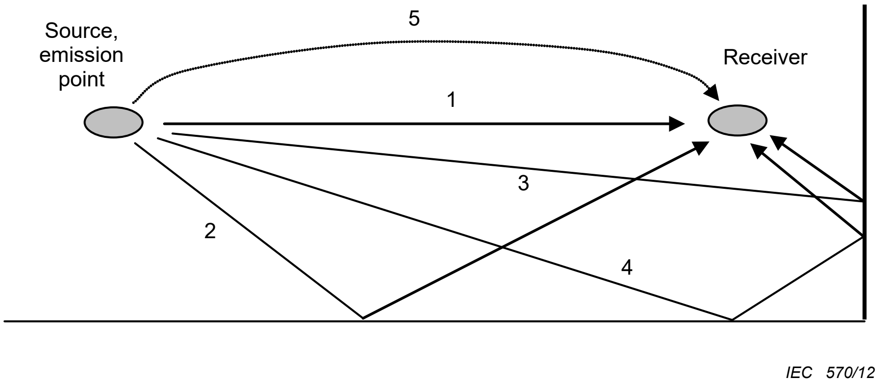
9.2.3 Source

Each real source is represented by an equivalent monopole source in the calculation model. A monopole is a model of a source where all surfaces of the source are moving in phase with each other. The sound sources in the model may be represented by their:

- sound power;
- acoustic frequency content;
- directivity pattern of sound radiation;
- geometrical source description (point source or surface);
- operational time (duration of emission).

9.2.4 Transmission path

For each source, the contribution to the sound pressure level at the receiver is calculated for each frequency band and transmission path from source to receiver (see Figure 23). Sound energy arriving from each of these paths has to be added to obtain the total sound pressure level at the receiver.



Key

1 direct path from source to receiver;

2 path reflected by the ground;

3 path reflected by an obstacle (e.g. building, screen);

4 path reflected by the ground and an obstacle;

5 path influenced by e.g. temperature layers, wind speed and direction (this path may be too complicated to be calculated).

Figure 23 – Examples of transmission paths from source to receiver

9.3 Calculation procedure

9.3.1 Sequence of calculation

The purpose of this general description is to briefly describe the different attenuation terms affecting sound propagation and some conditions to be accounted for when predicting sound levels. ISO 9613-1 and ISO 9613-2 specify calculation procedures for the attenuation of sound during propagation outdoors.

In general, a separate prediction of the sound pressure level contributions at the receiver for each individual source would provide the most flexible system and would ideally yield the highest degree of accuracy. It will, however, in practice often be useful to group as many individual sources as possible, thereby reducing the amount of calculation needed.

The formulas described here are meant for calculating the attenuation of sound from point sources. However, a group of point sources may be described by an equivalent point sound source situated in the middle of the group, particularly if the sources have:

- similar sound power levels, frequency characteristic, orientation and height above the local ground;
- same propagation conditions to the point of reception;
- distance from the single equivalent point source to the receiver exceeding two times the largest diameter of the relevant area of the sources.

If the measurement distance is smaller than described in Figure 24, or if the propagation conditions for the component point sources are different, e.g. due to screening, the total sound source must be divided into its component point sources.

The average sound pressure level at a receiver shall be calculated for each point source and for each octave band with nominal mid-band frequencies, normally from 63 Hz to 8 kHz. In accordance with ISO 266 the following set of centre-frequencies for the "octave" filter apply: 16, 31,5, 63, 125, 250, 500, 1 000, 2 000, 4 000, 8 000, 16 000. For the "1/3 octave" filter, the set of centre-frequencies is 16,0, 20,0, 25,0, 31,5... up to 17 780,0, 22 390,0. For audible noise, frequencies from 31,5 to 5 000 Hz are of interest.

The basic calculation procedure for each source, mid-band frequency and sound path is in three steps (the order of the procedure may differ-between calculation programs):

1) Calculation of the sound power level of each source – including the directivity in the direction of path i (indexed by i) belonging to that source – for each mid-band frequency f , L_{wfi}:

$$L_{wfi} = L_{wf} + DI \tag{16}$$

DI is the directivity index in dB (see 3.2.1). It describes the extent to which the sound radiation of the real source into different directions deviates from the emission of a non-directional point source.

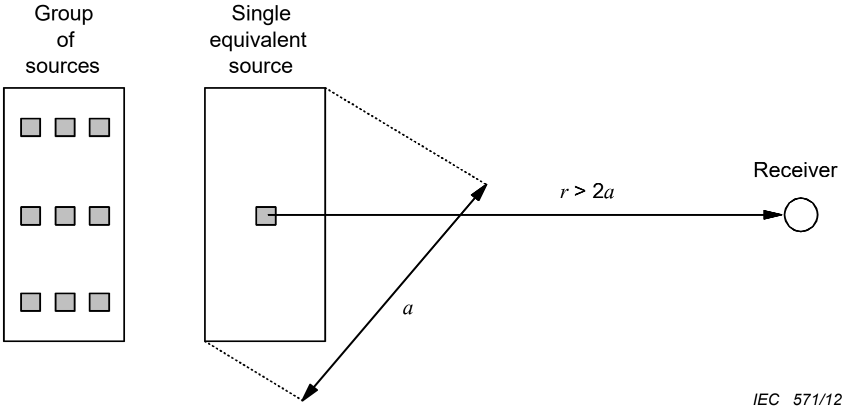


Figure 24 – Grouping of point sources to one equivalent source if the measurement distance (r) is larger than 2a

2) For each sound source (n), inclusion of its sound path from source to receiver, by calculation of the total sound pressure level in dB at the specific location for the frequency band f;

$$L_{p\text{TOT}(N)} = \sum_{n=1}^{N} \left(L_{wfi,n} - A_{fi,n} \right) \tag{17}$$

where:

$A_{fi,n}$ is the frequency dependent attenuation in dB for source n during propagation from source to receiver;

N is the total number of sound sources.

The attenuation term, $A_{fi,n}$, is given by

$$A_{fi,n} = A_{\text{div}} + A_{\text{atm}} + A_{\text{screen}} + A_{\text{reflex}} + A_{\text{ground}} + A_{\text{veg}} \tag{18}$$

where:

A_{div} is the attenuation due to geometrical divergence;

A_{atm} is the attenuation due to atmospheric absorption;

A_{screen} is the attenuation due to screening and transmission;

A_{reflex} is the attenuation due to absorption at reflecting obstacles;

A_{ground} is the attenuation due to the ground (which may include vegetation, e.g. grass);

A_{veg} is the attenuation due to sound propagation through vegetation.

3) Finally, sound pressure level summation, for each frequency band f, of different contributions L_{pTOT} (N) to the sound pressure level L_{pTOT} (dB), is performed by using the equation:

$$L_{p\mathrm{TOT}} = 10 \lg \sum_{f=1}^{n} 10^{L_{p\mathrm{TOT}}(N)/10} \tag{19}$$

where n is the total number of frequency bands.

9.3.2 Calculation of attenuation terms

9.3.2.1 Attenuation due to geometrical divergence

A source in a free-field radiates sound in all directions equally (spherically). The surface area of this sphere increases as the diameter increases. Since the source sound power is constant, the energy expressed in W/m^2 decreases with increasing diameter. Hence:

$$A_{\mathrm{div}} = 10 \lg \left[4\pi \left(\frac{r}{r_0} \right)^2 \right] \tag{20}$$

where:

r is the distance from source to receiver, in meters;

r_0 is the reference distance (or radius) giving a sphere of surface area 1 m^2.

For r < 0,28m (resulting in $A_{\mathrm{div}} < 0$), A_{div} is set to 0 giving, if no other attenuation terms contribute, a sound pressure level that equals the sound power level, i.e. $L_p = L_w$.

9.3.2.2 Attenuation due to atmospheric absorption

The attenuation due to atmospheric absorption is given by:

$$A_{\mathrm{atm}} = \frac{(\alpha_a \times d)}{1\,000} \tag{21}$$

where:

α_a is the atmospheric attenuation coefficient, in dB/kilometer;

d is the distance of the sound path in meters.

Table 4 lists examples of atmospheric attenuation coefficients.

Table 4 – Examples of atmospheric attenuation coefficients

T	RH	Nominal octave centre frequencies Hz							
air temperature	relative humidity	63	125	250	500	1 000	2 000	4 000	8 000
°C	%	attenuation in dB per 1 000 meters							
- 20	70	0,17	0,51	1,73	5,29	11,5	16,6	20,2	27,8
- 10	70	0,15	0,33	0,83	2,65	9,19	27,8	58,5	86,2
0	70	0,15	0,39	0,76	1,61	4,64	16,1	55,5	153
10	70	0,12	0,41	1,04	1,93	3,66	9,66	32,8	117
20	70	0,09	0,34	1,13	2,80	4,98	9,02	22,9	76,6
30	70	0,07	0,26	0,96	3,14	7,41	12,7	23,1	59,3
15	20	0,27	0,65	1,22	2,70	8,17	28,2	88,8	202
15	50	0,14	0,48	1,22	2,24	4,16	10,8	36,2	129
15	80	0,09	0,34	1,07	2,40	4,15	8,31	23,7	82,8
30	> 90	0,051	0,199	0,768	2,695	7,317	13,808	23,589	53,907
NOTE See ISO 9613-1.									

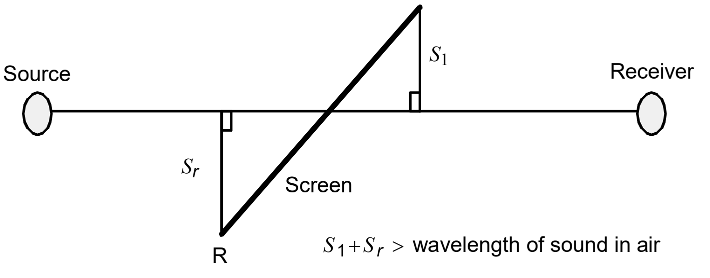
The atmospheric attenuation coefficient depends strongly on the frequency of the sound, the ambient temperature and relative humidity of the air, but only weakly on the ambient pressure. For estimates of environmental noise levels, an average attenuation coefficient should be used based on the range of ambient weather, which is typical for the locality.

9.3.2.3 Attenuation due to screening and transmission

The general principle in calculating the screening correction is to identify all screening obstacles between source and receiver. A simplifying approach is to represent each obstacle by a thin screen. The calculation procedure depends on the number of screens present. More details regarding calculation of the screening correction can be found in ISO 9613-1 and in [10].

There are three basic conditions that have to be met in order for an obstacle to qualify as an effective screen:

- The mass per unit area of the obstacle should exceed 10 kg/m^{2};
- there should be no slits or openings in the obstacle;
- the horizontal dimension perpendicular to the line between the source and receiver should be greater than the wavelength of the sound in air, i.e. $s_1+s_r > \lambda_c$ (see Figure 25).

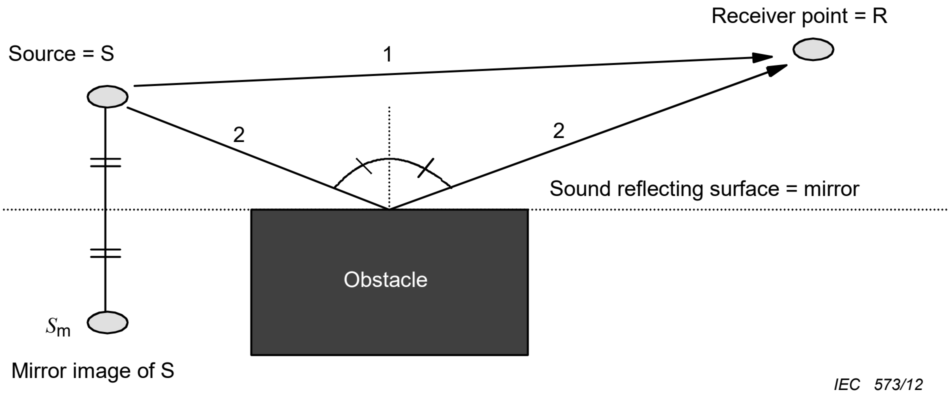


IEC 572/12

Figure 25 – Definition of the geometrical parameters used for calculation of screening

9.3.2.4 Attenuation due to reflection obstacles

In general, the effects of sound reflections from obstacle are treated in the prediction models by acoustical mirror considerations. The principle is illustrated in Figure 26 below.



Plan showing transmission paths between S and R. Note the mirror source S_m
Path 1: direct
Path 2: via reflection from building facade

Figure 26 – Reflecting obstacles are treated by mirror sources

The angle between the direction of the incident sound field and the normal to the reflecting surface is equal to the angle between this normal and the direction of the reflected sound field. The sound pressure level at the receiver can be considered to be built up by two separate individual contributions arriving via two transmission paths.

When sound hits a surface, some sound is reflected, some is transmitted and some is absorbed depending on the acoustic properties of the reflecting surface and on the properties of the sound.

The sound pressure level at the receiver can be calculated by adding the contributions from the real source, S, and the mirror source, S_m, respectively.

9.3.2.5 Attenuation due to the ground

Basically the attenuation due to the ground is calculated as the sum of three corrections (source, central and receiver), each of which is related to the properties of different regions of the ground surface between the source and the receiver (see Figure 27).

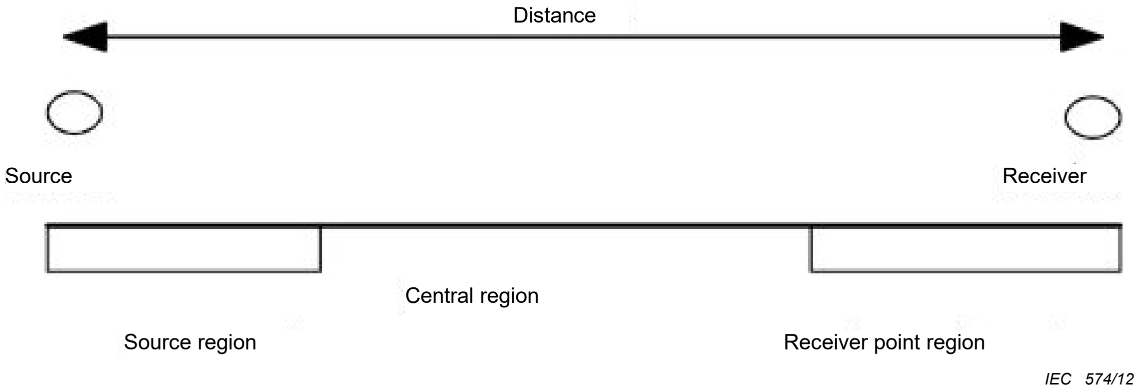


Figure 27 – Definition of parts for calculation of ground attenuation

The values of the ground correction contributions depend upon source and receiver height, type of ground surface, distance between source and receiver, and whether or not screening occurs along the transmission path. The ground correction contribution can be positive or negative, indicating amplification or attenuation.

There are two types of ground characterization. Hard ground, e.g. asphalt, pavement, concrete, water[2] and ground surfaces with many scattering obstacles are considered acoustically "hard". All surfaces on which vegetation could occur and on which only a few scattering obstacles exist are regarded as acoustically soft. Examples such as grassland, agricultural ground with and without vegetation, woods, moors and gardens can be regarded as having an acoustically porous surface.

9.3.2.6 Attenuation due to propagation through vegetation

A curved transmission path is considered, illustrated by the upper path in Figure 28. A group of trees and bushes is considered dense if – along the transmission path – it is impossible to see through the vegetation, i.e. if the transmission path is visually blocked. It must consist of a number of groups, each having a transmission path length d_{v} of 50 meters (see Figure 28).

Furthermore, if the transmission path passes through a number of consecutive groups of trees and bushes, and each of these groups visually blocks the transmission path, a maximum of four groups may be taken into account. The vegetation height should exceed the height of the curved transmission path by one meter or more (see Figure 28). The transmission path height, h, above the straight line between source and receiver is given by:

$$h = \frac{(d_1 \times d_2)}{16 \times d} \tag{22}$$

where:

h is the transmission path height above the straight line between source and receiver;

d_1 is the horizontal distance from source to “screen” in meters;

d_2 is the horizontal distance from receiver to “screen” in meters;

d is $d_1 + d_2$ in meters.

The attenuation due to the vegetation, A_{veg}, is calculated by

$$A_{\mathrm{veg}} = -n_{\mathrm{v}} \times \alpha_{\mathrm{v}} \tag{23}$$

where:

n_{v} is number of groups of vegetation;

α_v is the attenuation coefficient per group (see Table 5 below).

If $n_{\mathrm{v}} > 4$, n_{v} is set equal to 4.

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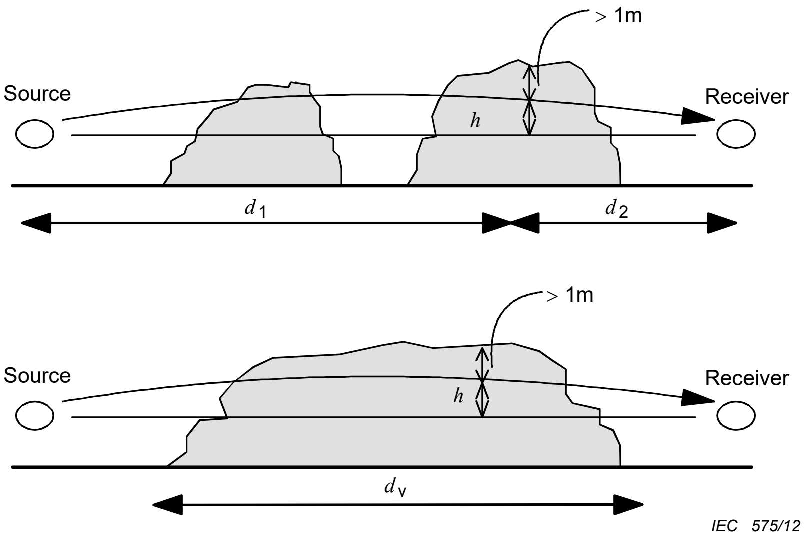
[2] When sound waves in air are incident on a water surface, the water is experienced as "hard". For sound incidence from water to air, the air is experienced as "soft".



Key

$n_v = 2$

$n_v = d_v/50$

Figure 28 – Definition of parameters used in Equation 22

Table 5 – Examples of attenuation coefficient values for octave bands

1/1 octave f_m [Hz]	63	125	250	500	1 000	2 000	4 000	8 000
α_v attenuation coefficient per group [dB/group]	0	0	1	1	1	1	2	3

The attenuation coefficient values are valid under both summer and winter conditions provided that the transmission path is visually blocked. Usually this is not the case in wintertime. If so, the values in the table above should be multiplied by 0,5.

As an example, a dense forest of 50 meters in depth gives a reduction of approximately one (1) dB(A).

9.3.3 Results presentation

A practical and useful method for presenting and studying the results of the calculated predicted sound levels is essential. There are basically two different types of results presentation:

- graphical presentation of e.g. sound level contours with equivalent sound levels (see Figure 29);
- table with predicted sound levels at a number of receivers.

The graphical presentation of the calculated result gives an overall view of the predicted sound pressure levels in and around the substation, but no information about which sources are dominating the contribution at specific points.

The tabular presentation of results is especially useful if the table also contains the contribution from each source or group of sources (see Table 6) on a total level and for each frequency, forming a ranking Table 7. This presentation of results indicates on which equipment noise reduction measures should focus.

CASE No	RECEIVER	X	Y	Z	NAME
303	1	570,00	130,00	1,50	Nearest House

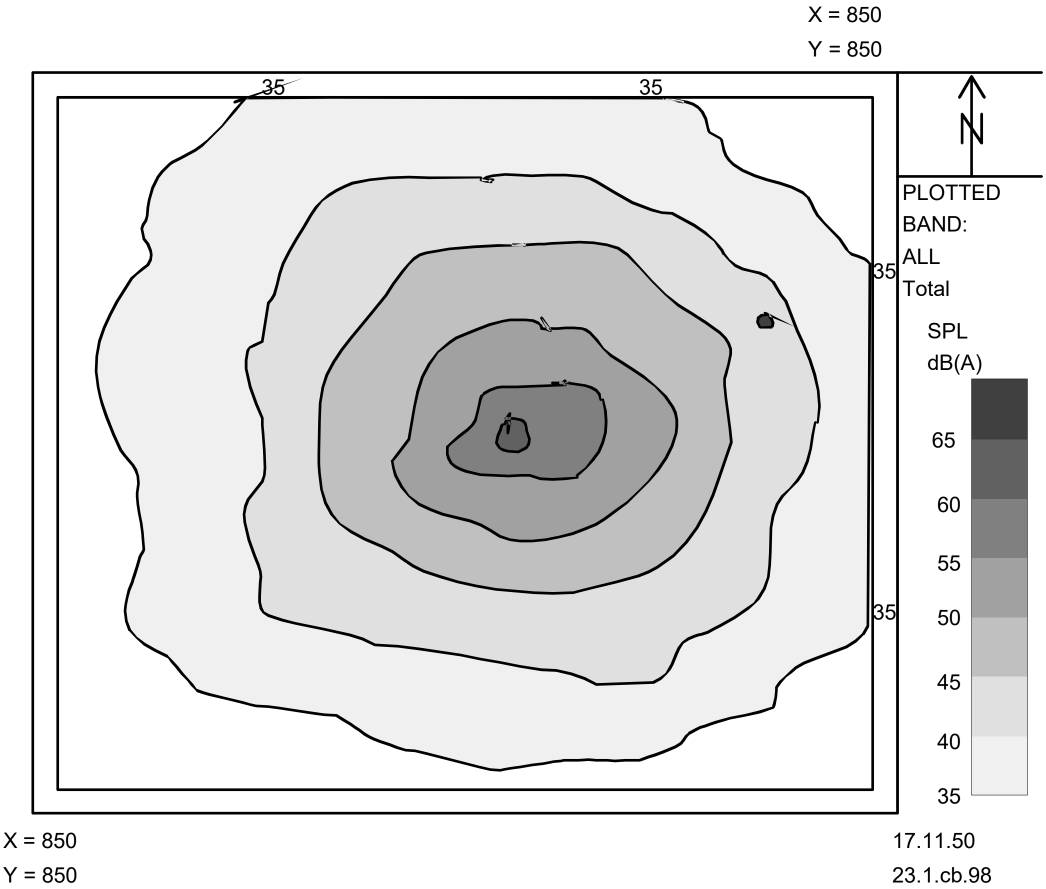


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Figure 29 – Example of graphical presentation of sound pressure level calculation

Table 6 – Groups of noise sources

Group 1	Transformers and transformer
Group 2	Valve cooling fans
Group 3	Smoothing reactor
Group 4	PLC filter
Group 5	AC shunt capacitors
Group 6	AC shunt reactor
Group 7	11th capacitor and reactor
Group 8	13th capacitor and reactor
Group 9	24th capacitor and reactor
Group 10	36th capacitor and reactor

Table 7 – Ranking of noise sources

FREQ	All/Total		1 000	500	700	600	250	125	2 000	1 200	Other
RANK	dBA	Source	dBA	dBA	dBA	dBA	dBA	dBA	dBA	dBA	dBA
Tot:	40,6	-	35,6	34,5	29,6	29,4	27,8	27,1	26,1	25,9	25,0
1	34,3	Grp.1	29,3	29,4	7,8	8,6	23,2	21,2	23,1	-	26,1
2	32,6	Grp.10	29,8	27,4	-	-	-	-	19,7	20,2	20,7
3	32,5	Grp.9	29,9	27,6	-	1,3	-	-	19,6	19,1	17,1
4	32,0	Grp.3	26,4	25,3	-	27,7	-	-	-	23,1	12,2
5	31,1	Grp.8	20,0	17,8	29,5	19,7	-	-	9,8	-	21,3
6	29.5	Grp.7	19,5	17,2	-	22,4	-	-	9,4	-	27,5
7	28,9	Grp.6	-	21,7	-	-	25,1	24,8	-	-	4,4
8	25,7	Grp.4	23,1	22,3	-	-	-	-	-	-	-
9	23,4	Grp.5	-	18,8	-	-	17,8	19,2	-	-	-
10	12,3	Grp.2	-	9,4	-	-	4,4	-	-	-	7,4

NOTE 1 The dash symbol (-) in the table above indicates that the source does not contain this frequency.

NOTE 2 Each column in the table represents an octave or narrow frequency band. Each row represents a noise source or a group of noise sources. Reference octave band mid frequencies are used for showing the calculation result per sound source group.

10 Verification of component sound power

10.1 General

This clause describes methods for verifying the component sound power. There are three different approaches to verification:

- calculation;
- measurement:
  - sound pressure measurements in an acoustic measurement room or outdoors;
  - preferably following a standard for sound measurements;
  - sound intensity measurements;
  - vibration measurements;
- combination of calculation and measurement.

The sound requirements for HVDC substations are conventionally specified in terms of the maximum allowed sound pressure level at a specific contour or at specific points surrounding the substation. In order to meet this target, the contractor has to break down the sound requirements to the component level. The verification of the component sound power should be performed before the component is installed at site. Once all components are installed it is almost impossible to correctly determine the noise contribution of each individual component. Provided that the background noise level is low enough, it may however be possible to verify the total sound power level of a group of components at site, e.g. of an a.c. filter.

10.2 Calculation

10.2.1 General

Sound power is the most important acoustic quantity for characterization of a sound source. It is a basic parameter used for assessment and comparison of sound sources. It is a measure of the acoustic output of a source. The sound power level can be used to assess the effect of noise on the surrounding environment, which allows efficient noise management.

The calculation of sound power emitted by electrical components is conventionally divided into three steps:

a) the electrical forces are calculated:
   - electrostatic for capacitors;
   - electromagnetic for windings of reactors and transformers;
   - magnetostrictive for cores of transformers and iron-cored reactors;

b) the system response, or transfer function, is extracted;

c) the vibration amplitudes and the resulting sound power are calculated.

The procedure is outlined in Figure 30:

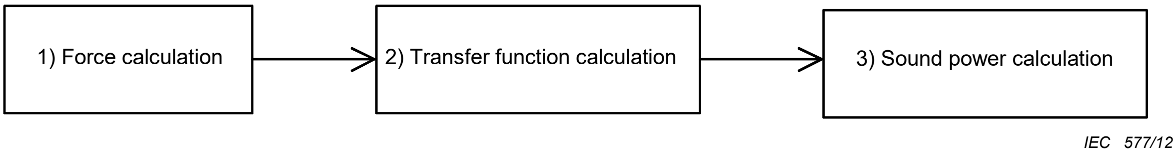

Figure 30 – Three steps to determine the sound power of HVDC components

10.2.2 Calculation of force spectrum

In the text below, the term "current" is used to describe the electrical load, but this term shall also be taken to cover "voltage". For details, see Clause 6 and in particular 6.2.4 and 6.4.2.

If a current energizes the component with a single a.c. frequency, this will result in an electro-mechanical force of twice the power frequency. This is however only true if no d.c. is present. With d.c. present, the power frequency will also appear in the force spectrum.

If the current consists of two frequencies, the force spectrum will contain two times the current frequencies and the sum and the difference of these frequencies. As an example, the fundamental tone 50 Hz and the 11th harmonic (550 Hz) would create force spectrum shown in Table 8.

Table 8 – Vibration force frequency spectrum resulting from the electrical fundamental frequency 50 Hz and its 11th harmonic

Force frequency Hz	**Derived from electrical frequencies** Hz
100	2 × 50
500	550 – 50
600	550 + 50
1 100	2 × 550

10.2.3 Transfer function calculation

When calculating the vibration amplitude from the applied force, the mechanical properties of a component play an important role. All electrical components are mechanical constructions, which possess natural modes of vibration; and each natural mode shape is associated with its resonance frequency and damping. The damping of the mode dominates the behavior of the response of the component close to the resonance frequency.

When a force is exciting a structure, a number of natural modes can participate in the motion. How much a mode will participate in the motion depends mainly on:

- how close the forcing frequency is to the resonance frequency of the mode;
- how large the damping of the mode is;
- the spatial force distribution has very low impact to the mode shape of vibration which is excited by the force.

The first and second reasons are obvious. Firstly, if the forcing frequency is the same as the resonance frequency, the structural vibration amplitude may be very large. Secondly, if one mode has a large damping compared to another, but both modes have resonance frequencies equal to the forcing frequency, the mode with the smallest damping will dominate the structural motion.

Thirdly, the vibration pattern, or the mode shape, of each natural mode, is very important. As an example, consider the can-type capacitor mentioned in 6.4.2. The excitation force on the capacitor is purely axial (see Figure 19). This means that the axial resonance frequencies of the capacitor will determine the radiated sound power. The resonance frequencies with mode shapes (and thus true motion) perpendicular to the exciting direction will also be excited by the electrostatic forces and will contribute to the sound power radiation, but to a much lower extent.

As an example of this discussion, consider the response between force and vibration amplitude of a mechanical system with one degree of freedom (1-DOF) in Figure 31. Near the resonance frequency, it is clear how important the damping is for the response of the system. For details about critical damping see [11].

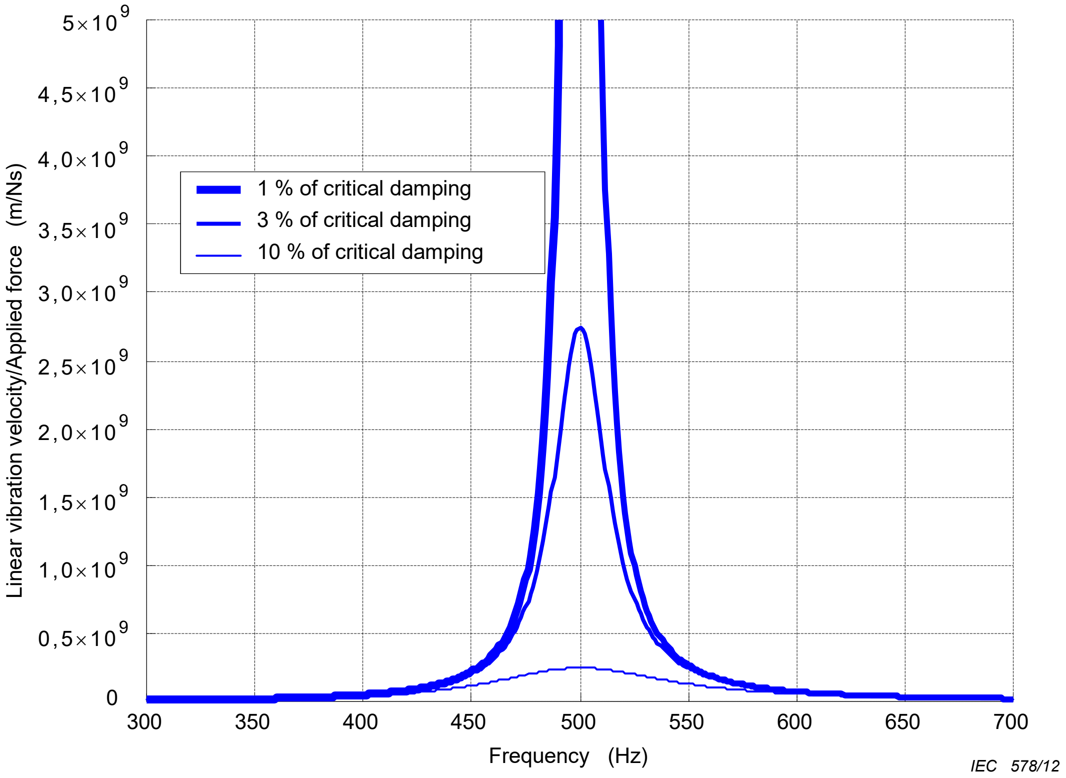

Figure 31 – Linear transfer function between e.g. force and vibration velocity for a 1-DOF system with the resonance frequency 500 Hz

10.2.4 Sound power calculation

Given a structural vibration velocity, v, the Equation (24) often gives a good estimation of the sound power in dB:

$$L_w = 10\,\mathrm{lg}\left(\frac{\rho c \times A \times \sigma \times \left\langle \tilde{v}^2 \right\rangle}{1 \times 10^{-12}}\right) \tag{24}$$

where:

ρc is the impedance of the surrounding fluid in Ns/m^3 (ρc = 410 Ns/m^3 for air);

A is the area of the vibrating surface in m^2;

σ is the radiation factor, or radiation efficiency (no unit);

$\left\langle \overset{-2}{v} \right\rangle$ is the squared and time averaged r.m.s vibration velocity of the vibrating surface in (m/s)^2;

1×10^{-12} is reference level for sound power in W.

What sometimes makes Equation (24) uncertain is the radiation factor σ, as briefly described in 6.3.2. For example, for bending waves the radiation factor generally is in the range from ~10^{-4} to 1. However for the breathing mode σ = 1 unless the wavelength of the sound is of the same order as the height of the reactor which decreases σ.

To achieve better accuracy of the radiation factor, BE (boundary element) or FE (finite element) methods could be used.

10.3 Measurement

10.3.1 General aspects on sound power determination

10.3.1.1 General

As mentioned in the introduction of this clause, sound power is the most important acoustic quantity for characterisation of a sound source. However, sound power cannot be measured directly with an instrument. There are several different methods to determine the sound power of an object. Each method has its benefits and drawbacks.

10.3.1.2 Classification of methods

The simplest and therefore the most common method to determine sound power is to use sound pressure measurements. Most of the standards are based on the measurement of sound pressure. This requires a sound level meter, which should have the capability to analyze the frequency content of the measured sound. One way to achieve this is to use a Fast Fourier Transformation (FFT) analyzer; another is to use real-time filters. The method either requires a measurement room (not necessarily an acoustic laboratory, though) or free field conditions and the use of an acoustic standard. ISO 3743-2 specifies a relatively simple engineering method for determining the sound power levels of small, movable noise sources. In this direct method the A-weighted sound power level of the source under test is determined from a single A-weighted sound pressure level measurement at each microphone position, rather than from a summation of octave-band levels. This method eliminates the need for a reference sound source, but requires the use of a special reverberation test room. ISO 3744 specifies methods for determining the sound power level or sound energy level of a noise source from sound pressure levels measured on a surface enveloping the noise source (machinery or equipment) in an environment that approximates to an acoustic free field near one or more reflecting planes. The sound power level (or, in the case of noise bursts or transient noise emission, the sound energy level) produced by the noise source, in frequency bands or with frequency A-weighting applied, is calculated using those measurements. ISO 3745 specifies methods for measuring the sound pressure levels on a measurement surface enveloping a noise source in anechoic and hemi-anechoic rooms, in order to determine the sound power level or sound energy level produced by the noise source. It gives requirements for the test environment and instrumentation, as well as techniques for obtaining the surface sound pressure level from which the sound power level or sound energy level is calculated, leading to results which have a grade 1 accuracy. ISO 3746 specifies methods for determining the sound power level or sound energy level of a noise source from sound pressure levels measured on a surface enveloping a noise source (machinery or equipment) in a test environment for which requirements are given. The sound power level (or, in the case of noise bursts or transient noise emission, the sound energy level) produced by the noise source with frequency A-weighting applied is calculated using those measurements. Although having the benefit of being simple, sound pressure measurements can be sensitive to background noise and reflections. Furthermore, the safety of personnel must be considered when using any measurement technique, which involves working in the proximity of energized equipment.

The sound intensity method reduces the influence of background noise provided that it is constant during the measurement. This makes it possible to perform measurements in an environment, which would not be ideal for sound pressure measurements. ISO 9614-1 and ISO 9614-2 specify a method for measuring the component of sound intensity normal to a measurement surface which is chosen so as to enclose the noise source(s) of which the sound power level is to be determined. The one-octave, one-third-octave or band-limited weighted sound power level is calculated from the measured value. The method is applicable in situ or in special purpose test environments to any source for which a physically stationary measurement surface can be defined, and on which the noise generated by the source is stationary in time. The method is more time consuming and requires more experienced personnel to give an accurate result. Correctly performed though, the intensity measurement is a very accurate way to determine the sound power, but is for safety reasons great care has to be taken if audible noise measurements are done in HVDC substations.

10.3.1.3 Directivity

Vibration patterns on sound emitting components often create noise radiation with a spatial non-symmetry – the noise radiation is said to have directivity. These directivity effects cause maxima and minima of the sound in some directions. When sound pressure measurements are performed, it is important that a sufficient number of measurement points are used to get a good average of the spatial variations of the sound pressure level. Otherwise large errors in sound power determination may be the result. The same principles regarding the number of measurement points hold for vibration and sound intensity measurements as well. Recommendations are given in the acoustic standards, for example, ISO 3744.

Another example of directivity is the result of the actual placement of the noise source in relation to reflecting surfaces. This is explained in 3.2.1 and is of course very important to bear in mind when sound power determinations are performed.

10.3.1.4 Test environment

Sound power verifications at a manufacturer's works may be complicated due to space limitations. Firstly, the manufacturer may not have a special test area designated for acoustic measurements. Secondly, high background levels may make sound pressure measurements hard to perform. However, it is usually possible to find a test location at the factory, which fulfils the requirements of an acoustic standard, even if is outside in the car park or involves working at night when background levels are reduced. Requirements for acoustic test environments are given in the acoustic standards (see ISO 3745, ISO 3744 and ISO 3740).

Furthermore, in a test laboratory it not always possible to produce the high currents and/or voltages which exist at site. Also, on site, the load spectrum consists of several harmonics. In the test laboratories, it is more practical to excite a component with one frequency at a time and at a smaller load than will occur in normal operation. The sound power at normal, full load can then be calculated according to scaling laws (see e.g. Equation (9)). For this procedure to work, the test load must give sound levels higher than the background noise levels (recommendations are given in relevant standards).

If it is necessary to verify the sound power of an object with very high accuracy, it may be necessary to use specially designated acoustic test rooms, e.g. anechoic chambers or reverberation rooms. In these cases, the manufacturer could work with acoustic consultants and/or universities. These kinds of measurements should be exceptions though, as it is impractical, time consuming and expensive to use such acoustic test rooms.

10.3.2 Sound pressure measurement

As already mentioned, the sound pressure measurement is a simple method for measuring radiated sound, and is therefore most commonly used. However, sound pressure measurements are sensitive to noise produced by sources other than the object to be measured and to reflections. To avoid ambient influences, sound pressure measurements are usually performed in test laboratories or in special outside test areas at the component manufacturers [12].

Since the sound level distribution measured around sound sources is usually non-uniform, it is necessary to assess noise levels on spatial average figures gained from several measurement positions rather than from one single position. The measurement positions should be located on the surface of a hypothetical envelope enclosing the source. The average sound pressure level ($\overline{L}_{p\mathrm{A}}$) is calculated from the measured values of the A-weighted sound level ($L_{p\mathrm{A}i}$) in dB by using the following equation:

$$\overline{L}_{p\mathrm{A}} = 10\ \lg\left(\frac{1}{N}\sum_{i=1}^{N}10^{0{,}1L_{p\mathrm{A}i}}\right) \qquad (25)$$

where:

N is total number of measurement points.

The A-weighted sound power level ($L_{W\mathrm{A}}$) of an object (in dB) may be determined from the average sound pressure level, $L_{p\mathrm{A}}$, according to the following equation;

$$L_{W\mathrm{A}} = L_{p\mathrm{A}} + 10\ \lg\left(\frac{S}{S_0}\right) \qquad (26)$$

where:

S is the area of the envelope in square meters and S_0 is a reference area of 1 m^2 (see Figure 32).

This procedure is valid only if the measurement points are located at approximately the same distance from the acoustical centre of the sound source. If however, the background noise level is too high to allow an accurate determination of the sound power of the test object, the sound pressure method will not give reliable results. However, under these circumstances, the sound pressure method will always give a value for sound power, which is too high. If this high value of sound power still meets the required limit (guarantee value), then it may not be necessary to make further measurements. If a more accurate value is required, measurements should be performed closer to the sound source and another measuring method should be used.

Specific noise level is defined here as the "true" noise level of a measured object. If the background noise level is within 10 dB of the total measured noise level, it is necessary to correct the total noise level for the influence of background noise. Theoretically this is possible, as long as the background noise level does not exceed the specific noise level, but in practice the correction will be very uncertain if the difference is small, i.e. only a few dBs. Some ISO standards set this lower limit to 6 dB.

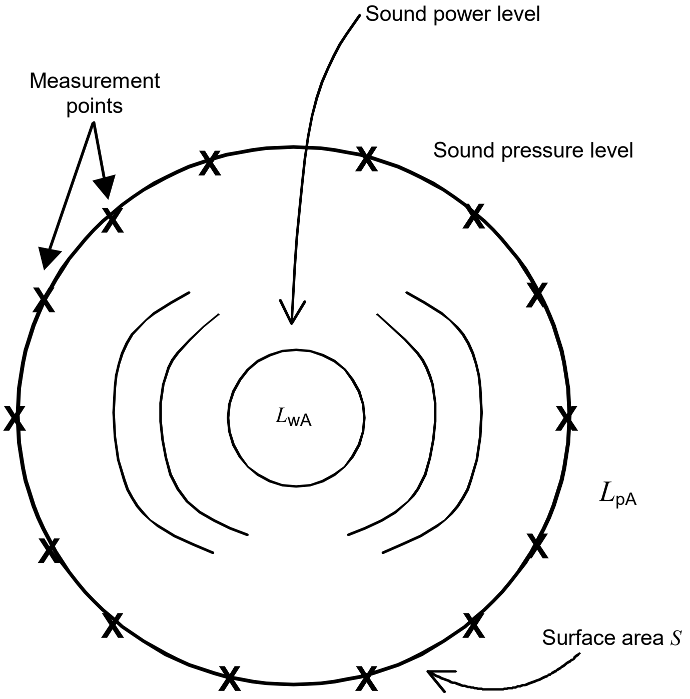

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Figure 32 – Definitions of the parameters used in Equation (26)

10.3.3 Corrections for background noise

Equation (27) gives the relationship between the total measured noise level $L_{p,\mathrm{t}}$, the background noise level $L_{p,\mathrm{b}}$ and the (true) specific noise level $L_{p,\mathrm{s}}$ (dB).

$$L_{p,\mathrm{s}} = 10\lg\left(10^{(L_{p,\mathrm{t}}/10)} - 10^{(L_{p,\mathrm{b}}/10)}\right) \tag{27}$$

10.3.4 Sound intensity measurement

Sound intensity is defined as sound energy emitted by a sound per unit time flowing through unit area in a direction perpendicular to that area. It is computed as a vector quantity equal to the time-averaged product of the instantaneous sound pressure and its corresponding instantaneous particle velocity. The component of intensity in the direction r is given by

$$\vec{I}_r = \langle p(t) \times v_r(t) \rangle \tag{28}$$

where:

~~$\bar{I}_r$~~ $\vec{I}_r$ is sound intensity in direction r;

$p(t)$ is instantaneous sound pressure;

$v_r(t)$ is instantaneous particle velocity in direction r.

NOTE Symbol < > implies a time average.

In contrast to sound pressure, which as a scalar quantity has only magnitude, sound intensity is a vector quantity with both magnitude and direction.

The sound pressure of Equation (28) can be measured by a simple method using one or several microphones. It is however difficult to measure the particle velocity directly, but it can be determined by measuring the sound pressures p_1 and p_2 with two microphones along the vector r at r_1 and r_2 ($r_1 > r_2$).

Sound intensity can then be determined from the following expression:

$$\vec{I}_r = \frac{1}{2\rho\Delta r}\left\langle (p_1 + p_2)\int_0^t (p_1 - p_2)dt \right\rangle \tag{29}$$

where:

p_1, p_2 is the sound pressure measured at r_1, r_2;

Δr is the distance between the two microphones (= $r_1 - r_2$);

ρ is the mass density of the environment (for air, ρ is 1,2 kg/m^3 at 20 °C).

Sound power can be calculated by integrating the sound intensity around an enclosing surface (imaginary contour), which completely surrounds the sound source:

~~$W = \oint_A \bar{I}\, d\bar{A}$ (30)~~

$$W = \oint_A \vec{I}\, \overrightarrow{dA} \tag{30}$$

where:

W is total sound power;

$\vec{I}$ is intensity vector measured by the sound intensity meter;

$\overrightarrow{dA}$ is element of surface area A.

The sound radiated by the sound source always travels out from the source through the imaginary contour. Sound radiated by external sources (including sound from reflecting obstacles), i.e. those outside the imaginary contour, will flow into this hypothetical volume and then out of the region on another side. Hence, this "external" sound will not contribute to the total integral. Consequently, sound intensity measurement allows discrimination between the test object sound power and that produced by other constant sound sources.

In practice, an enclosing surface of integration has to be chosen which is close to the sound source in order to increase the signal-to-noise ratio for the sound intensity measurement. One has to spatially average over the entire surface by sweeping the sound intensity probe over a region of surface for an adequate time, or to measure at a number of discrete measuring points. During the measurement period, the background noise has to be constant. Otherwise there will be a difference in ambient energy entering and leaving the surface of integration, because all the measurement points on this surface are not measured at the same time.

To conclude this subclause, sound intensity measurement can be a useful tool in some cases, but requires more experience from the personnel.

10.4 Combination of calculation and measurement

10.4.1 General

The sound power of a component must be determined for the full, normal operational loading, which means the correct voltage for capacitors and the correct current for reactors. The power frequency of the test load must be correct. Based on the relationship between load and sound power for an electric component, it is however possible to use a test load during the measurement and to scale the sound power to correspond to the operational loading. For capacitors, the sound power level is proportional to voltage to a power of four, (U^4) and for air-cored reactors it is proportional to current to a power of four, (I^4).

To illustrate the procedure, an example is given. Assume that sound pressure measurements have yielded a sound power for a capacitor of 56 dB(A). The test voltage used was 1/5 of the planned operating voltage. The sound power under real operating conditions will therefore be 56 + 10lg(5^4) dB(A) = 56 + 40lg(5) dB(A) = 83 dB(A).

For transformer cores, there is a linear relationship between voltage and sound power up to a certain value of the magnetic flux density. For flux densities greater than this value, the relationship is extremely non-linear. Sound power determination at flux densities other than the ones where linear conditions prevail would therefore be subject to errors. In these cases, it is necessary to rely on measurements.

Two methods for sound power determination are summarized: the verification of individual components (at the manufacturer's) and the verification (of several components) at site. See 10.3 for further details.

10.4.2 Verification of key components

The two general methods for determining the sound power of individual components are summarized in Table 9.

Table 9 – Summary of different methods for sound power determination

Method	Required equipment	Benefits	Drawbacks
Sound pressure	Sound level meter, preferably together with an Fast Fourier Transformation (FFT) analyzer or real-time filters	– simple and relatively fast – less expensive measuring equipment – physically correct measurement of sound power if measured in the acoustic near field	– requires sound kind of measurement room or free-field conditions – sensitive to background noise and reflections – overestimates the sound power level systematically if measured in the acoustic near field
Sound intensity	Sound intensity equipment	– when correctly performed, probably the most accurate method – not sensitive to constant background noise – a good tool for diagnostic purposes	– time consuming – needs two microphones and special software, more expensive equipment than for sound pressure measurement – for safety reasons not applicable to HVDC substations

10.4.3 Verification of key components at site

The most common method to use for sound power verification at site is the sound pressure measurement. It might however be very difficult, if not impossible, to verify the sound power of an individual component, e.g. the components of an a.c. filter. One exception may be the smoothing reactor, which normally dominates the noise in its vicinity. Vibration measurements can however give a fair estimation of a component's sound power.

When the verification measurements at site are performed, the actual values of the current I, voltage U, etc., should be recorded. These values should be compared with the ones used for noise predictions for the site. If there are large discrepancies between the current and/or voltage values used for predictions and the values during verification measurements, the predictions might be repeated with the updated values of the voltage and/or current.

When measuring sound pressure on an object, which generates tonal noise, it is important to use a rotating boom or to measure the noise at a great number of points in order to get a good spatial average. Otherwise the sound power determination will be subject to errors due to interference effects of the tonal sound field. Recommendations can be found in ISO 3744.

11 Verification of sound levels from the HVDC substation

11.1 General

Depending on electric load, background harmonics related to the a.c. network, meteorological variations and irregularities in the measurement environment (e.g. reflecting obstacles), the sound level at any point around a site will fluctuate considerably during a period of 24 hours. This is important to bear in mind, both for those defining the noise requirements and for those who perform sound level measurements.

The verification of specified sound levels is normally performed by measurements at the receiver location, often corresponding to the nearest inhabited house. In cases when the background noise level at the receiver locations is high, perhaps higher than the allowed contribution from the HVDC substation, measurements at the receiver will not give the required information (see 10.3.2 for details about background noise). In such cases, sound level measurements closer to the HVDC substation are necessary. These results allow the expected sound level at the receiver location to be calculated by considering the additional attenuation over distance (see 9.3.2 and 3.2).

If a suitable measurement point between the nearest inhabited houses and the substation cannot be found, sound pressure measurements close to or within the substation are necessary. These measurements are used to determine the sound power level of the multi-source plant, and hence to evaluate the sound pressure levels outside the substation. Such measurements may however suffer from interference phenomena due to the complexity of the sound field. If a simple measuring method has been used, e.g. a stationary microphone at just a few locations, the measured sound pressure levels may contain great variations depending on the spatial location of the microphone. This problem may be solved by using a rotating microphone with a radius of at least half the wavelength of the lowest frequency of interest.

There are in practice two approaches to sound measurements in HVDC substations. The first approach is to verify the result (in terms of Sound Pressure Level) of the customer requirements directly and the second is to determine the sound power (in terms of Sound Power Level) of the sound sources. The first type of measurement is often made at some distance from the HVDC substation. In this case the problem is how to extract the sound from the plant from the background sound. Often these measurements have to be performed over longer periods of time to get a good time average where the influences of meteorological influences are averaged out. The difficulty with the second type of measurements is that there are several sound sources and also high voltages which make it impossible to get close to the sound source. The solution may be to measure at different distances from the sources, as the law of distance then can be used (see also 9.3.2).

One further method for evaluating the overall sound power level of multi-source industrial areas is given in ISO 8297.

11.2 Acoustic environment

When measuring sound inside or near an HVDC substation, there will normally be pure tones and electromagnetic fields present. The sound measuring equipment thus has to be suitable for this environment. Condenser microphones should be used because dynamic microphones are influenced by the magnetic fields. Therefore it may be necessary to use a measuring technique that evaluates the sound sources from a distance. Also, the analysis instruments should be of two types: real time analyzers for sound level information and frequency analyzers for quantifying the total content and identifying individual noise sources.

The sound field outdoors, in the substation and in the vicinity, may be similar to the standing wave pattern of discrete tones indoors in a reverberation room. There are many different sound sources emitting sound at discrete frequencies. When many sources emit the same frequency, or when there are reflecting obstacles adjacent to a source – thus acting like "mirror sources" – an interference pattern is formed. At one point, the contribution from several sources, at the same frequency, will be in phase resulting in a high sound level whereas at another point the level will be lower because of destructive interference. The distance between these minima and maxima depends on the wavelength in air of the sound involved. Therefore sound measurements always have to be performed with rotation or translation of the microphone, or a sufficient number of measurement positions has to be used. In practice this is achieved either by moving a hand-held sound level meter in a circular motion during the measurement or by using a microphone mounted on a rotating boom. At larger distances from the substation, of the order of hundreds of meters, the microphone may be substationary because the transmission path attenuation fluctuates due to variations in meteorological conditions. Over long distances, the intensity of the interference patterns decreases due to ground reflections, wind, temperature gradients etc.

11.3 Conditions for verification

There are four main factors, which affect the sound pressure level measured at a specific point and these are:

- operating conditions of the sound sources (see Clause 8);
- meteorological conditions (see Clause 4);
- type of ground and topography included (see Clauses 4 and 9);
- background noise (see Clauses 4 and 10).

The operational state of the sound sources is important because the sound radiated from the sources is dependent on the currents and voltages present in the sources during the measurement. Weather conditions can affect the measured sound levels in a complicated way, as described in Clause 4. When verification measurements are performed, special meteorological conditions normally have to be fulfilled (see ISO 1996-2):

- wind direction within an angle of ± 45 degrees of the direction connecting the centre of the dominant sound source and the receiver, with wind blowing from source to receiver;
- wind velocity of between 1 m/s and 5 m/s, measured at a height off to 10 m above ground, or equivalently, propagation under a well-developed, ground-based temperature inversion.

Among the meteorological parameters temperature, humidity, pressure, cloudiness precipitation and wind, wind is the most important parameter. See Clause 4 for details.

11.4 Calculation

Calculations are very helpful tools when designing and planning HVDC substations. They give indications of the acoustic performance of the substation. Very often it is however necessary to rely on calculations combined with measurements as described in 11.6.

11.5 Measurement

Sound level measurements, for the purpose of verifying if a specified sound level requirement is fulfilled, has to involve several measurements over time. One single short measurement will not give a correct representative result. The measurement time for each single measurement of the equivalent sound pressure level L_{eq} from a constant sound source shall be at least 1 minute. For night-time measurements, at least three such measurements, with at least one hour between the measurements, shall be used to form an energy equivalent average. For daytime measurements, five different single measurement periods shall be used.

The measurement time is chosen to fit the meteorological conditions for moderately downwind sound propagation. It will normally be long enough to average out the effects of a varying wind velocity over several gusts with a measurement time in the range of 10 minutes to one hour.

11.6 Combination of calculation and measurement

In some cases, measurements of the sound level originating from the converter substation may be impossible at a remote receiver location, e.g. due to high background sound levels. In such a case measurements can be performed closer to the substation, between the source and the receiver. The expected sound level at the receiver location can then be calculated based on the measured level at a point between the source and receiver. This method can give reasonably accurate results provided the landscape is fairly smooth and there are no obstacles in the transmission paths.

The sound pressure level is measured at point A and is then calculated at point B by using the measurements at point A. For example, in Figure 33 if the sound pressure level measured at point A is 50 dB(A) the calculated pressure level at point B is equal to $L_{\mathrm{B}} = L_{\mathrm{A}} - 20 \lg (b/a)$, i.e. $L_{\mathrm{B}} = 50 - 20 \lg(500/200) = 42$ dB(A).

Sometimes measurements between the source and receiver, as described above, may be impossible to perform due to e.g. difficult terrain, dense traffic on nearby roads or other circumstances disturbing the sound level measurements. Then measurements close to the different sources at site can be done and the source sound power level calculated. These calculated source sound power levels are then used for predicting the expected sound pressure levels at the receiver points by calculation alone. Calculation is then performed as described in Clause 9.

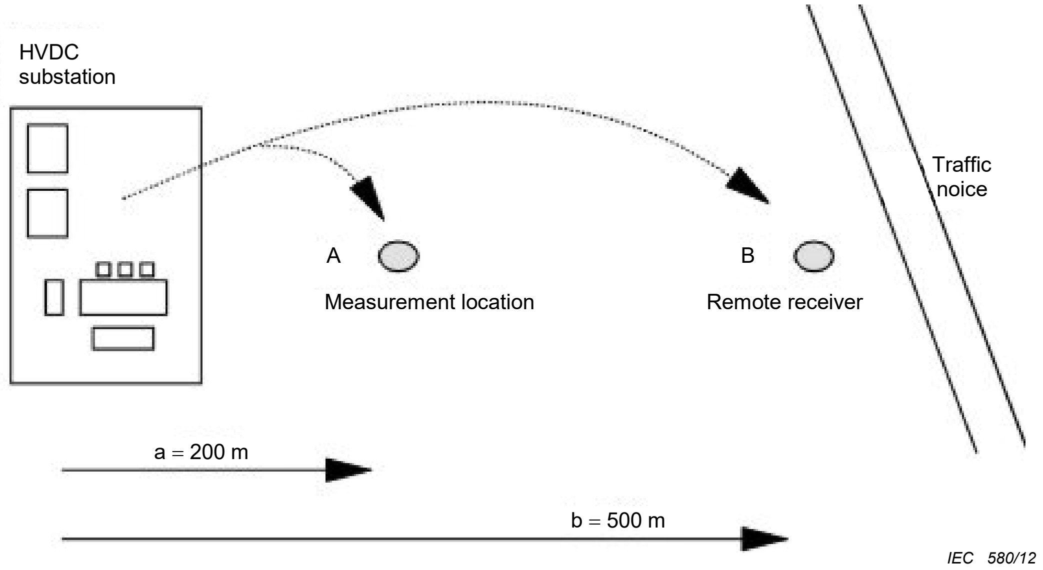
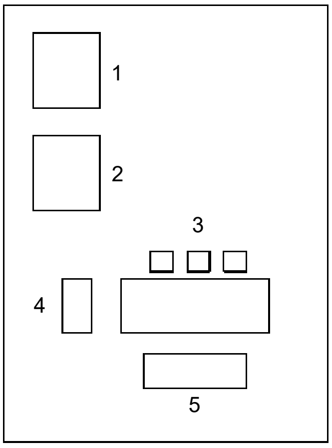


Figure 33 – Combination of calculation and measurement in determining the sound pressure level

Practical limitations often make it impossible to study one single source by this measuring technique. Instead the substation can be divided in larger sub-sources, e.g. a.c. filter, transformers, valve cooling fans, d.c. filter (see typical layout in Figure 34). Suitable measurement methods can then be chosen for sound level measurements around these different parts of the substation. Also for these measurements around larger groups of sound sources there are often limitations for the microphone height, for example due to overhead buswork. Sometimes a desired microphone location is not accessible due to fences or safety regulations at site. In each different case a practical method has to be found, based on specific circumstances at site. Figure 35 shows an example of measurement positions around the a.c. filters for sound pressure level measurements for determining the sound power of the complete filters.



1 AC filter 1
2 AC filter 2
3 Converter transformers
4 Cooling system fans
5 DC yard

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Figure 34 – Example of layout of noise sources of an HVDC substation

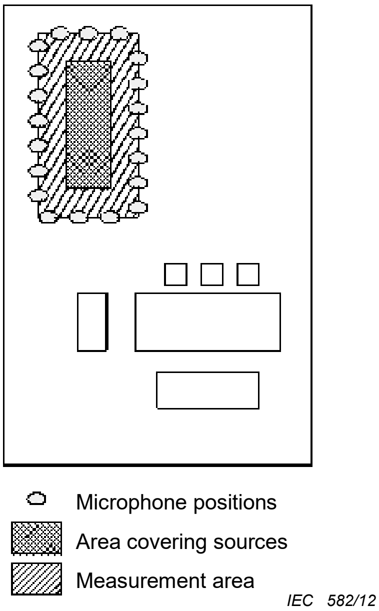


Figure 35 – HVDC substation and example of microphone positions for determination of sound power levels

There are instructions (see ISO 8297 and [10]) defining the area of the measurement surface depending on the area covering the sound sources, defining the distance from source area to the measurements points, number of measurement points, microphone height and how to use the results of the sound pressure level measurements to determine the sound power level of the source.

12 Parameters to be specified

12.1 General

This clause deals with data and information required for the acoustic design of an HVDC substation. The clause also covers the subsequent verification of the sound levels in and around the substation. Examples are given of the specification data, which is required for audible noise concerns. The data can be used as a checklist for an HVDC substation for the design of audible noise. The list intends to contribute to more rational acoustic design of HVDC substations.

For planning the HVDC substation in the given situation, it is often helpful to get an acoustical report about the current situation at site containing actual background measurements.

12.2 Noise level measurement

Existing regulations specify applicable conditions for an acceptable measurement. The following requirements may be specified:

- number and duration of measurements at single points required to secure a representative description of the sound level;
- measuring equipment to be used;
- allowable distances between obstacles and microphones;
- weather conditions, e.g. wind direction and maximum allowable wind speed.

In addition to these conditions, it is important that the "measurement accuracy" is described, i.e. the measurement uncertainty. An example of how this may be written is 45±3 dB.

12.3 Data to be presented by customers, or to be investigated by contractors

12.3.1 Land-use classification, noise regulation and limits

a) Land-use classification of the site for the HVDC substation

A map shall be presented, preferably a topographical map of the area which defines the classification of the land where the substation will be located (see Table 10). This map shall also define the type of surrounding areas as well as the location of the nearest neighbors, commercial, public or industrial. See also Clauses 4, 5 and 11.

Table 10 – Land use classification

	industrial area		commercial area		residential area
	recreation area		other area		

NOTE 1 Enclose the land-use classification map if a border with other land-use classification exists near the site.

b) Noise limits for the site for each time of day

Reference to applicable noise regulations shall be given, as well as the location of the points where these regulations shall be met. Also specific requirements during different hours of the day, if applicable, shall be noted (see Table 11). The presence of other acoustic regulations, e.g. corrections for tonal components or short-term noise shall be defined (see Table 12).

Table 11 – Existence different noise limits at different times

Noise limit, dB(X)/dB(A)	Time of day

NOTE 2 Limits in terms of sound power level or sound pressure level dB(X) could be e.g. dB(L) or dB(C), where L means Linear (no weighting) and C means C-weighting

Table 12 – Existence of noise limits due to further regulation

Item	yes	no
Existence of another regulation for single or special frequency		
Existence of another regulation for short time noise		

Identify all applicable noise regulations. Indicate from what regulation the limits have been derived.

c) Location for the noise limit(s) (see Table 13)

Table 13 – Definition of noise limits at different locations

	At the fence surrounding the substation		At the border of customer’s property
	At a given distance from the centre of the substation		At the border of a nearby property
	At a given distance from the fence surrounding the substation		Other point

Illustrate the location point on the map.

12.3.2 Environmental condition

a) Existing background noise levels during verification measurements

Existing background noise levels influence the results of the subsequent verification measurements of the HVDC substation, as they are present at the area where the substation will be located (see Table 14). The levels of background noise sources, e.g. existing installations, road noise or air traffic noise, are usually depending of the time of day. Such noise sources should be acoustically mapped and the information submitted in the specification. If the background noise levels cannot, or have not, been determined in advance, they have to be presumed during the verification measurements.

Table 14 – Existence of background noise limits at different locations and different times

Maximum background noise, dB(X)/dB(A)	Location	Time of day

b) Topography (see Table 15)

Table 15 – Compilation of relevant topographical features

Item	yes	no
existence of reflective mountain or hill		
existence of high undulation		

NOTE 1 Attach the contour map if marking “yes”.

c) Meteorological condition for verification of audible noise requirements (see Tables 16 and 17)

Table 16 – Compilation of relevant meteorological conditions

Maximum temperature (°C)	Minimum temperature (°C)
Maximum humidity (%)	Minimum humidity (%)

Table 17 – Compilation of further noise related weather conditions

Item	yes	no
existence of a strong wind*		
existence of heavy snow*		

NOTE 2 Explain the contents if marking “yes”. These factors may have a significant impact on sound propagation.

d) Neighbors (see Tables 18 and 19)

Table 18 – Existence of additional locations with relevant noise limits

Location of nearest neighbor (commercial, public or industrial) where noise requirements must be fulfilled

Table 19 – Possibility of future development

Item	yes	no
high possibility of a nearer neighbor in future		

NOTE 3 Applicable if sound requirements are specified at adjacent properties. Attach a sketch, drawing or map.

e) Others (see Table 20)

Table 20 – Other sources of audible noise

Item	yes	no
existence of a substation or a power substation nearby		
existence of corona noise from the transmission line		
existence of a significant noise source nearby		

12.3.3 Operation condition of HVDC substation

a) Normal operating conditions

The operating conditions for the substation, during the acoustic verification measurements, need to be specified in detail (see Tables 21 and 22).

NOTE Clause 8 contains information regarding conditions to consider.

Table 21 – Definition of operating condition during audible noise measurement

Maximum power %	Minimum power %	Maximum voltage kV	Minimum voltage kV	Negative Phase Sequence(NPS) %
Harmonics in a.c. voltage (%)	3rd	5th	7th	others
Maximum frequency Hz	Minimum frequency Hz			

Table 22 – Further conditions relevant for audible noise measurement

Power system condition to be considered

b) Operating conditions for noise control design

List the parameters, which are to be considered outside normal operating conditions.

12.4 Data to be clarified by contractors

12.4.1 Noise of components

The list of audible noise sources planned to be installed should be prepared (see Table 23).

Table 23 – List of audible noise sources to be installed

Component’s name				
Noise level, dB (X) / dB (A)				
Sound reduction measures				
Method of sound measurement				
Method of sound correction (e.g. "scaling", see 10.4)				
Voltage and current condition				
Note				

12.4.2 Noise prediction of the HVDC substation

The acoustic design includes predicting the contribution from the substation to the surrounding area. The results of this process are normally presented in a report describing the calculation method, sources included, the results and possible noise reduction measures necessary (see Table 24).

Table 24 – Contents of an audible noise prediction report

Operating conditions and other assumptions	
Method of sound calculation	
Substation layout	Show on the map
Result of sound calculation dB (X) / dB (A)	Show on the map or as a table

12.4.3 Noise measurement on the site

Verification measurements normally follow existing rules and regulations. The results of all the work is presented in a report describing the measurement method, instrumentation, operating conditions, weather conditions and measured levels (see Table 25). An assessment regarding the fulfillment of the requirements is also done in this report as well as suggestions about possibly necessary reduction measures.

Table 25 – Contents of an audible noise measurement report

Date and time					
Method of sound measurement					
Measuring instruments					
Measuring location points (show on the map)					
Measured noise levels, dB (X) / dB (A)					
Weather condition					
Operation condition					
Note					

Annex A
(normative)

Procedure to correct for background noise in HVDC and SVC plants

Sound sources in electrical power plants such as HVDC and SVC are mainly transformers, air core reactors, shunt reactors and capacitors. The total sound power emission is characterized by discrete tonal contribution starting with the fundamental frequency at double the main electrical frequency (100/120 Hz for 50/60 Hz systems). Power control circuits, with the thyristor switching combined with different tuned electrical filters causes multiple harmonics up to 1 kHz for SVC and 2 kHz for HVDC.

A-weighted logarithmic addition of all tonal contributions constitutes the total sound impact from a plant.

Background sound level, in a traditional measurement situation, is the sound level without the plant contribution. Sound from HVDC/SVC-plants is normally very stable with variations only related to the voltage/current circulating in the circuits. Background noise, on the other hand, can change very fast in an uncontrolled manner.

If a measurement is made in narrow band the correction for the background can be done frequency by frequency. Highest accuracy, in the correction procedure, is achieved when each tonal contribution is corrected for the background level on both sides of the measured tone taken during the same measurement during the same time sequence.

The same procedure is also possible for a frequency resolution up to 1/24 –octave bands when the highest harmonic frequency is < 2kHz. If a measurement is made in 1/3 – octave band the correction for the background can only be done by switching the plant on/off. There is no clear visual information of the tonal contribution in a 1/3 octave spectrum. A change in the background level, between "on and off", will be unknown and the correction accuracy becomes very uncertain.

<u>Illustrating case</u>

Sound contribution from an SVC:

$$\overline{L}_{p\text{A}} = 10\ \lg\left(10^{0,1\overline{L_{p\text{A0}}}} - 10^{0,1\overline{L_{\text{bA}}}}\right) \tag{A.1}$$

where;

$L_{p\text{A0}}$ is the measured sound pressure level at an identified tone;

L_{bA} is the measured background sound noise to the left/right of the zone.

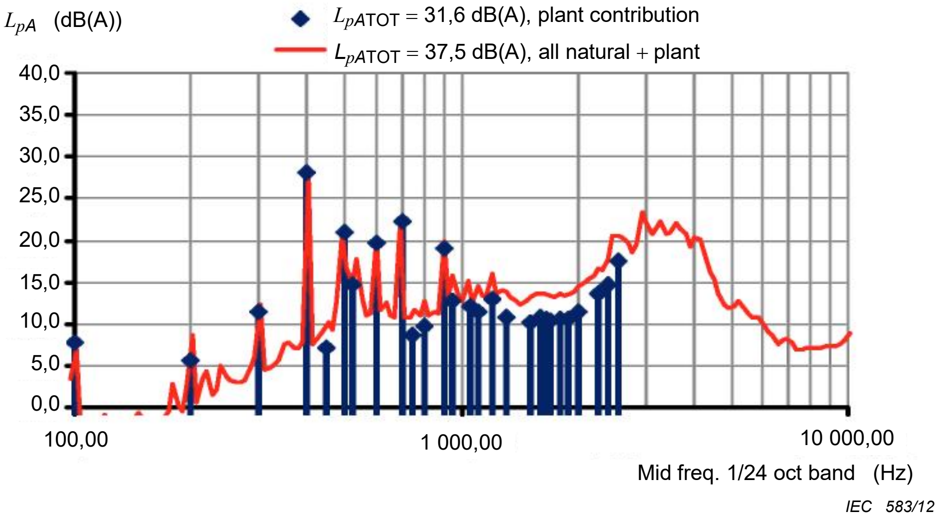


Figure A.1 – Example of a background correction at 1/24 octave band resolution

Example of a background correction at 1/24 octave band resolution (Figure A.1) gives the opportunity to distinguish tonal source (SVC) from a real background measured during the same conditions. A contribution from a fan must be treated separately – first measured on/off – and then added back into the total spectrum before summing up the total 1/3 octave band plot.

Table A.1 – Total sound level for the SVC example

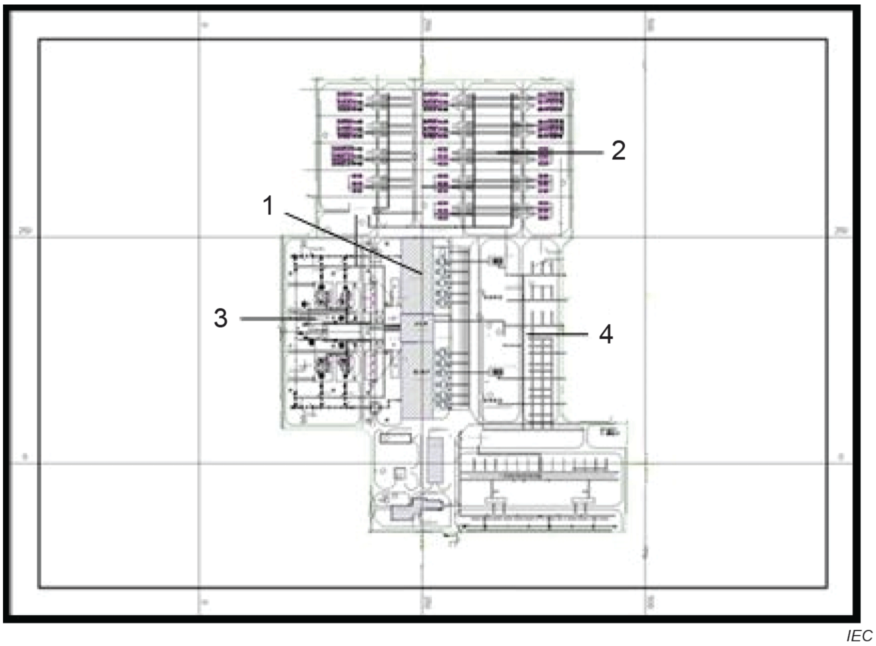
Frequency: Hz	Plant contribution L_{pA} dB (A)	All Natural + Plant L_{pA} dB (A)
100	7,9	6,9
200	5,6	8,6
300	11,4	12,3
400	28,0	28,1
450	7,1	10,1
500	20,9	21,1
525	14,6	17,6
600	19,6	20,2
700	22,4	22,7
750	8,7	11,7
800	9,8	12,8
900	19,1	19,9
950	12,7	15,7
1 050	12,1	15,1
1100	11,5	14,5
1 200	13,0	16,0
1 300	10,9	13,9
1 500	10,2	13,2
1 600	10,7	13,7
1 650	10,6	13,6
1 700	10,4	13,4
1 800	10,5	13,5
1 900	10,5	13,5
2 000	11,4	14,4
2 250	13,6	16,6
2 400	14,8	17,8
2 550	17,5	20,5
L_{pAtot} [dB (A)]	< 31,6	37,5

Total sound level is measured to 37,5 dB (A) and the plant contribution is < 31,6 dB (A).

Annex B
(informative)

Typical twelve-pulse and dual twelve-pulse HVDC substation layouts

The converter valve hall is the largest building in the HVDC substation, so its layout is very important. The typical twelve-pulse HVDC substation layout is shown in Figure B.1.



Key

1 valve hall and transformer

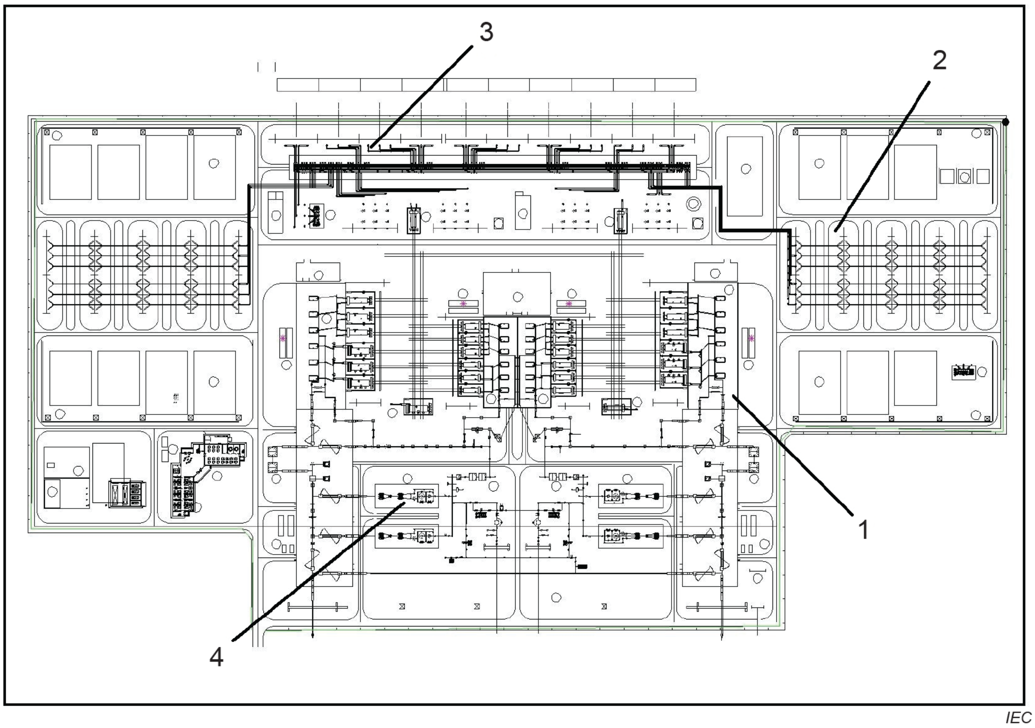
2 AC filter

3 DC switch yard

4 AC switch yard

Figure B.1 – Example of typical twelve-pulse HVDC substation layout

For the dual twelve-pulse forms, the valve hall can be arranged in face-to-face form, the converter transformers arranged on the inside of the buildings, which have significance for controlling the noise of the HVDC substation. The typical dual twelve-pulse HVDC substation layout is shown in Figure B.2.



Key

1 valve hall and transformer

2 AC filter

3 AC switch yard

4 DC switch yard

Figure B.2 – Example of dual twelve-pulse HVDC substation layout

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High voltage direct current (HVDC) substation audible noise

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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

HIGH VOLTAGE DIRECT CURRENT (HVDC) SUBSTATION AUDIBLE NOISE

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IEC TS 61973 edition 1.1 contains the first edition (2012-04) [documents 22F/243/DTS and 22F/260/RVC] and its amendment 1 (2019-05) [documents 115/197/DTS and 115/207/RVDTS].

This Final version does not show where the technical content is modified by amendment 1. A separate Redline version with all changes highlighted is available in this publication.

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

IEC 61973, which is a technical specification, has been prepared by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment, with the participation of IEC technical committee 115: High voltage direct current (HVDC) transmission for DC voltages above 100 kV.

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

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

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HIGH VOLTAGE DIRECT CURRENT (HVDC) SUBSTATION AUDIBLE NOISE

1 Scope

This technical specification applies to the specification and evaluation of outdoor audible noise from high voltage direct current (HVDC) substations. It is intended to be primarily for the use of the utilities and consultants who are responsible for issuing technical specifications for new HVDC projects with and evaluating designs proposed by prospective contractors. It is primarily intended for HVDC projects with line-commutated converters. Part of this technical specification can also be used for the same purpose for HVDC projects using voltage sourced converters, and for flexible a.c. transmission systems (FACTS) devices such as static Var compensators (SVCs) and static synchronous compensators (STATCOMs).

2 Normative references

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

IEC 60076-10, *Power transformers – Part 10: Determination of sound levels*

IEC 60076-10-1*, Power transformers – Part-10-1: Determination of sound levels – Application guide*

IEC 61672-1, *Electroacoustics – Sound level meters – Part 1: Specifications*

IEC 61672-2, *Electroacoustics – Sound level meters – Part 2: Pattern evaluation tests*

ISO 1996-2, *Acoustics – Description, assessment and measurement of environmental noise – Part 2: Determination of environmental noise levels*

ISO 266:1997*, Acoustics – Preferred frequencies*

ISO 3740*, Acoustics – Determination of sound power levels of noise sources – Guidelines for the use of basic standards*

ISO 3743-2, *Acoustics – Determination of sound power levels of noise sources; engineering methods for small, movable sources in reverberant fields – Part 2: Methods for special reverberation test rooms*

ISO 3744, *Acoustics – Determination of sound power levels and sound energy levels of noise sources using sound pressure – Engineering methods for an essentially free field over a reflecting plane*

ISO 3745, *Acoustics – Determination of sound power levels of noise sources using sound pressure – Precision methods for anechoic and hemi-anechoic rooms*

ISO 3746, *Acoustics – Determination of sound power levels and sound energy levels of noise sources using sound pressure – Survey method using an enveloping measurement surface over a reflecting plane*

ISO 8297, *Acoustics – Determination of sound power levels of multisource industrial plants for evaluation of sound pressure levels in the environment – Engineering method*

ISO 9613-1, *Acoustics – Attenuation of sound during propagation outdoors – Part 1: Calculation of the absorption of sound by the atmosphere*

ISO 9613-2, *Acoustics – Attenuation of sound during propagation outdoors – Part 2: General method of calculation*

ISO 9614-1, *Acoustics – Determination of sound power levels of noise sources using sound intensity – Part 1: Measurement at discrete points*

ISO 9614-2, *Acoustics – Determination of sound power levels of noise sources using sound intensity – Part 2: Measurement by scanning*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1 Sound and noise terms

3.1.1
sound
any pressure variation in air, water or other elastic medium

Note 1 to entry: Sound is expressed as sound pressure, sound intensity or sound power (see 3.1.3).

Note 2 to entry: In this technical specification, the medium is assumed to be air.

3.1.2
sound waves in air
traveling sound pressure fluctuations

3.1.3
sound pressure
p
fluctuating pressure superimposed on the static pressure

Note 1 to entry: Sound pressure is expressed in pascal.

Note 2 to entry: Sound pressure is usually expressed through the use of a decibel scale, as sound pressure level (see 3.1.4).

3.1.4
sound pressure level
L_p
logarithm of the ratio of the r.m.s. value of a given sound pressure to the reference sound pressure

$$L_p = 10 \text{ lg}\left(\frac{(p)^2}{(p_0)^2}\right) = 20 \text{ lg}\left(\frac{p}{p_0}\right)$$

where:

p is the measured r.m.s. sound pressure in pascal;

p_0 is the reference r.m.s. pressure of 2×10^{-5} pascal, which corresponds to the 0 dB as threshold of audibility.

Note 1 to entry: lg(x) means the 10th logarithm of x; this convention is used throughout the document.

Note 2 to entry: The sound pressure level (L_p) is expressed in decibels (dB).

Note 3 to entry: Sound pressure level is measured with sound level meters, which normally incorporate a frequency-weighting filter. For further details see 3.2.3.

Note 4 to entry: Since the sound level distribution measured around sound emitting objects is usually non-uniform it is normally necessary to assess sound levels on spatial average figures gained from several measuring positions rather than on one single discrete position.

3.1.5
average sound pressure level

$\overline{L}_{p\mathrm{A}}$

$$\overline{L}_{p\mathrm{A}} = 10\ \lg\left(\frac{1}{N}\sum_{i=1}^{N} 10^{0{,}1 L_{p\mathrm{A}i}}\right)$$

where:

$\overline{L}_{p\mathrm{A}}$ is the average sound pressure level in dB(A);

$L_{p\mathrm{A}i}$ is the measured sound pressure level at location i in dB(A), if required corrected for the influence of background noise;

N is the total number of measurement locations.

Note 1 to entry: The summation of several frequency bands (1/1-octave, 1/3-octave etc.) is performed in a similar fashion:

$$\overline{L}_{p\mathrm{A,TOT}} = 10 \lg\left(\frac{1}{N}\sum_{i=1}^{N} 10^{0{,}1 L_{p(f_j)}}\right)$$

where:

$\overline{L}_{p\mathrm{A,TOT}}$ is the total sound pressure level in dB(A);

$L_P(f_j)$ is the sound pressure level in frequency band f_j in dB(A), if required, corrected for the influence of background noise;

N is the total number of frequency components.

Note 2 to entry: See 3.2.2 for more information on 1/3-octave and 1/1-octave bands.

3.1.6
sound intensity

I_I

for a plane propagating sound wave, the sound intensity, I_I at a given point is defined as

$$I_I = \frac{p^2}{\rho \times c}$$

where:

p is the r.m.s. value of the measured sound pressure in pascal;

ρ is the constant density of air in equilibrium in kg/m^3;

c is the speed of sound in air in m/s.

3.1.7
normal sound intensity

I_{In}

for a plane propagating sound wave, the sound intensity, I_I at a given point in the normal direction n is defined as

$$I_{In} = \frac{p^2}{\rho \times c}$$

where:

p is the r.m.s. value of the measured sound pressure in pascal;

ρ is the constant density of air in equilibrium in kg/m^3;

c is the speed of sound in air in m/s.

3.1.8
sound intensity level

L_I

expressed in decibels ratio of the sound intensity to the reference sound intensity

$$L_I = 10 \text{ lg}\left(\frac{|I|}{I_0}\right)$$

where, $I_0 = 1 \times 10^{-12} \text{Wm}^{-2}$

3.1.9
normal sound intensity level

L_{In}

ratio of the normal sound intensity to the reference sound intensity

$$L_{In} = 10 \text{ lg}\left(\frac{|I_n|}{I_0}\right)$$

where, $I_0 = 1 \times 10^{-12} \text{Wm}^{-2}$

Note 1 to entry: Normal sound intensity level is expressed in decibel.

Note 2 to entry: I_n may be negative if there is a sound wave into the enclosing surface, which may happen in the acoustical near-field. The level is then expressed as – “xx” dB. The equation in 3.1.6 however assumes a plane propagating wave in the far-field of a sound source, in the direction defined as positive.

3.1.10
sound power

W

rate at which sound energy is radiated by a source

Note 1 to entry: Sound power is a scalar quantity and is expressed in watt.

Note 2 to entry: The total sound power is defined as:

$$W = \oint_A \overline{I}\, d\overline{A}$$

where:

A is a closed surface of integration;

$\overline{I}$ is the vector of sound intensity on an elementary surface $d\overline{A}$.

3.1.11
sound power level

L_W

$$L_W = 10 \lg \left(\frac{W}{W_0} \right)$$

where:

W is the emitted sound power in watt;

W_0 is a reference sound power of 1×10^{-12} W and corresponding to 0 dB as the threshold of audibility.

Note 1 to entry: The sound power level is expressed in decibel.

Note 2 to entry: The A-weighted sound power level ($L_{W\mathrm{A}}$) of an object may be determined from the surface sound pressure level ($L_{p\mathrm{A}}$) according to ISO 3744.

$$L_{W\mathrm{A}} = L_{p\mathrm{A}} + 10 \lg \left(\frac{S}{S_0} \right)$$

where:

S is the area of the “measurement surface” enclosing the object (in m^2);

S_0 is a reference area of 1 m^2.

Note 3 to entry: The sound power within an enclosing surface is independent of the distance to the sound source, but the sound pressure depends on the distance, reflections etc.

3.1.12
sound propagation

for hemispherical propagation over a reflecting plane, the sound pressure level at a given point depends on the distance from the source, the source sound power and the geometry involved as expressed by the following equations

$$L_p = L_W - 10 \lg (2\pi r^2)$$

or alternatively

$$L_p = L_W - 10 \lg (2\pi) - 20 \lg (r)$$

Note 1 to entry: This expression is sometimes called “the law of distance” in acoustics, when dealing with sound propagation from stationary sources. The law of distance implies that the sound pressure level decreases by six decibels (6 dB) for each doubling of distance from the sound source, provided that the measurements are performed in the *far-field* of the sound source. The boundary of the far-field depends among other things on the size of the sound source, the spatial complexity of the sound field and on the radiated frequency. For example; for a large transformer, the far-field may begin at a distance of 30 m from the transformer. For a small reactor which radiates sound at e.g. 1 kHz, the far-field may begin at a distance of 5 m.

The law of distance is strictly speaking only valid for point sources. Many sources can however be treated as point sources at a sufficient distance from the source. Care must however be taken when applying the formula on real sources.

3.1.13
noise

unwanted sound

3.1.14
audible noise

unwanted sound with frequency range from 20 Hz to 20 kHz

3.2 Sound radiation terms

3.2.1
directivity of sound radiation

$$L_p = L_W - 10\ \lg \frac{4\pi r^2}{Q}$$

where:

L_p is the sound pressure level at distance r from the sound source;

L_W is the sound power of the sound source;

r is the distance between the source and the receiver;

Q is the directivity factor of the sound radiation, e.g.

$Q =$ 1 for spherical sound propagation (see Figure 1);

$Q =$ 2 for hemispherical sound propagation (see Figure 2);

$Q =$ 4 for quarter spherical sound propagation (see Figure 3).

Note 1 to entry: The directivity of sound radiation may also be expressed in decibel and is then called directivity index (DI) which is defined by

$$DI = 10\ \lg Q$$

For example, for $Q = 2 \Rightarrow DI = 3$ dB, or for $Q = 4 \Rightarrow DI = 6$ dB.

Note 3 to entry: The directivity index is a correction index (dB-adder) which quantifies the deviation of the sound propagation from uniform spherical spreading. The sound pressure level may then be calculated from:

$$L_p = L_W + DI - 10\ \lg 4\pi r^2$$

3.2.2
sound measurement filters

standard filters used for sound measurement equipment and measuring the total level of sound pressure in a defined frequency band

Note 1 to entry: Usually “1/1-octave” or “1/3-octave” filters are used for these measurements. One 1/1-octave band contains three 1/3 octave bands. For example, the 31,5 Hz 1/1-octave band contains the 25 Hz, 31,5 Hz and 40 Hz 1/3-octave bands.

The top (f_1) and bottom (f_2) clause frequencies of the filter are related as follows:

$$f_2 = 2^a f_1$$

where:

a is 1 for the “octave” filter;

a is 1/3 for the “1/3 octave” filter.

The centre frequencies of the filters to be used should meet applicable standards (see ISO 266, [1[1]]).

3.2.3
A-weighting sound pressure level
A-weighted sound pressure level

incorporating the sound level measurement, is a frequency-weighting filter which differentiates between sounds of different frequency in a similar way to the human beings. It is expressed in dB (A)

A-weighted integrated sound pressure level, $L_{p\mathrm{A}}$ or L_{Aeq} is given by

$$L_{p\mathrm{A}} = L_{\mathrm{Aeq}} = 20\ \mathrm{lg}\frac{\left(\frac{1}{T}\cdot\int_0^T p_{\mathrm{A}}{}^2(t)d(t)\right)^{\frac{1}{2}}}{p_0}$$

where

T is the averaging time interval;

$p_{\mathrm{A}}(t)$ is the A-weighted instantaneous sound pressure;

p_0 is the reference sound pressure.

Note 1 to entry: There are other frequency weightings, for example ”C-weighting”, “D-weighting” etc. Measurements in dB (A) generally agree with people’s assessment of “loudness.” For more information about sound level meters and A-weighting see IEC 61672-1 and IEC 61672-2.

3.2.4
reflecting plane

any surface which fully reflects sound

3.2.5
principal radiating surface

hypothetical surface surrounding the test object, which is assumed to be the surface from which sound is radiated

3.2.6
prescribed contour

horizontal line on which the measuring positions are located and spaced at a defined horizontal distance (the "measurement distance") from the principal radiating surface

3.2.7
measurement surface

hypothetical surface enveloping a sound source, on which the measurement points are located ,and terminating on one or more reflecting planes

---

[1] Numbers in brackets refer to the Bibliography.

3.2.8

measurement distance

X

horizontal distance between the principal radiating surface and the measurement surface

3.2.9

background noise

sound pressure level with the test object inoperative

Note 1 to entry: In this case, the test object can be the whole HVDC substation or a single component.

3.3 Acoustic fields

3.3.1

acoustic near field

region of space within a fraction of a wavelength away from a sound source

Note 1 to entry: According to this definition, the outer boundary of the near-field region varies inversely with frequency. In the near field, pressure fluctuations are typical and the sound pressure p and the particle velocity shows an arbitrary phase difference.

For the site location of and the frequencies emitted by an HVDC substation, the sound measurements are normally performed in the acoustic far field. Sound measurement in the near-field of structural sound sources is difficult in HVDC substations, since

- for safety reasons it is prohibited to access energized equipment like capacitor banks and air cored reactors; and
- it is also prohibited to access the top of the transformers while energized.

With regard to air-cored reactors considerations must be given to the influence of the magnetic field on the test equipment.

3.3.2

acoustic far field

region of space when, in the far field, the sound pressure and the particle velocity are almost in phase and show approximately plane sound wave propagation

Note 1 to entry: Since the plane sound wave propagation is a good approximation of spherical wave conditions in the far-field , it can be used as the best engineering approach for sound measurements. For further details, refer to ISO 9614-1 and ISO 9614-2.

4 Environmental influences

4.1 General

When sound is emitted from a source with a certain sound directivity, the surrounding environment influences how the sound propagates and is perceived over distance [2, 3]. This clause describes those environmental influences, namely "background noise", "topography" and "meteorological conditions". Above all, meteorological conditions have a significant influence on sound propagation over large distances (of order hundreds of meters).

4.2 Directivity of sound radiation

The simplest method to predict sound propagation (and one which is still frequently used) is to assume that the sound emitting source has a uniform pattern of sound radiation following the hemispherical spreading theory (see Figure 2).

However, some sound-emitting sources or groups thereof show a distinct directivity of sound radiation, which needs to be considered in the HVDC substation layout. Other effects, such as screening, reflection and absorption may also be included in sound propagation considerations.

The directivity of sound radiation may also be expressed in dB and is then called directivity index (DI) which is defined by:

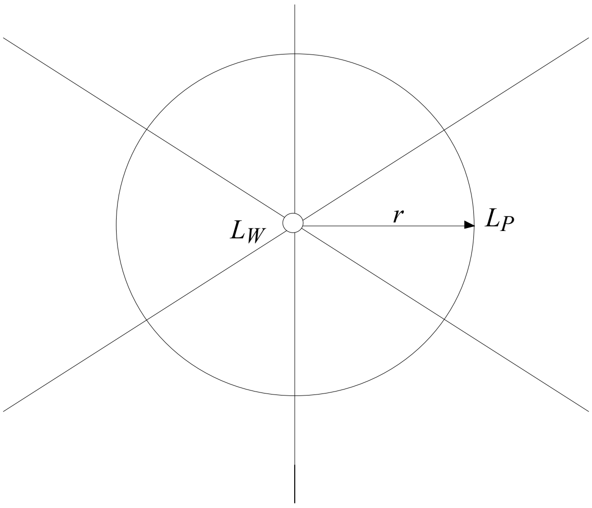
$$DI = 10 \lg Q \tag{1}$$

For example, for $Q = 2 \Rightarrow DI = 3$ dB, or

for $Q = 4 \Rightarrow DI = 6$ dB

The directivity index is a correction index (dB-adder) which quantifies the deviation of the sound propagation from uniform spherical spreading. The sound pressure level may then be calculated from:

$$L_p = L_W + DI - 10 \lg 4\pi r^2 \tag{2}$$



IEC 548/12

Key

$L_P = L_W - 10 \lg(4\pi r^2)$

L_P is the sound pressure level (dB rel. 20 µPa);

L_W is the sound power level (dB rel. 1 pW);

$(4\pi r^2)$ is the surface area of sphere (m^2).

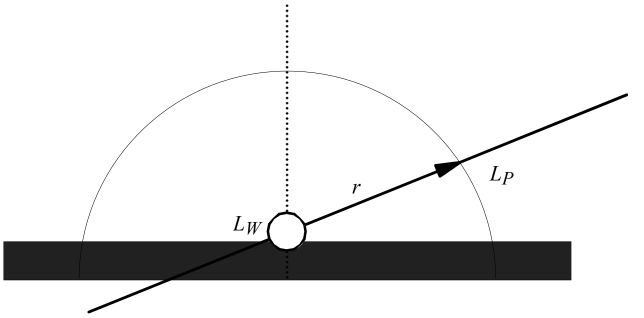
Figure 1 – Spherical spreading in a free-field from a point source

4.3 Background noise

In the situation where a specific noise is heard or measured at a given measuring point, background noise is the sound which is still heard at the point substation when the specific noise stops. As shown in Figure 4, the specific and background noise levels together give the total measured level.

At a proposed location for an HVDC, there background noise will always exist. Since background noise is a combination of man-made and natural sounds, each noise source may produce noise either during the day or night, or at some particular time. Therefore it is important to recognize the difference in the background noise at different times. Generally speaking, background noise levels are usually lowest when human activities are at a minimum, i.e. between midnight and 4 a.m.

It is most important to consider the background noise level when it is close to the regulatory maximum or is equal to the total measured sound level.



IEC 549/12

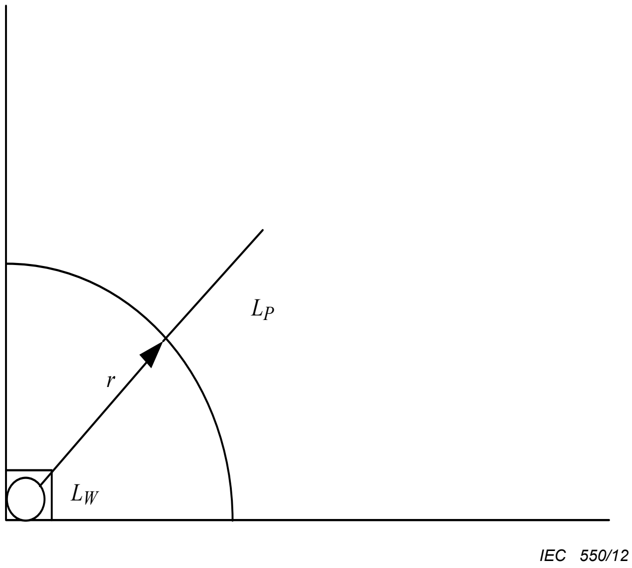
Key

$$L_P = L_W - 10\lg(4\pi r^2/2)$$

where;

L_P	is the sound pressure level (dB rel. 20 μPa);
L_W	is the sound power level (dB rel. 1 pW);
$(4\pi r^2/2)$	is the surface area of 1/2 sphere (m^2).

Figure 2 – Hemispherical spreading from a point source



Key

$$L_P = L_W - 10\lg(4\pi r^2/4)$$

where;

L_P is the sound pressure level (dB rel. 20 µPa);

L_W is the sound power level (dB rel. 1 pW);

$(4\pi r^2/4)$ is the surface area of 1/4 sphere (m^2).

Figure 3 – Quarter-spherical spreading from a point source

It is desirable to measure the background noise level for a predetermined HVDC site before its construction so as to confirm whether the level is close to the regulatory maximum or not. Once a substation has been built, and if the difference between the background noise level and the total measured level is less than 10 dB, it is important to consider the influence of the background noise when measuring. It might be impossible to determine the specific noise level accurately, even if the total measured level can be corrected.

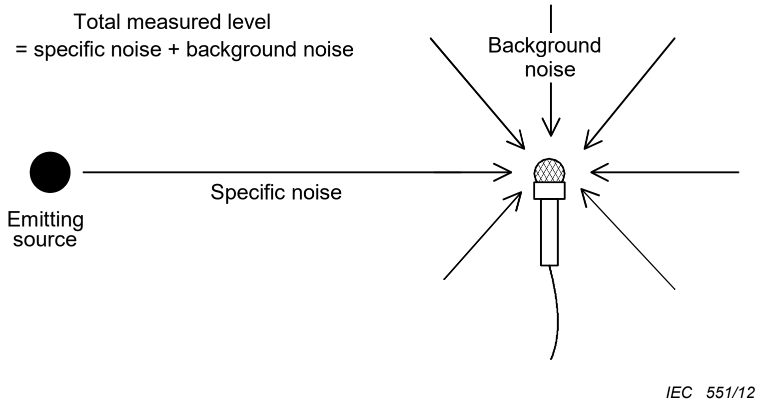


Figure 4 – Explanation of specific and background noise

NOTE See 10.3.3 for details on background noise.

4.4 Topography

The topography surrounding HVDC substation sites differs, e.g. some may be located close to the sea, some may be in the mountains or valleys and others may be in the plains. Topography influences sound propagation. Especially noticeable are the reflection, absorption, screening and attenuation of sound by land features, such as mountains, and the ground itself. In addition, when there is a difference in altitude between from the substation site and the chosen measuring point, the sound propagation will be different from the situation where they are at similar altitudes.

For instance, in Figure 5, there is a hill, which reflects sound, and low ground, which is in the shadow of the sound. Here sound attenuation will vary from place to place even if the distance from the source is the same. It is also important to be aware that the amount of surface reflection or absorption depends on the surface characteristics.

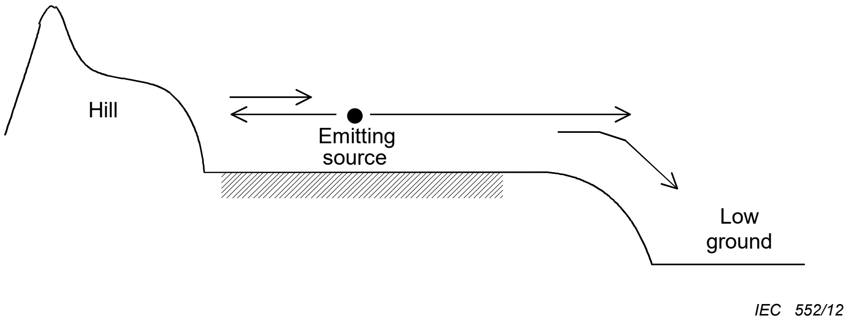


Figure 5 – Example of reflecting hill and low ground

As shown, low ground is a plane below the emitting source.

Therefore, when an accurate calculation of the sound emitted by a HVDC substation is required, it is important to take into account not only the topographical conditions, but also the ground-cover, such as forest, rocks, grassland etc.

However, when the land is basically flat and the groundcover is uniform and low-level, it is usually sufficient to calculate the attenuation over distance without detailed consideration of the sound propagation variation caused by topography.

4.5 Meteorological conditions

Over large distances, sound propagation through air can be influenced by meteorological conditions such as wind, temperature, rain, fog, and snow. In particular wind and temperature have a great impact on sound propagation. Therefore careful attention to meteorological conditions must be paid while measuring sound at the substation site.

a) Impact of wind speed and direction

   The wind velocity near the ground is usually lower than at higher altitude because of frictional resistance. The sound is refracted as shown in Figure 6 because the sound velocity is the vector summation of the wind velocity and the original sound velocity. Therefore there is a difference between the sound propagation on the downwind side and on the upwind side.

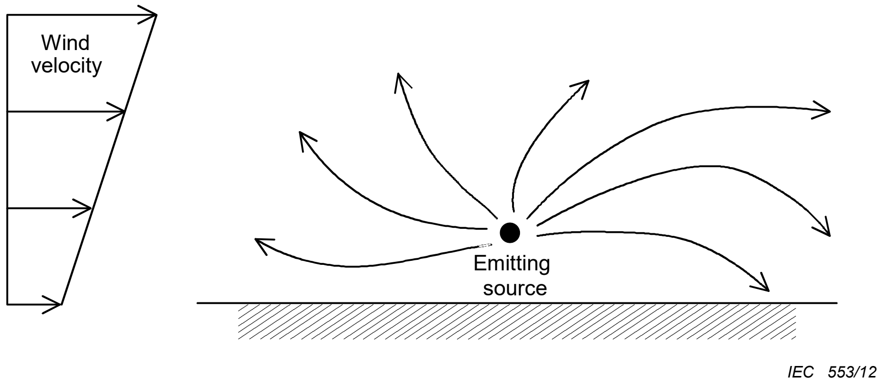


Figure 6 – Example of sound refraction with the shown wind gradient

For example, if there is a strong prevailing wind in the area selected for an HVDC substation, sound levels will be lower on the upwind side than on the downwind side. Careful consideration of this may enable optimization of the design of the substation layout and soundproofing equipment (N.B. If measurements are made on a windy day, it should be remembered that wind-induced noise on the microphone would produce so-called self-noise, which may be reduced by using a windscreen mounted on the microphone).

b) Impact of temperature gradients

Heated or cooled ground may cause vertical temperature gradients in the atmosphere, which may have a strong effect on sound propagation because sound travels faster in warm air than in cold (see Figures 7 and 8).

Consequently, sound attenuation for an observer at ground level is reduced for the condition shown in Figure 8. This phenomenon usually occurs at night.

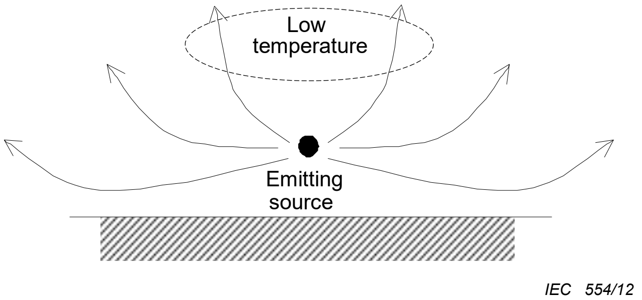


Figure 7 – Sound travels faster near the ground

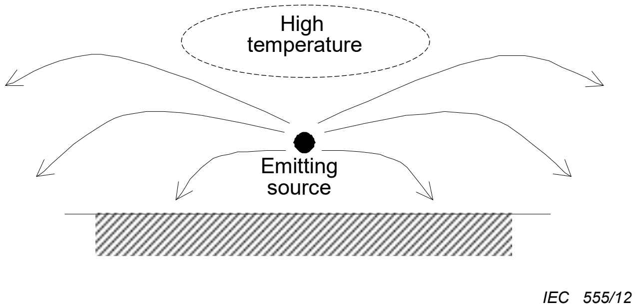


Figure 8 – Sound travels slower near the ground

c) Impact of atmospheric conditions (temperature, humidity, and pressure)

A sound wave propagating through air loses its intensity as the air absorbs its energy. The viscosity of the medium and the relaxation phenomenon of oxygen (O_2) and nitrogen (N_2) molecules mainly cause the absorption. On the whole attenuation is so small that it is negligible at lower frequencies, but it becomes quite large at higher frequencies (see 9.3.2.2 on atmospheric absorption).

d) Impact of rain, fog, and snow

Sound is sometimes carried further on a rainy or foggy day. The main reason is not the acoustic properties of rain or fog, but instead the effect of a temperature gradient or wind which accompanies this weather (see Figures 7 and 8). Experimental evidence has shown that the attenuation of sound by rain or fog is relatively small.

On the other hand, a surface covered with new-fallen snow has a high absorption coefficient for sound, and the attenuation is significant. Conversely, background noise levels are increased by the sound of falling raindrops on a rainy day.

e) Typical example data

Typical changes in sound attenuation caused by meteorological conditions are as follows:

- Up to 20 dB (A) lower sound levels when measured upwind as compared to measured when there is no wind.
- The effect of low or moderate wind velocities overrides the effect of even large temperature gradients.
- It is difficult to measure noise levels below 40 dB (A) correctly when wind velocity exceeds 3-4 m/s. This upper limit of wind velocity may be increased by the use of a windscreen, but the difference is normally only in the order of a few m/s.
- Large difference between dry and moist ground at low frequencies (10 dB (A) lower sound level on moist ground at 63 Hz).

Meteorological conditions may be different from one day to the next and from one area to another, so it is necessary to consider the influence of these conditions on sound propagation very carefully.

5 Noise level limits

5.1 General

No general international standards exist, such as ISO or IEC, which state noise emission level limits specific for substations. Different countries have local noise regulations. In general, these regulations are similar but for each case they may require separate consideration.

In almost all countries, there are however public regulations or recommendations for environmental sound. These sometimes include measurement methods to be used for verification. Such requirements or recommendations are established by federal or regional authorities and normally specify maximum allowable noise levels for various classifications of land use. There are also different frequency weightings of the sound such as A-weighting and C-weighting.

5.2 Regulations

5.2.1 Noise level limits

The only international noise standard on environmental noise descriptions and measurement methods in existence today is ISO 1996-2. However, standards for determining the sound level of specific equipment like power transformers (e.g. IEC 60076-10 and/or IEC 60076-10-1) and methods for determination of sound pressure and sound power levels (e.g. ISO 3746) do exist. IEC 61672-1 and IEC 61672-2 specify sound level meters.

From a regulatory point of view, environmental noise level limits are often related to land use classification and not to a specific distance from an audible noise source such as an HVDC substation. In cases where noise level limits are given at specific distances it is normally due to a more suitable verification procedure which is specified by the customer or the local planning authority. Furthermore, it may also be necessary to define more than one set of limits to cover different operating conditions.

Existing federal or regional regulations can be divided into two main approaches.

- Maximum allowed A-weighted sound pressure levels for different land-use classifications, including background noise.
- Maximum allowed increases over existing background noise.
- There may also be combinations of A-weighting and C-weighting, e.g. the C-weighted total sound level may not exceed the A-weighted total sound level by more than 15 dB.

Some of the regulations do not define a sound level limit for an entire area. For instance they give a limit at the border of properties. In areas with low background noise levels, the first approach is reasonable but in areas with high background noise levels the second approach would be more reasonable.

5.2.2 Noise level measurement

Existing regulations specify applicable conditions for an acceptable measurement. For further details, see 12.1.

5.3 Land-use classifications

Most human activities produce sound. This sound is emitted into the surroundings and may disturb human conversation or sleep. Therefore, most countries have legislation or guidelines on acceptable noise levels.

If the sound was suppressed at source, there would be no noise problem. The cost of suppression may however be disproportionately high for the benefit gained, and it is sometimes difficult to suppress the sound at its source, e.g. mobile sources such as airplanes.

Therefore land use is classified and, where possible, noisy sources are concentrated in one place away from residential and recreation areas. The site proposed for an HVDC substation and its surroundings may currently be in use for some other purpose, such as industry, recreation, farmland, or open-land. In each area, sound level limits are often specified in local legislation or regulations, which may be based on land-use classifications.

When the site for an HVDC substation is selected, it is necessary to examine the land use and sound level regulations in advance, so as not to encounter problems once construction is under way, or at any time in the future. In a residential area, it is especially necessary to understand the life and expectations of the future neighbors of the substation. It should also be recognized that the existing background noise level may be the result of land use regulations currently in effect.

5.4 Location of required performance limits

5.4.1 General

The boundary or location where the required noise performance limits shall be defined should follow the country’s regulation. The locations where the required noise limits shall be fulfilled as well as their advantages and disadvantages are described below.

5.4.2 At the fence surrounding the HVDC substation or at the border of the substation owner’s property

Advantages	Disadvantages
• Less affected by background noise.	• Verification at location where nuisance typically does not affect people.
• Less impact on measurement from weather conditions.	• May influence the substation layout unnecessarily.
• Less affected by surrounding topography and groundcover.	• More complicated and time consuming verification due to interference phenomena of the sound field.
	• Higher cost because the contractor may have to take actions to lower the radiated noise which, due to interference phenomena, has very pronounced maxima of the noise close to the substation.

5.4.3 At the given contour away from the HVDC substation (e.g. on a circle perimeter or beyond a property border line)

Advantages	Disadvantages
• Simplified prediction of the noise levels compared to predictions close to the fence. The reason is that the substation may be treated as a point source (see 9.3).	• Verification at location where nuisance may not affect people.
	• Affected by background noise, weather conditions, topography and groundcover.

5.4.4 At the border of a nearby property

Advantages	Disadvantages
• Verification at locations where real nuisance can exist.	• Difficult to perform verification fulfilling all measurement conditions at the same time, i.e. the meteorological conditions.
• Corresponds to regulations for outdoor audible noise.	• Need access to private property.
• Simplified prediction of the noise levels.	• Affected by background noise.

Of course, in the future, houses may be built on previously uninhabited land. The local planning authority may be able to advise regarding known developments. Otherwise, future housing developments should take into account the existing noise climate, including the operational HVDC substation, when planning their development layout and considering landscape options.

5.5 Relationship of performance limits to time duration

In general, noise from an HVDC substation is continuous, but there are some noise sources of the substation, which produce impulsive noise, such as circuit breakers and disconnectors. Critical features of impulsive noise include:

- peak noise level;
- time duration;
- time of day;
- frequency of occurrence;

- regularity (the same tone every day may be worse than variable tones);
- single tones;
- time variation of noise impulse.

Equation (15) provides a method of evaluating impulsive noise as an equivalent continuous level. Many federal and regional authorities specify noise limits for daytime as well as night time.

In many cases, the limits dictated by safety regulations for the working staff are probably most significant for impulsive noise.

5.6 Typical noise performance limits

5.6.1 General

Before giving typical noise performance limits, it is important to recognize that the cost implication of changing the noise performance limits may be significant, even if the change is only a few dB (A).

As stated earlier in this clause, there are no international standards setting limits. However, a review of several national or regional regulations shows that there are two ways of specifying noise performance limits. These two ways are presented below.

5.6.2 Specific A-weighted sound pressure levels

Outdoor sound pressure levels are normally divided into a number of categories related to land use classification. Please note that local regulations in the same country may differ. Typically the following apply (only night time values are given):

– Working premises where industrial noise is not generated:	< 50 dB (A) – 70 dB (A)
– Residential areas, education premises and hospitals:	< 40 dB(A) – 55 dB (A)
– Recreation areas:	< 35 dB (A) – 45 dB (A)

The requirements are typically more stringent if dominant single tones exist. A definition of a single tone is then given in each regulation. In case of dominant single tones, the levels given above may be decreased.

5.6.3 Maximum allowable increase over background noise levels

It is hard to give specific examples of maximum allowable increase over background noise levels because the span of required levels is quite wide. However, a range of allowable increases over existing noise levels appears to be 0 dB (A) to 7 dB (A). This form of specification is generally used at the boundary of a property considered sensitive to background noise. These allowable increases are also normally reduced if single tones are present.

A method for distinguishing the background noise from substation noise is proposed in Annex A.

6 Sound emitting sources

6.1 General

The purpose of sound requirements is to limit the level of noise emitted into the area surrounding an HVDC substation. This goal is accomplished by the contractor identifying the noise management required.

Efficient noise management requires an understanding of the acoustic behavior of each sound-emitting component, as well as knowledge of the relative acoustic strength of each of these sources. The target is to break down the audible noise requirement for the complete HVDC substation to the component level to allow the verification of the audible noise level in the laboratories of the component manufacturers. Once all the components have been installed, it is almost impossible to correctly determine the noise contribution of each individual component.

In this clause, the major sound emitting sources of an HVDC substation are introduced and the acoustic behavior of each source is discussed briefly. The most prominent components are:

- converter transformers;
- reactors;
- capacitors;
- cooling fans.

Other sources may contribute to the overall noise level, for instance:

- switching devices;
- cooling circuit pumps;
- synchronous compensators;
- outdoor valves;
- diesel generators;
- air conditioning plant;
- air compressors;
- corona discharge sources.

This clause describes the main parameters which affect each component's sound power. The correlation between sound power and sound pressure is explained in Clause 3 and Clause 10.

6.2 Converter transformer

6.2.1 Noise sources in a converter transformer

The converter transformer has the highest sound power of any single component in an HVDC substation and is therefore an important part of the audible noise considerations [4].

The noise from an HVDC converter transformer is generated by three sources:

- magnetic core (noise generated by magnetostriction and joints);
- electromagnetic forces in windings, tank walls and magnetic shields;
- fans/pumps of the cooling system of the transformer.

Fans and pumps are not strictly part of the transformer, and may be supplied by different manufacturers (see 6.5 and 6.6.5)

6.2.2 Comparison with a.c. power transformers

More is known about the mechanism of sound generation for a.c. power transformers, and this is discussed in the following paragraphs. International standards on the determination of sound levels in power transformers are available (see [5, 6]).

In the past, the core vibrations had been identified as the main source of transformer noise. The noise emission was primarily dependent on the rated power of the transformer and the magnetic flux density in the iron core, but not on the loading.

Technological advances in the core design, such as the use of high quality core sheets to reduce the magnetostriction and the use of improved core-joint technologies (e.g. step-lap cores), have reduced the core noise such that the load-dependent winding noise, generated by electromagnetic forces, has become increasingly significant.

The sound power of the winding noise of modern a.c. power transformers could be equal to the core noise, and may even exceed it, if the core induction level at rated voltage is reduced to approximately 1,4 T or lower. The sound power level of the winding noise can be roughly estimated from:

$$L_{\mathrm{WA,Ir}} \approx 39 + 18 \lg\left(\frac{S_{\mathrm{r}}}{S_{\mathrm{p}}}\right) \text{ for 50 Hz power frequency} \tag{31}$$

$$L_{\mathrm{WA,Ir}} \approx 44 + 18 \lg\left(\frac{S_{\mathrm{r}}}{S_{\mathrm{p}}}\right) \text{ for 60 Hz power frequency} \tag{32}$$

where

$L_{\mathrm{WA,Ir}}$ is the estimated A-weighted sound power level of the transformer at rated current and rated frequency at the short-circuit condition;

S_{r} is the rated power in MVA;

S_{p} is the reference power of 1 MVA.

The normal a.c. operation of a transformer generates a noise spectrum containing frequencies, which are typically below 1 kHz. The winding noise at sinusoidal load current contains almost exclusively double the power frequency (power frequency is fundamental electrical frequency). The core noise frequency spectrum additionally contains large components of the 2nd to 5th harmonics of double the power frequency, depending on the flux density level. Therefore the noise of a loaded a.c. transformer is essentially dominated by a 100 Hz tone or 120 Hz tone (according to whether the power frequency is 50 Hz or 60 Hz) superimposed on the no-load spectrum.

6.2.3 Special features of HVDC converter transformers

HVDC converter transformers normally have a higher sound power level than a.c. transformers of the same rated power. There are two factors, which increase the noise level:

- Load current of a converter transformer has a high harmonic content.
- Converter transformer will experience a small d.c. bias current in the valve – and temporarily in the network – side windings.

These factors are capable of generating a sound power level increase of more than 10 dB over normal a.c. operation.

The sound spectrum generated by converter transformers contains frequencies of up to several kHz and in therefore more audible to humans (as demonstrated by A-weighting of the sound level). As the dominating frequencies are above 300 Hz for converter transformers, external sound reduction measures (such as screening and absorption arrangements) are more effective.

The noise generated by the d.c. magnetization is not directly dependent on the load level, as the small d.c. current is governed by:

- Asymmetry in the firing of the thyristor valves, which in turn depends upon the accuracy of the firing control system

- Impedance differences in the converter transformers
- Potential difference between the ground electrode and substation ground for monopole ground-return operation.
- Positive sequence 2nd harmonic voltage.

DC magnetization of a transformer core will increase the transformer audible noise also at moderate levels of d.c. content. The reason is that the d.c. magnetization will add a 50 Hz or 60 Hz tone (dependent on power frequency) and harmonics at the odd multiples of 50 Hz or 60 Hz. In addition the audible sound at normal even harmonics (100 Hz or 120 Hz, 200 Hz or 240Hz, 300 Hz or 360 Hz, etc.) will be increased by the d.c. magnetization.

For an HVDC converter transformer, the winding is generally the dominant audible noise source and thus the audible noise level increases with transformer load.

In this context, reference is made to [4], which described the difference between the actual noise level in service and the values recorded during the standard factory substation tests under no-load conditions. One of the conclusions presented in this paper is that the sound power levels of the converter transformers – estimated from sound pressure measurements in various HVDC systems – operated up to their nominal loads-generally increase with the transformer load. However, there is hardly any correlation between the levels of this noise increase and the assigned power ratings of the transformers subjected to this investigation. The difference between no-load sound power level and sound power level at nominal load may be anything between a few dB up to more than 20 dB.

The additional sound power generated by the cooling equipment needs to be considered, especially for transformers employing a low-noise design. Some aspects of the acoustic performance of cooling fans are discussed in 6.5.

6.2.4 Transformer winding noise

Electromagnetic forces in the transformer windings generate winding noise when the current carrying winding conductors are exposed to the stray magnetic flux of the winding. The forces in the winding are proportional to the current multiplied by the magnetic flux in the winding. The magnetic flux is, however, proportional to the current during normal operation range, thus giving:

$$F \sim B \times I \sim I^2 \tag{4}$$

where:

F is the vibration winding force in N;

B is the magnetic flux density in the winding in T;

I is the winding current in A.

The vibration amplitude and velocity are directly proportional to the force. As the sound power is proportional to the square of the vibration velocity, it can be derived that the sound power is proportional to the fourth power of the load current:

$$W \sim v^2 \sim (\omega \times x)^2 \sim F^2 \sim I^4 \tag{5}$$

where:

W is the radiated sound power;

v is the vibration velocity;

x is the vibration amplitude;

$\omega = 2\pi f$ is the angular acoustical frequency.

6.3 Reactors

6.3.1 Type and design of HVDC reactors

In an HVDC system, reactors are used for various functions:

- HVDC smoothing reactors connected in series with the HVDC transmission line and/or cable or inserted in the intermediate d.c. circuit of a back-to-back link to reduce voltage/current pulsations and the harmonics on the d.c. side, to reduce the current rise caused by failures in the d.c. system and to improve the dynamic stability in the HVDC system;
- filter reactors installed for harmonic filtering on the a.c. and on the d.c. side;
- power line carrier- and radio interference filter reactors employed on the a.c. and/or d.c. side of the HVDC substation to reduce high frequency noise propagation on the lines;
- shunt reactors may form part of an HVDC substation to provide inductive compensation for a.c. harmonic filters, especially under light load conditions, where a certain minimum number of harmonic filters is required to satisfy harmonic filters performance requirements;
- ELIS (Electrode Line Impedance Supervision) reactors which together with capacitors and resistors will form an electrode line supervision system.

When considering the impact of audible noise emanating from an HVDC substation, the a.c. filter reactors and the HVDC smoothing reactor are the main types of reactors which need to be considered.

It is common practice to employ air-core dry-type reactor technology for all the above applications, unless special circumstances require the use of tanked oil-type HVDC smoothing reactors (e.g. at sites with extreme pollution and climatic conditions).

The following descriptions of reactor design and mechanisms of sound generation are essentially confined to the air-core dry-type technology. For tanked oil-type reactors, see also 6.2 which deals with converter transformers as the sound generation mechanisms and sound reduction measures are similar, apart from the additional noise source created by the gaps in the magnetic core.

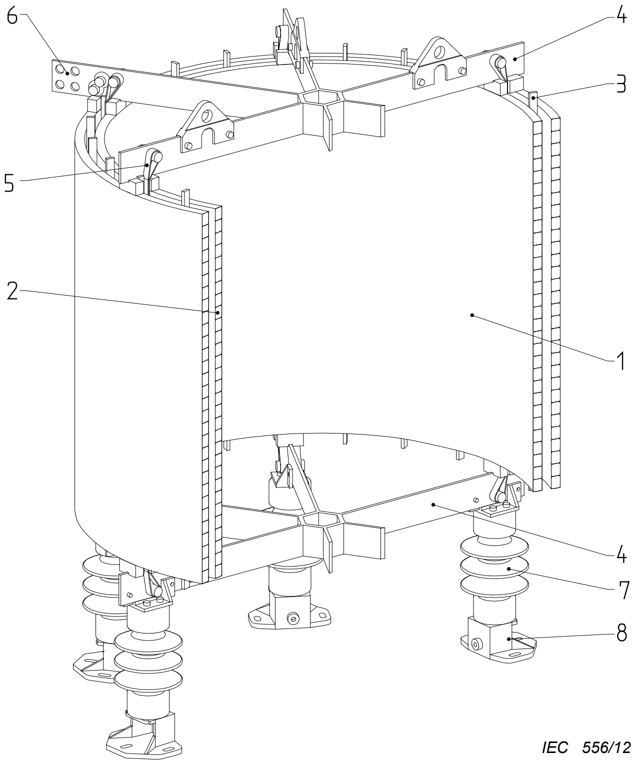
The major construction features of an air-core dry-type reactor are illustrated in Figure 9.

The winding of the reactor consists of one or multiple resin-impregnated and encapsulated winding layer(s) made of insulated aluminum conductors. The concentric layers are connected in parallel by welding their ends to metallic beam structures (spiders). Both the top and bottom spider are clamped together by several sets of fiberglass ties located along the winding. The packages are radially spaced by circumferentially arranged fiberglass-reinforced sticks, which form vertical air ducts for natural convective cooling of the windings.

6.3.2 Mechanism of sound generation

The noise generated by air-core reactors mainly results from vibration winding forces caused by the interaction of the current flowing through the winding and its magnetic flux.

In case of iron-core reactors, forces acting in the magnetic circuit induce further vibrations of the apparatus. If gapped iron-cores are used, the noise contribution by the forces in the air gaps needs to be considered. This noise contribution is generally higher than the noise caused by magnetostriction.



Key

1 – Winding	5 – Fiberglass tie
2 – Conductor	6 – Electrical terminal
3 – Duct stick	7 – Support insulator
4 – Spider	8 – Mounting fitting

Figure 9 – Dry-type air-core reactor

Any current-carrying conductor experiences forces when it is exposed to a magnetic field. Consequently, the magnetic field crossing the winding area generates electromagnetic winding forces. As an example, Figure 10 shows the distribution of the magnetic field of an air-core reactor of 30 MVAr power rating.

As already outlined under 6.2.4, the forces in the winding are proportional to the current multiplied by the magnetic field in the winding, and thus they are proportional to the square of the current.

When calculating the winding forces, it can be shown that the frequency spectrum of the forces differs from the electrical frequency spectrum. In case of single frequency a.c. current, the forces are oscillating with twice the frequency of the current. If, however, the reactor is simultaneously loaded by several currents of different frequencies, in addition to vibration modes at double the electrical frequencies there are also additional vibration frequencies (see 6.3.3).

The oscillatory forces on the winding cause the reactor to vibrate in the axial and in the radial direction. While the oscillating forces can be clearly determined, the analysis of the vibration response of the winding structure is rather complex. As with any mechanical structure, the dynamic behavior of the reactor may be described in terms of vibration modes. Since the oscillating forces are of almost rotational symmetry, it would be expected that only symmetrical modes of the structure coinciding with the shape of the force distribution would be excited. However, the finite number of duct sticks between concentric winding layers, the spiders attached at the winding ends and manufacturing tolerances result in the excitation of modes other than those of rotational symmetry. The fundamental modes of the cylindrical reactor structure are:

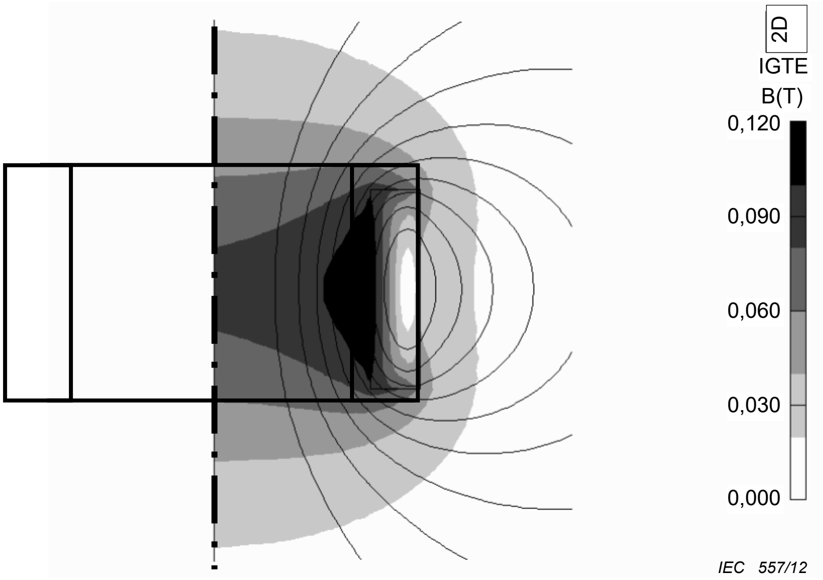


Figure 10 – Magnetic field of an air-core reactor winding

- So-called "breathing mode" where the reactor winding is deformed like a cylindrical pressure vessel. This modal frequency essentially depends on the material parameters of the winding and is inversely proportional to the winding diameter. Typically the breathing mode frequency is between several hundreds of Hz and 1 kHz. The breathing mode is fully symmetrical (see Figure 11) and its shape coincides with the distributed exciting electromagnetic force resulting from the axial magnetic field component.
- "Compression modes" in the axial direction where the reactor is symmetrically compressed towards the reactor midplane. This mode is excited by the radial magnetic field component.
- "Flexural modes" (bending modes) of the winding layers, characterized by the number of nodes in circumferential and axial direction. The frequencies of interest for these modes are usually lower than the breathing mode frequency. Although the flexural modes are not of rotational symmetry they become excited by the electromagnetic forces (see Figure 12).

The vibrations of the surface of the apparatus radiate to the surroundings as airborne acoustic noise. The radiated sound power in defined by

$$W = \rho_0 c A_W \sigma v^2 \tag{6}$$

by introducing:

$$v = \omega x \tag{7}$$

The radiated sound power at a certain acoustic frequency is defined by:

$$W = \rho_0 c A_W \sigma \omega^2 x^2 \tag{8}$$

where:

W is the radiated sound power;

ρ_0 is the air density in kg/m^3;

c is the speed of sound in air in m/s;

A_W is the sound radiating surface in m^2;

σ is the radiation efficiency (no unit);

ω the is angular acoustical frequency ($= 2\pi f$);

χ is the vibration amplitude in m.

The vibration amplitude and the size of the sound radiating surface of the apparatus essentially determine the sound power. Therefore the sound emission of a dry-type air core reactor is governed by the magnitude of the winding vibration on the radial direction, since the winding represents the main part of the radiating surface. The contribution of axial winding vibrations and that of other components to the total sound emitted is relatively low.

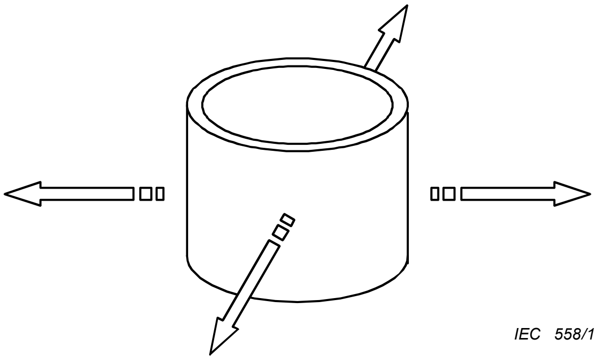
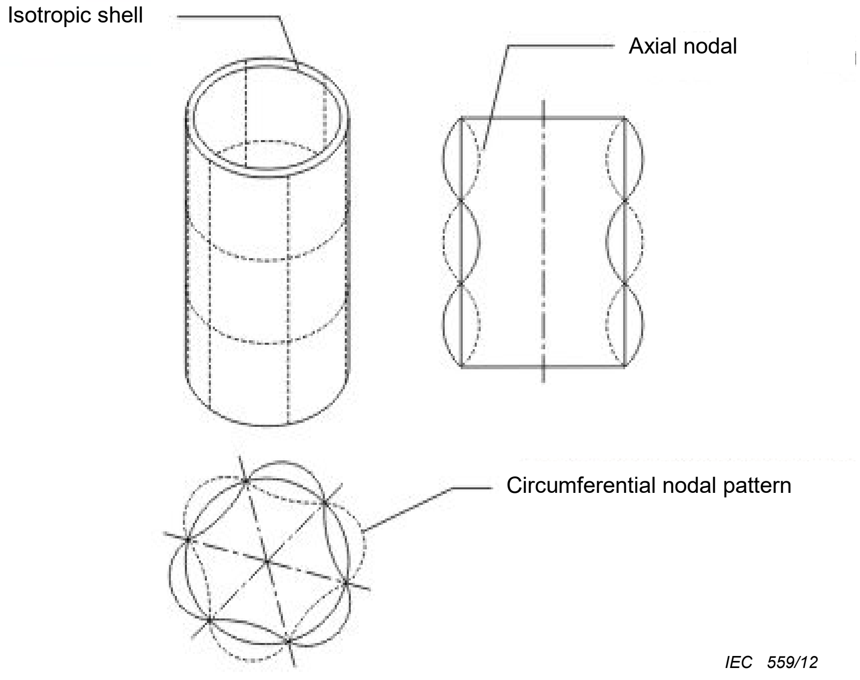


Figure 11 – Simplified shape of the symmetrical breathing mode of a reactor winding



NOTE I is the number of circumferential wavelengths = 3 and j is number of axial half wavelengths = 3..

Figure 12 – Example of flexural modes (bending modes) for a simply supported winding layer without axial constraint

To avoid dynamic resonance amplification of the vibration amplitude, the forcing frequencies (which are governed by the electrical frequency spectrum), should not coincide with the structural resonance frequencies.

As the vibration amplitude is directly proportional to the vibration force, it can be derived that the sound power of the reactor is proportional to the fourth power of the load current (see 6.2.1). For specifying sound criteria, it is therefore necessary to clearly specify the substation's operating conditions. The specified current ratings for the thermal design of the reactor may not necessarily be the same as the ratings specified for the acoustic design.

The radiation efficiency σ depends on the frequency and the geometrical and structural properties of the component. For example, if a surface vibrates at a frequency at which the structural wavelength is considerably greater than the acoustic wavelength in the ambient medium, e.g. air, then the air cannot move out laterally to cancel out pressure differences, and the particle velocity of the air will be equal to the velocity of surface, even outside the immediate vicinity of the surface. Thus $\sigma=1$. If the situation is the opposite, then $\sigma < 1$. At frequencies where the wavelength of the vibrating structure is about the same as the wavelength in air, σ can become greater than 1. See 10.2.4.

As explained above, the sound power increases with the fourth power of the load current. This allows direct scaling of test load results, which is useful to achieve because operational currents are often hard to achieve in laboratories. Assuming linearity, the sound power level L_{W1} measured at current I_1 can be scaled to another current I_2 as follows:

$$L_{W2} = L_{W1} + 40 \lg\left(\frac{I_2}{I_1}\right) \tag{9}$$

where:

L_{W1} is the sound power level in dB at current load I_1;

L_{W2} is the sound power level in dB at current load I_2.

The total sound power level, including all acoustic frequencies, is derived by logarithmic summation (see Clause 3). The acoustic frequency spectrum depends on the load current spectrum of the reactor, and is thus very much dependent on the reactor application, as outlined below.

6.3.3 AC filter reactors

As an example, Figure 13 shows the simplified current spectrum of an a.c. filter reactor. It is assumed that the current consists of a component with fundamental frequency f and one harmonic component with harmonic number, h. In reality, the current always consists of more than one harmonic component.

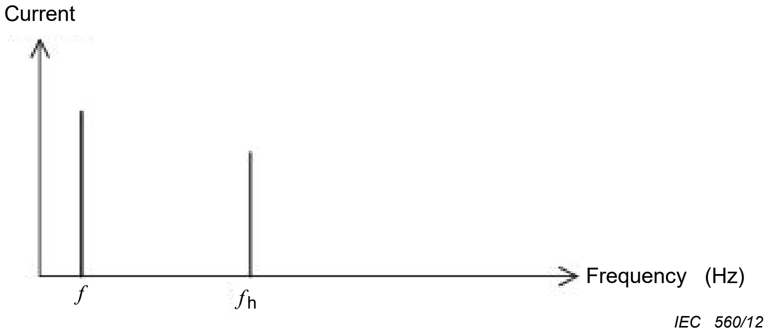


Figure 13 – Example of spectrum of currents through a.c. filter reactor

Figure 14 below depicts the force components acting on the winding of the reactor. The force consists of a static pre-load and components with frequencies $2f$, $f_{(h-1)}$, $f_{(h+1)}$ and $2f_h$. Only the vibration force components are generating noise; the static pre-load does not affect the sound power.

When going from electrical load to electrical force, a frequency shift occurs and the number of force components is equal to or less than the squared number of load components. The acoustic frequency spectrum will therefore increase significantly if the reactor's current spectrum includes several harmonics.

Like any mechanical structure, a reactor with distributed mass and structural properties has an infinite number of structural resonances. Amplification of the equipment vibrations, and thus increased sound generation, may occur if one or several frequencies of the force spectrum coincide with these structural frequencies. For proper consideration of the acoustic behavior of the filter reactors, it is therefore necessary to include both the fundamental and the harmonic content of the current.

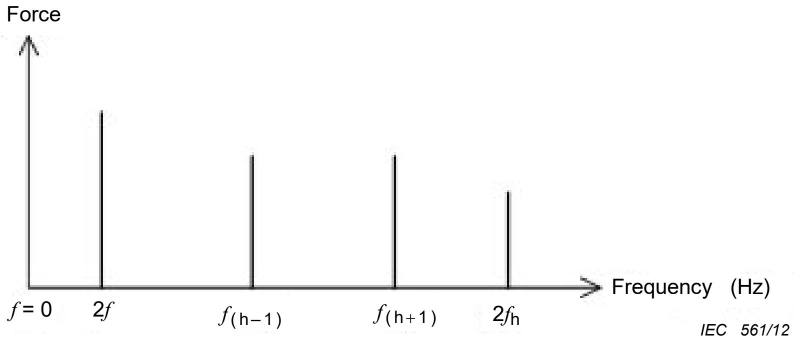


Figure 14 – Example of spectrum of forces acting on the reactor winding

6.3.4 HVDC smoothing reactors

The most significant components of the noise radiated from an air-core dry-type smoothing reactor winding are caused by the vibration of the winding due to the interaction of the d.c. current with the harmonic currents. Since modern converter substations generally operate with 12-pulse bridges, the main harmonics are the 12th and the 24th. Therefore for 60 Hz a.c. systems, the corresponding frequencies are 720 Hz and 1 440 Hz.

As an example, Figure 15 shows the simplified current spectrum of an HVDC smoothing reactor. It is assumed that the current consists of a d.c. component and one harmonic of the power frequency with harmonic number h. In reality, the current always consists of more than one harmonic component.

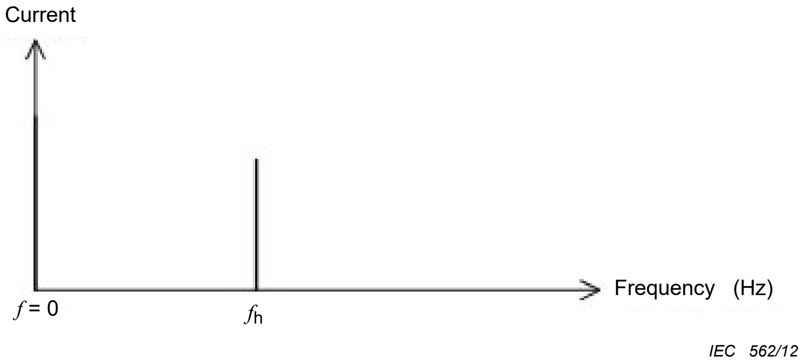


Figure 15 – Example of a spectrum of currents through an HVDC smoothing reactor

Figure 16 depicts the force components acting on the winding of the reactor. The force consists of a static pre-load and vibration components with frequencies f_h and $2f_h$.

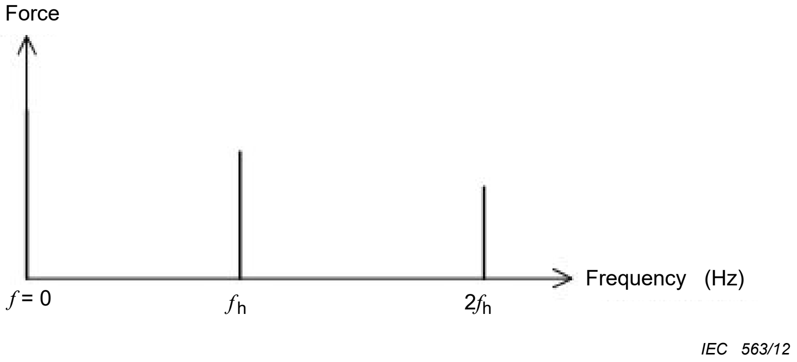


Figure 16 – Example of spectrum of forces acting on the reactor winding

The static pre-load (force with frequency $f = 0$) does not in practice affect the total noise.

6.3.5 Self-tuned filter reactors

AC filters need to have a certain bandwidth to limit the consequences of filter detuning. Self-tuned filter reactors can be adjusted to follow frequency excursions and component variations. These reactors have an iron core with a control winding, see Figure 17. A d.c. current in the control winding affects the permeability of the core and changes the inductance of the reactor. Further harmonic components can appear due to unsymmetrical magnetic saturation. The a.c. cable is wound on a fiberglass cylinder, which surrounds the iron core. A sound screen encloses the whole reactor.

Sound measurements have shown that the reactor essentially behaves as a conventional air-cored reactor as a function of the a.c. current. The d.c. current in combination with the a.c. current creates forces at the a.c. frequency as shown in Figure 16. A change of the d.c. current thus only affects the sound at the a.c. frequency (and e.g. not double the a.c. frequency). There will be no sound radiation at the frequency 0 Hz.

Radial vibrations of the fiberglass cylinder seem to determine the radiated sound power, and not as has been found on air-cored reactors, the radial vibrations of the a.c. winding. See also Clauses 9 and 10.

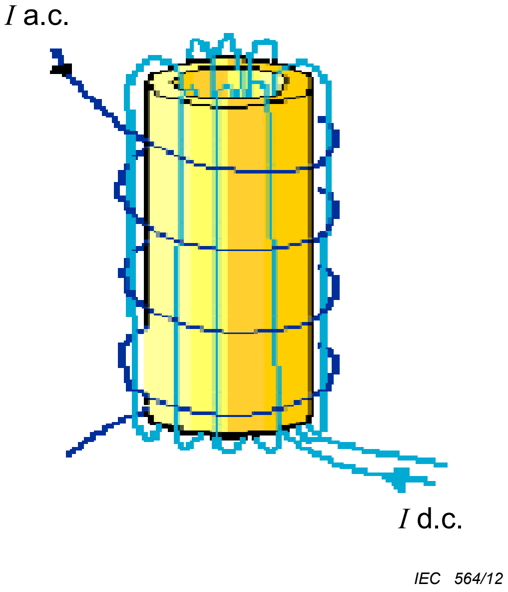


Figure 17 – Reactor for self-tuned filter applications

6.4 Capacitors

6.4.1 Type and design of capacitors

After transformers and reactors, capacitors are the main noise sources in an HVDC substation. Capacitors are used for various functions in an HVDC scheme, such as for a.c. and d.c. filters, reactive power compensation, for power line carrier (PLC) circuits and as capacitive voltage transformers (CVTs).

Capacitors used in filters and for reactive power compensation are typically stacks of power capacitor cans. Other capacitor types, which employ insulator housings, are coupling capacitors in PLC circuits and capacitive voltage transformers for measurement and protection. For sites subject to space restrictions, polluted environment and/or frequent earthquakes, tanked capacitors may be used.

In general, it is the can-type capacitor, which needs to be considered for noise limits. Therefore the following description of the capacitor design mainly refers to can-type capacitors.

In order to explain the mechanism of sound generation, the design of a capacitor and some terms need to be explained. A capacitor stack consists of a number of capacitor cans. The capacitor can is the steel covered capacitor including bushings. Each capacitor can is filled with oil and contains a capacitor element package that is built up by a number of capacitor elements (see Figure 18), which are connected in series or parallel. The capacitor element is made by winding two aluminum foils and a number of plastic or paper films of a specific length.

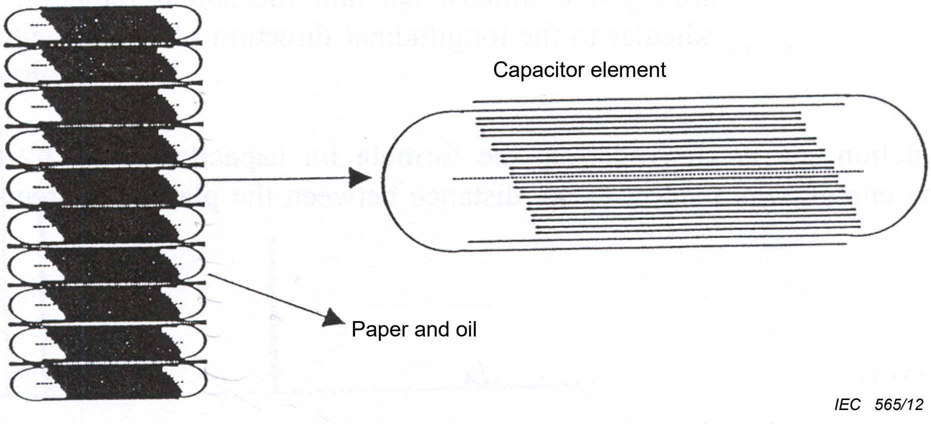


Figure 18 – Capacitor element package with capacitor elements

The design of the capacitor elements and the capacitor element packages of capacitors in porcelain housings, such as coupling capacitors and capacitive voltage transformers, is basically the same. Therefore the mechanism of sound generation described below refers to all types of capacitors.

6.4.2 Mechanism of sound generation

The section across an energized capacitor element (see Figure 19) shows that most of the charge-carrying aluminum foils are in force equilibrium because they have an attracting foil on each side. The only foils that are not in equilibrium are those on the edges (force F_1) and in the middle of the capacitor element (force F_2). As the stiffness of the thin oil layer in the middle of the capacitor element is quite high, the middle forces cancel each other with a very small displacement. The net forces on the capacitor element are then the forces on the edges.

Therefore, the parts contributing most to the generation of audible noise are the top and the bottom of the capacitor element. This is also valid for the capacitor element packages; the mechanical response is therefore governed by the first longitudinal resonance in the package. The sound generation is essentially one-dimensional and the sound radiation is mainly confined to the surfaces perpendicular to the longitudinal direction of the capacitor element package.

The force calculation can be derived from the formula for capacitor plates by taking the derivative of the energy with respect to the distance between the plates (theorem of virtual displacement):

$$F = \frac{dW}{dx} \tag{10}$$

where:

W is energy stored in the capacitor in W;

x is distance between the capacitor plates in m.

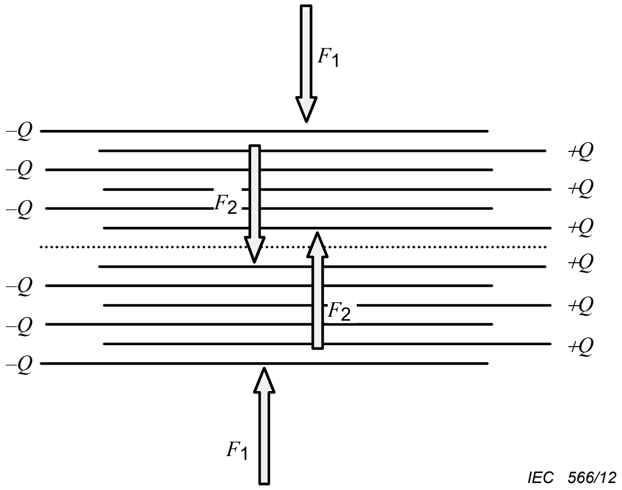


Figure 19 – Forces in a capacitor element

By introducing the formula for the energy stored in a capacitor

$$W = \frac{U^2 C}{2} \tag{11}$$

where:

U is r.m.s voltage across the capacitor in V;

C is capacitance in F.

The force can then be calculated by:

$$F = -\frac{U^2 C}{2x} \tag{12}$$

If U is a sinusoidal voltage

$$U(t) = \sqrt{2}\,U \sin(\omega t) \tag{13}$$

The force will be composed of one static and one oscillating (harmonic) force. It must also be remembered that the acoustic frequency spectrum will increase significantly if the voltage spectrum includes several harmonics.

As an example, Figure 20 shows the simplified voltage spectrum of an a.c. filter capacitor. It is assumed that the voltage spectrum consists of a component with fundamental frequency f and one harmonic component with harmonic number h. In reality, the voltage always consists of more than one harmonic component.

Going from voltage stress to force, a frequency shift occurs and the number of force components equals the number of voltage components squared. The forces in the capacitor element packages finally cause vibrations of the steel enclosure of the capacitor unit and thus generate acoustic noise, which is radiated as airborne sound.

To calculate the sound power and the sound power level at a certain acoustic frequency, the same formulae mentioned in 6.3 can be used. If all equations are considered, it can also be derived that the sound power is proportional to the fourth power of the dielectric stress in the capacitor.

Figure 20 shows the voltage of the basic frequency, f, and the harmonic frequency, f_h, for the filter.

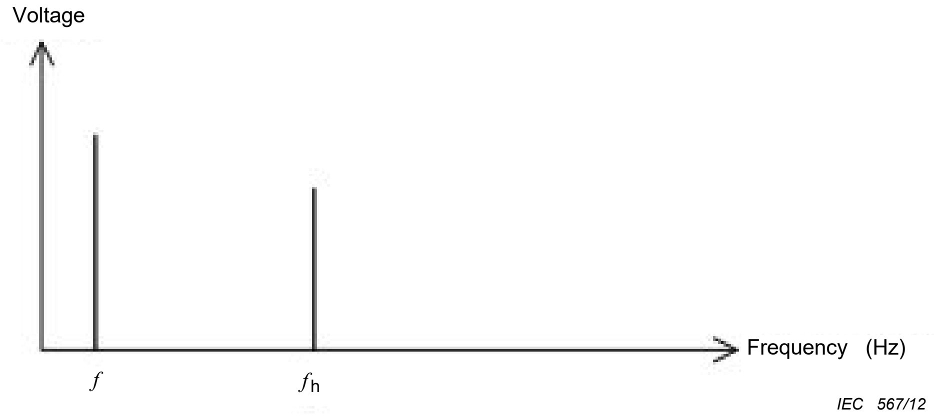


Figure 20 – Example of spectrum of voltages across the capacitor

Figure 21 depicts the vibration force components acting on the winding of the capacitor. The force consists of components with frequencies $2f$, $f_{(\text{h-1})}$, $f_{(\text{h+1})}$ and $2f_\text{h}$.

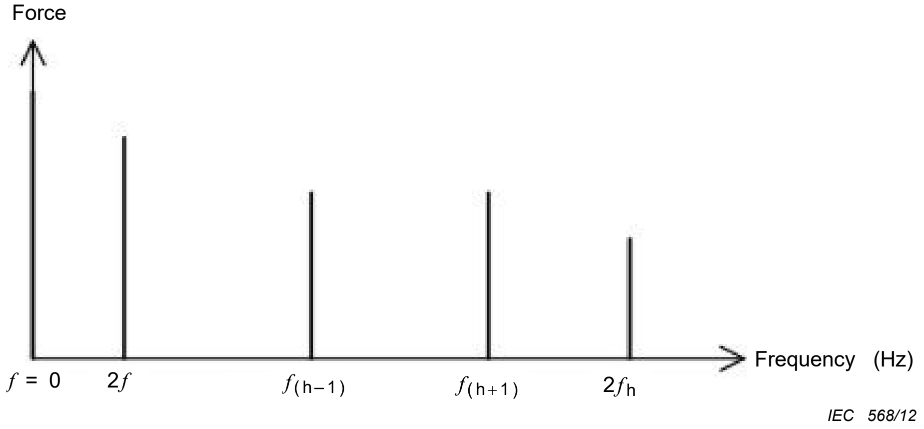


Figure 21 – Example of spectrum of electrostatic forces in a capacitor

In order to determine the sound power level of the complete capacitor stack, the sound power level of all capacitor units can be added as uncorrelated sound sources:

$$L_W^{\text{stack}} = L_W^{\text{unit}} + 10\lg(n) \tag{14}$$

where

L_W^{stack} is the sound power level of the complete capacitor stack in dB;

L_W^{unit} is the sound power level of a capacitor unit in dB;

n is the number of capacitor units.

The sound power radiation from a stack of capacitors is essentially dependent on:

- fundamental and harmonic a.c. voltage across the capacitors;
- mechanical stiffness;
- mechanical resonance frequencies (of capacitor element packages, housing and rack);
- number of capacitor units;
- position/location of the units/racks.

The above formulae for the radiated sound power, as well as for the sound power level, are considering a single acoustic frequency only.

The total sound power level considering all acoustic frequencies is derived by logarithmic summation (see Clause 3). The acoustic frequency spectrum depends on the frequency spectrum of the voltages across the capacitor.

6.5 Cooling fans

Forced air coolers are normally used for thyristor valve cooling; these consist of heat exchangers (with cooling media of water/ethylene glycol and air) and axial flow fans. Usually several fans are used per cooler module. The fans are separated from one another by a partition. This enables stepwise controlling of the cooler capacity (kW-capacity) by successively switching each fan on and off according to the cooling demand.

By selecting the optimum cooler size for a specific application, the optimum fan speed (typically between several hundred and 1 000 rpm) and the number of fans, the noise level can be kept to a minimum. Low-noise axial flow fans, with large diameters and operating at low rotational speeds, may reduce noise emission. Two-speed motors or motors with frequency control for speed regulation may be employed. The manufacturers are able to optimize the acoustic design of the coolers by combining adequate standardized cooler modules for which acoustic ratings is available.

For un-enclosed converter transformers of normal acoustic design, the noise of the cooling equipment is insignificant. For enclosed or low-noise converter transformers, the additional sound power generated by the cooling fans needs to be considered.

Cooling of transformers with very high rated powers may require separate radiator banks. Such free-standing coolers are also advantageous as they allow enclosure of the transformers themselves.

6.6 Other sound-emitting sources

6.6.1 Switching devices

In contrast to the components described above, switching devices such as circuit breakers and disconnectors only generate audible noise when operated. This noise is short-term, but may significantly exceed the background noise. The audible noise produced by the opening and/or closing of a circuit breaker is classified as impulsive noise. The duration of a single acoustic impulse is usually less than one second.

One approach to evaluate impulsive noise is to express it as an equivalent continuous noise level. The equivalent continuous A-weighted sound power level of a noise over a time interval T, can be derived from the A-weighted sound power levels during the periods T_i by using Equation (15). There is however no standard values for T_i. The values of T_i should be chosen to give an appropriate description of the impulsive event, e.g. 10 seconds for air-break connectors or earth switches (see 7.3.7).

$$L_{W\text{Aeq}} = 10\ \text{lg}\left[\left(\frac{1}{T}\right)\sum T_i 10^{0{,}1 L_{W\text{Aeq},T_i}}\right] \qquad (15)$$

where:

$L_{W\text{Aeq}}$ is the equivalent continuous A-weighted sound power level in dB over time interval T (rel. 1 pW);

T is the total time interval ($T = \sum T_i$) in s;

$L_{W\text{Aeq},T_i}$ is the equivalent continuous A-weighted sound power level in dB during period T_i (rel. 1 pW);

T_i is the time period in s during which the noise occurs at the level (L_{WAeq}, T_i).

Depending on the definition of the total time interval T, different A-weighted quantities may be used to evaluate the effects on the environment, such as

- equivalent continuous sound level;
- daytime average sound level;
- night time average sound level;
- day-night averaged sound level with a dB-adder for the night sound level;
- hourly average sound level.

Normally the noise generated by switching devices does not have a significant impact on the overall noise level of an HVDC substation since the accumulated noise dose is relatively low compared to sources continuously producing noise. In many cases, circuit breakers are operated just a few times per year, except filter bank circuit breakers, which may be operated several times daily. However, the accumulated noise dose during a working day has to be within the sound level limits established to limit the risk of causing hearing damage for staff on site. These limits, which may be taken from local safety directives, are dependent upon the accumulated sound exposure duration, and are usually getting lower for higher frequency sound.

The acoustic impulse generated during a switching operation depends upon the type of switch (e.g. air-blast circuit breakers, vacuum or SF_6 circuit breakers) as well as on the breaker operating mechanism (e.g. spring-operated, hydraulic-operated). The level of sound is highest for air-blast circuit breakers, whereas modern vacuum or SF_6 circuit breakers produce a relatively low level of sound.

Air break disconnectors and earth switches can produce significant sound levels for up to 10 s, during a switching operation.

6.6.2 Synchronous compensators

Synchronous compensators tend to run continuously and are enclosed in a building or a prefabricated acoustic and weatherproof housing. There will be some residual noise from the equipment inside the enclosure, such as exciters, slip ring/brush assembly and auxiliary transformers. However, the most significant noise from the enclosed synchronous compensator will be noise produced by the cooling plant. Thus, the sound aspects listed for cooling fans apply in this case also.

6.6.3 Diesel generators

A diesel generator is almost always enclosed in a building, but the level of sound outside the building due to the exhaust vent can be substantial. However, diesel generators only operate occasionally, either for routine testing of under emergency conditions. Routine testing can be confined to the daytime in the normal working week, and hence noise sensitive periods will – on the whole – be avoided.

6.6.4 Air conditioning plant

Whilst the direct noise of an air-handling plant is generally contained in a building, there may still be a substantial residual sound emanating from the inlet and outlet air vents. The sound emanating from these sources includes airflow and louver noises and residual noise from the air-handling plant, although acoustic louvers are available. With regard to the fan noise generated by air-conditioning systems, the factors described in 6.5 apply.

6.6.5 Cooling circuit pumps

If cooling system pumps are installed outdoors, they may have to be included in noise management considerations.

6.6.6 Converter valves

As this clause only describes those components emitting sound into the area surrounding an HVDC substation, the acoustic behavior of the thyristor valves is not discussed as they are almost always installed indoors. The noise of the valves themselves is mainly generated by the magnetic components such as the valve reactors. The coolers of the thyristor valves, however, are generally installed outdoors and are discussed under 6.5.

In the rare case of tanked valves installed outdoors, valve reactors and the fans of the cooling equipment may be dominant sound-emitting source.

6.6.7 Air compressors

If air compressors are installed outdoors, they may be one of the major noise sources.

6.6.8 Corona sources

Practically all high voltage connections emit a certain level of corona. For reasons other than just sound (e.g. radio interference requirements and the risk of flashover), corona should be limited to low levels and low levels of corona should trigger remedial actions.

In particularly sensitive sites it may be necessary to suppress corona levels by methods described in 7.2.9.

6.7 Typical sound power levels of sound emitting sources

The figures stated below in Table 1 for component sound power are based on a "standard design" of each component. A modern standard design includes the use of common practices for internal noise reduction, for instance avoidance of critical mechanical resonances. The stated sound power figures, however, do not include the use of external noise reduction measures, such as sound shields, enclosures, etc.

Table 1 – Examples of component sound power level

Sound emitting source	**Component sound power** L_{WA} in dB (A)
HVDC converter transformer	
– nominal load	90 to 125
– no load	85 to 110
HVDC smoothing reactor	85 to 100
Self-tuned filter reactors	90 to 100
AC and d.c. filter reactor	65 to 90
AC and d.c. filter capacitor bank (can-type capacitors)	55 to 105
Cooling fans (forced air coolers for valve cooling)	
– fan speed approx. 300 rpm	
Cooling capacity 30 kW / 300 kW	approx. 55/85
– fan speed approx. 900 rpm	
Cooling capacity 500 kW / 1 300 kW	approx. 90/105
Switching device	(Impulsive noise)
– air blast circuit-breaker	150 to 160
– oil and SF_6 circuit-breaker	105 to 130

7 Sound reduction measures

7.1 General

Where there are components, which generate significant levels of sound so that noise limits, are exceeded, it is necessary to use sound reduction measures. This is generally the case for HVDC substations.

Ideally sound reduction should be part of the original design and is a combination of substation layout techniques and component design measures. The aim is to use two techniques in conjunction to produce an effective and cost-efficient design.

Very often encapsulation and screening are required to contain sound in an area where high sound levels are not permitted. Retrofitted sound reduction measures may be required when measurements are made after installation of the equipment. These may include more screens, further encapsulation and even active noise reduction techniques.

Additional information concerning sound reduction methods is given in other publications [7, 8].

7.2 Substation layout

7.2.1 General

The maximum possible separation between the area designated for sound-emitting components and the sound-sensitive area should be chosen. This can be done by arranging significant sound-producing components so as to hinder the propagation of sound waves in sound-critical directions by making use of the natural topography of the area, or by using the screening effects of the converter equipment and other buildings.

Some of the major sound sources notably pumps and thyristor valves are indoor equipment and the noise considerations here are related to the effects on workers and visitors to the converter substation. In general, the level of sound emitted outside the rooms by these components is not considered a nuisance and, where access is required for inspection whilst in service, ear defenders are considered acceptable. Specific information can be found in the local health and safety guidelines.

General sound reduction measures, which can prove very effective for the whole site, include:

- surrounding the site with either a wall or a substantial earth mound;
- building the site in a hollow or locating the site in a suitable valley, preferably without steep rock sides.

The typical twelve-pulse and dual twelve-pulse HVDC substation layouts are shown in Annex B.

7.2.2 Transformers and tanked reactors

In terms of layout, the sound suppression measures to be adopted for transformers and tanked reactors is based on the concept of constraining the sound to an enclosure (absorbing sound energy in the process, e.g. with a special lining such as “Rock-wool”). An alternative would be radiating it in a particular direction where it will cause an acceptable level of disturbance.

Thus it is possible in some instances to consider orienting the converter building and converter transformers, and even the entire converter substation, to shield a sound-sensitive area from transformer noise.

For converter transformers and tanked d.c. reactors, it is often the case in a modern HVDC scheme that the connections to the converters are via bushings directly through the valve hall wall. Consequently, there is a highly effective barrier to sound transmission in one direction, provided the valve hall is significantly taller than the transformer or reactor.

Very often it is a requirement to provide fire barriers between transformers or even around transformers and these can also provide useful sound attenuation – again provided they are high enough compared to the transformer/reactor. Where a complete enclosure is not provided, one must be aware that the part enclosure provided may result in a magnification of noise in a particular unprotected direction due to resonance and/or reflection effects.

7.2.3 Air-cored reactors

Air cored reactors can be significant sound producers, particularly those in filters. Air cored reactors can be enclosed, if care is taken to consider in- and outlet air and electric insulation distances.

From a site layout point of view, there are two possibilities for air-cored reactors:

- Locate them at the maximum practical distance from sound-sensitive areas. Since many reactors are in harmonic filters, there is some flexibility in terms of relocation.
- Locate them in a location which uses the converter buildings (and other site buildings) to shield sound-sensitive areas from unacceptable levels of sound.

7.2.4 Capacitors

In some cases, capacitors can be significant sound generators and they can be treated in the same way as air-cored reactors for layout-based sound reduction techniques.

The capacitor stacks in HVDC filters have large dimensions and a complex radiation pattern. Capacitor stacks may have a very pronounced directivity and thus the location, orientation, height and screening technique can be optimized with respect to the acoustic layout of the HVDC substation.

7.2.5 Cooling fans

In many respects the same considerations as for air-cored reactors apply on cooling fans. There is the significant point that some fans are strongly directional from a sound emission point of view. This gives the added opportunity to orient the fans in a direction in which the sound levels are less of a nuisance.

7.2.6 Diesel generators

For a diesel generator, the main noise source is usually the exhaust vent (as described in 6.6.3). In this case further sound reduction in terms of site layout is as for air-cored reactors and dependant on site size and location of buildings.

7.2.7 Switching devices

Whilst switchgear produces a significant level of sound in its occasional operation, this is generally acceptable and is no different from a conventional substation. For particularly sensitive locations consideration may need to be given to locating the switchgear in a building.

7.2.8 Air conditioning plant

Whilst the direct noise of air-handling plants is generally contained in a building, there is still the substantial residual sound from the inlet and outlet air vents. Although the sound emanating from these sources includes not just airflow but also louver noises (remembering that "acoustic louvers" are available) and residual noise from the air handling plant, the same concepts that apply to fans are generally suitable.

7.2.9 Corona sources

In particularly sensitive sites it may be necessary to suppress even normally acceptable levels of corona and a number of methods may be used to achieve this:

- use of adequate electrode configurations for the outline design of the components;
- increased clearances between phases and between busbars;
- use of cables or gas insulated busbars.

7.2.10 Synchronous compensators

As described in 6.2.2, the most significant noise from an enclosed synchronous compensator will be noise produced by the cooling plant. Thus the considerations that apply to cooling fans also apply in this case.

7.3 Component design

7.3.1 General

Low-noise designs of equipment normally seek to minimize the vibration amplitudes of the component’s sound radiating surface. For this purpose, it is essential to design the equipment so that the natural frequencies of the component do not coincide with the frequencies of the major excitation forces.

The sound producing process is described in more detail in Clause 6; this clause highlights the design features that lead to a component that produces less sound.

One technique, which reduces sound for many types of equipment, is the use of resilient mountings. By providing vibration isolation, that limits the spread of low frequency sound.

7.3.2 Transformers and tanked reactors

Many of the sound reducing design issues are standard aspects of transformer and reactor design; for example:

- modern core materials;
- lower magnetic flux operation;
- utilizing modern core-joint technologies;
- avoiding critical mechanical resonances;
- provision of mechanical damping both in the tank and in the installation;
- better control of manufacturing tolerances;
- use of low noise fans (see 7.3.5 below);
- use of separate cooler banks may reduce the requirement for forced cooling and ease the enclosure of the transformer.

7.3.3 Air-cored reactors

The key issue for controlling reactor noise is to limit vibration of the windings. Typical techniques used for this include:

- adjustment of physical dimensions, spacers and mechanical supports to move resonance frequencies away from critical frequencies;
- use of larger conductors (to increase inertia and thus reduce vibration amplitude). However, this is usually not an economic approach to reduce the generation of reactor noise. A doubling of the cross-section, and thus doubling the winding weight, gives a noise reduction of maximum 6 dB.

7.3.4 Capacitors

The sound reduction techniques applicable to capacitors aim to reduce the vibration of the surface of the capacitor units.

The following are internal sound reduction measures, which are applicable to capacitors with steel cases, as well as to those with porcelain housings:

- by increasing the number of series connected capacitor elements, the dielectric stresses in the capacitor can be reduced and thus the vibration forces;

- stiffness of the capacitor element packages may be increased by compacting the stacked capacitor elements through improved mechanical damping;
- considering resonance frequencies in the capacitor design.

7.3.5 Cooling fans

The technology for low-noise fans is well established. A number of techniques have a significant effect on the sound produced:

- axial flow fans with large diameters and low rotational speeds;
- silencers and air baffles.

Such measures for transformer coolers may dictate the need for freestanding coolers.

7.3.6 Pumps and diesel generators

Since in normal operation pumps and diesel generators produce a large amount of sound, this can be greatly increased and damage may occur if some basic precautions are not observed. It is recommended to ensure that the alignment of the rotating parts is correct. This needs to be performed very accurately.

7.3.7 Switching devices

The level of sound emitted by switchgear is dependent on the switchgear technology in use.

The level of sound is highest for air-blast circuit breakers, whereas modem SF6 circuit breakers produce a relatively low level of sound. Additionally the breaker operating mechanism (spring, hydraulic) may have an effect on the noise produced. Given a particular type of circuit breaker, there is little to be done with the sound level that is produced by operation.

Methods for limiting the noise produced include:

- reconsidering the switching sequence of such switches, but this must be secondary to safety considerations;
- restricting switching operations to daytime, where possible.

7.3.8 Air-conditioning plant

The same considerations than those for fans apply to air-conditioning plant.

7.3.9 High voltage connections

If it is necessary to reduce corona levels, then the solution is to use higher voltage class connectors and larger conductors or conductor bundles. Corona rings and fittings should also be considered.

7.4 Sound enclosures

7.4.1 General

Sound enclosures include buildings, screens, encapsulation, and other methods of containing and absorbing sound. Enclosures or sound barriers are more practical for higher frequency noise (above 300 Hz). For a barrier to be effective, the receiver location must be in the acoustic shadow zone of the wall. There are formulas for determining the shadow zone and hence the wall height necessary to protect the receiver location [9].

A number of considerations should be made when using enclosures, for example their availability, reliability, and cost.

7.4.2 Transformers and tanked-reactors

Enclosure of transformers and tanked reactors is well established as a noise-reduction technology. Screening and absorption arrangements are very efficient due to the frequency spectrum of the sound (dominating frequencies are above 300 Hz). Indeed, it is standard practice in some utilities to enclose all transformers and tanked-reactors.

One common element of such enclosures is that the enclosure design is greatly simplified by having freestanding coolers, which can be placed outside the enclosure.

The most basic form of enclosure is a brick-built one or an extension to the fire/blast enclosure. This completely encloses the transformer/reactor and contains no sound absorbing material. Depending on the nature of the enclosure, this will give a sound reduction of up to 14 dB (A) without a roof, of 20-35 dB (A) with a roof. However this is strongly dependent on the construction and surface finish of the enclosure walls, and also the relative dimensions of the transformer and the enclosure. It should be noted that a badly designed enclosure of this type might actually amplify sound.

An alternative to the complete enclosure, particularly where blast and fire-containment walls are provided, is the use of sound-absorbing cladding on these walls. This is particularly relevant for converter transformers as these are usually placed against the valve hall wall and so there is a significant amount of sound reflected unless there is some sound absorbent material installed.

Where very significant noise reduction is required, a complete enclosure (possibly with two layers) with sound absorbing material on the inside will be needed to both contain and absorb the sound from the transformer. Such an enclosure might provide attenuation of up to 40 dB (A). A detailed summary of noise abatement methods is given in [8].

7.4.3 Air-cored reactors

These pose a much more significant noise reduction problem. There is a need to ensure that the airflow is not interrupted such that the reactor does not overheat and that electrical clearances are not infringed. Clearly any noise enclosure must be designed in conjunction with the reactor designer. Noise enclosures come in two basic varieties – buildings and reactor-mounted. Buildings must allow substantial heat removal and are often fitted with roof-mounted fans. The same comments concerning the effectiveness of sound reduction provided by the building apply as for the transformer enclosures. Care must also be taken not to create any magnetic loops around the reactors, which may overheat due to the reactor's magnetic field.

Reactor mounted sound enclosures are an integral part of the reactor design. These may vary from a simple extra package on the outside of a reactor to complex fiberglass housing with an independent support structure and lined with sound absorbing material. Such housings may give an attenuation of up to 15 dB (A), but possibly at a cost exceeding the cost of the reactors. However, with regard to the voltage strength of the reactor winding, there might be restrictions on providing sound shields or enclosures, especially for high-LIWL reactors in wet and polluted conditions. Typical maximum attenuation ranges are:

– screening	(3 to 5) dB (A)
– partial enclosures	(5 to 10) dB (A)
– total enclosures	(10 to 25) dB (A)

7.4.4 Capacitors

To limit sound from capacitors, encapsulation can be used. The complication for capacitors is that they are often high voltage equipment with graded insulation. Therefore the encapsulation must either observe the maximum clearance requirement or alternatively be applied in separate sections throughout the capacitor structure. For tanked capacitors, no such complication exists and standard transformer enclosure techniques can be used.

As is the case with all enclosures, they can be simple non-absorbing barriers or complex (and expensive) sound-absorbing enclosures depending on the noise requirements and economic considerations. With partial screening of each rack level in a capacitor stack, reductions of up to 10 dB can be achieved. Higher reductions may be achieved by complete enclosures.

7.5 Retrofitable techniques

7.5.1 Enclosures

Subject to layout, thermal and electrical considerations, it may be possible to erect noise barriers around equipment, which proves to be much noisier in operation than expected. This is nearly always significantly more expensive than building the equivalent enclosure at the construction stage and also involves interruption to the operation of the HVDC link.

7.5.2 Damping

It is sometimes possible to add additional damping to some components, and this may provide some sound reduction where it can be shown that the noise is due to an interaction between the equipment and the foundation or a support structure.

This may either involve modifications to the support structure or the equipment itself such as by adding mass. For example, filling the transformer ribs with sand can help control radiated noise.

7.5.3 Active noise and vibration mitigation

There are methods of sound cancellation, which use microphones installed at the sound radiating surface or installation of loudspeakers close to a sound-radiating component. Such a technique requires a very detailed noise study with precise modeling of all structures.

Active noise and vibration control (ANVC) is most practical for low frequency noise. Effective installations in operation today on power transformers use a combination of vibration actuators mounted directly on the tank and acoustic (speaker-like) actuators that are mounted close to the tank. Error-sensing microphones are placed in the far-field to measure the noise levels and provide input to the controller. On a new transformer, it is possible to use near-field microphones or vibration sensors that are mounted on the transformer tank. An electronic controller takes the inputs from the microphones and minimizes the noise at multiple locations by driving actuators.

If the installation is successful, ANVC can give better noise cancellation at low frequencies than can be achieved with a sound barrier. However, active control is more difficult for sound and vibration problems in three dimensions than it is for problems with one dimension. The successful implementation of ANVC is in general easier and cheaper for small noise sources than for large sources, such as transformer tanks.

8 Operating conditions

8.1 General

This clause deals with the specification of the operating conditions under which the noise requirements shall be fulfilled.

There are many operational factors affecting the acoustic noise from an HVDC substation. These factors include:

a) HVDC substation operating parameters such as:
   - power
   - power direction

  - poles in service
  - firing angle
  - filters/shunt capacitors/shunt reactors in service
  - usage or not usage of redundant equipment e.g. coolers

b) External a.c. parameters influences such as:
  - a.c. system voltage and frequency
  - background harmonics
  - other converters and SVCs

c) Environmental influences such as (see also Clause 4):
  - time of day
  - ambient temperature
  - wind and other meteorological factors
  - external noise sources

Operating conditions affect the acoustic noise level because the load on the equipment (e.g. coolers and fans), the production of harmonics from the converter and to some extent the amount of equipment in operation (e.g. coolers and a.c. harmonic filters) is dependent on the operating conditions.

When looking at the operating conditions for a complete HVDC substation, it is necessary to split up the noise into an "internal part" and an "external part". The HVDC equipment itself produces the internal part while the external part is generated by a.c.-related equipment and harmonics related to the a.c. network.

The a.c. harmonics on the a.c. network will contribute to the total noise level of an HVDC substation. These harmonics are an external contribution, and the customer has to include data on harmonics on the a.c. network in the technical specification, so that the contractor can take it into account when making calculations for the complete substation (see Figure 22).

In practice, it is of most interest to the customer to look at the total substation noise level, but when specifying it is important for the customer to know the different noise sources if, at a later stage, it should be necessary to take further noise reduction measures.

The customer has to specify the requirements in such a way that it is possible for the contractor in a reasonable way to verify that the requirements are fulfilled. On the other hand it is also important that the customer get qualified verification of the noise level of the HVDC substation which can be used as documentation for the authorities.

When specifying noise requirements in the technical specification and subsequently verifying the noise level, it is important to know how the operating conditions will influence the noise level.

Operating conditions can be split up into the following categories:

- normal operating conditions;
- exceptional operating conditions;
- operating conditions specified for verification.

8.2 Normal operating conditions

Normal operating conditions are conditions that are achievable for extended periods of time, or are likely to be repeated regularly. The normal operating conditions include:

Table 2 – Normal operating conditions

Power range	From minimum to nominal
d.c. voltage range	nominal (for long distance transmission systems)
a.c. voltage & frequency	normal continuous
filter configuration	corresponding to power levels
control strategy	normal
redundancy	operation without redundant equipment

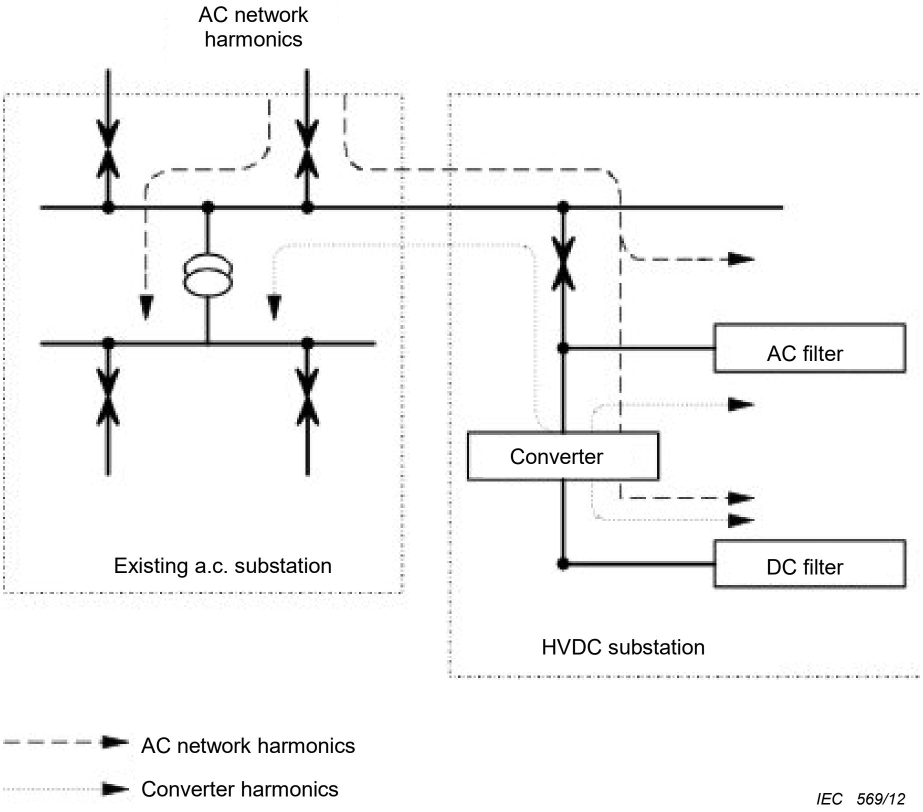


Figure 22 – Explanation of a.c. network harmonics and converter harmonics

8.3 Exceptional operating conditions

Exceptional operating conditions are defined as the occasions when special control functions are used or during temporary (short time) operation such as switching of a.c. filters and frequency or voltage deviations of the a.c. network. Exceptional operating conditions are listed in Table 3.

If the sound levels are to be within the specified requirement limits under all operating conditions, it is recommended that these limits are specified separately, one for normal conditions and one for exceptional conditions.

Table 3 – Exceptional operating conditions

Power range	From minimum power to maximum possible power
d.c. voltage range	full operating range (for long distance transmission systems)
a.c. voltage & frequency	normal continuous
filter configuration	corresponding to power levels
control strategy	for example, using increased firing angles and/or reduced d.c. voltage
redundancy	all redundant equipment in operation (e.g. thyristor and transformer cooling)

8.4 Operating conditions specified for verification

For verification of sound level limits, it is recommended to use the normal operating conditions or a specifically agreed condition. Due to practical on-site measurement constraints, verification will often be via a combination of measurement and calculation. The measurements will be a "verification" of the calculations for a particular operating condition, with the calculations predicting the worst case for normal and – if specified – exceptional conditions. Thus, the preconstruction studies should list the following cases if applicable:

- worst normal operation;
- worst exceptional operation;
- a few typical cases which one may reasonably expect to be measured.

9 Sound level prediction

9.1 General

Prediction of noise emission is important when planning a new installation, an expansion of an existing site, a change in operating conditions of existing plant or noise reduction measures for plant.

Calculation of expected environmental noise resulting from a new development, or when modifying existing installations, is important and often necessary for obtaining the necessary permits. Evaluating alternative design plans for a site is another case where sound level prediction is important. Finally, the calculated predicted sound levels can be compared to the specified levels at the points of interest (see Clause 4 for further details).

The prediction of sound levels in the vicinity of an HVDC substation is based on the sound generated by equipment at site. Thus, such predictions only include the contribution from the HVDC substation to the sound level at a point of interest. A predicted sound level does not include existing background noise level. The background noise level varies with the time of day depending on weather conditions, road traffic noise, railway or air traffic, and operation of other industrial installations or construction work. The background noise level does not therefore influence the contribution from the HVDC substation; however it has a significant influence on measurements of the sound level.

The accuracy of predicting sound levels in or around a converter substation is dependent on reliable acoustic data for the different sound sources at the site. Further, large buildings or other obstacles acting as sound screens must be accounted for in the prediction, as these may obstruct or reflect the sound in different directions. Also, the landscape in the vicinity of the substation affects the sound propagation.

9.2 Modelling of plant

9.2.1 General

Modeling of the plant requires selection of the important components and structures, and use of these as input data for a model for calculation purposes. This is done by the contractor; normally both in the tender and contract stage. In practice, such calculations are most often performed using an engineering tool, such as a computer program, especially when a large number of sound sources and frequencies are included. These computer programs should be commercially available.

An HVDC substation normally consists of a.c. and d.c. filters, transformers, smoothing reactors, thyristor valves and cooling fans. Buildings included in a normal installation consist of a service building and the valve hall. The model of the plant, for calculating the predicted sound levels in and around the substation, should include the dominant sound sources, and also the most important buildings. In addition, the substation layout and the transmission paths should be considered.

9.2.2 Layout

The converter substation layout defines the location and orientation of all equipment at site. Buildings and the site area are also included in the model of the substation. Further, there may be different types of ground surfaces at site, e.g. asphalt pavement, gravel or cultivated grass. The ground at site may therefore range from acoustically hard (asphalt) to soft (grass). This influences the reflection of sound and thus also the propagation.

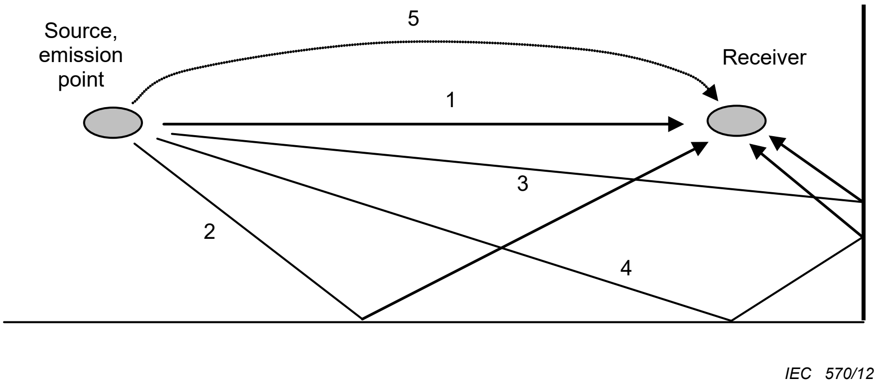
9.2.3 Source

Each real source is represented by an equivalent monopole source in the calculation model. A monopole is a model of a source where all surfaces of the source are moving in phase with each other. The sound sources in the model may be represented by their:

- sound power;
- acoustic frequency content;
- directivity pattern of sound radiation;
- geometrical source description (point source or surface);
- operational time (duration of emission).

9.2.4 Transmission path

For each source, the contribution to the sound pressure level at the receiver is calculated for each frequency band and transmission path from source to receiver (see Figure 23). Sound energy arriving from each of these paths has to be added to obtain the total sound pressure level at the receiver.



Key

1 direct path from source to receiver;

2 path reflected by the ground;

3 path reflected by an obstacle (e.g. building, screen);

4 path reflected by the ground and an obstacle;

5 path influenced by e.g. temperature layers, wind speed and direction (this path may be too complicated to be calculated).

Figure 23 – Examples of transmission paths from source to receiver

9.3 Calculation procedure

9.3.1 Sequence of calculation

The purpose of this general description is to briefly describe the different attenuation terms affecting sound propagation and some conditions to be accounted for when predicting sound levels. ISO 9613-1 and ISO 9613-2 specify calculation procedures for the attenuation of sound during propagation outdoors.

In general, a separate prediction of the sound pressure level contributions at the receiver for each individual source would provide the most flexible system and would ideally yield the highest degree of accuracy. It will, however, in practice often be useful to group as many individual sources as possible, thereby reducing the amount of calculation needed.

The formulas described here are meant for calculating the attenuation of sound from point sources. However, a group of point sources may be described by an equivalent point sound source situated in the middle of the group, particularly if the sources have:

- similar sound power levels, frequency characteristic, orientation and height above the local ground;
- same propagation conditions to the point of reception;
- distance from the single equivalent point source to the receiver exceeding two times the largest diameter of the relevant area of the sources.

If the measurement distance is smaller than described in Figure 24, or if the propagation conditions for the component point sources are different, e.g. due to screening, the total sound source must be divided into its component point sources.

The average sound pressure level at a receiver shall be calculated for each point source and for each octave band with nominal mid-band frequencies, normally from 63 Hz to 8 kHz. In accordance with ISO 266 the following set of centre-frequencies for the "octave" filter apply: 16, 31,5, 63, 125, 250, 500, 1 000, 2 000, 4 000, 8 000, 16 000. For the "1/3 octave" filter, the set of centre-frequencies is 16,0, 20,0, 25,0, 31,5... up to 17 780,0, 22 390,0. For audible noise, frequencies from 31,5 to 5 000 Hz are of interest.

The basic calculation procedure for each source, mid-band frequency and sound path is in three steps (the order of the procedure may differ-between calculation programs):

1) Calculation of the sound power level of each source – including the directivity in the direction of path i (indexed by i) belonging to that source – for each mid-band frequency f , L_{wfi}:

$$L_{wfi} = L_{wf} + DI \tag{16}$$

DI is the directivity index in dB (see 3.2.1). It describes the extent to which the sound radiation of the real source into different directions deviates from the emission of a non-directional point source.

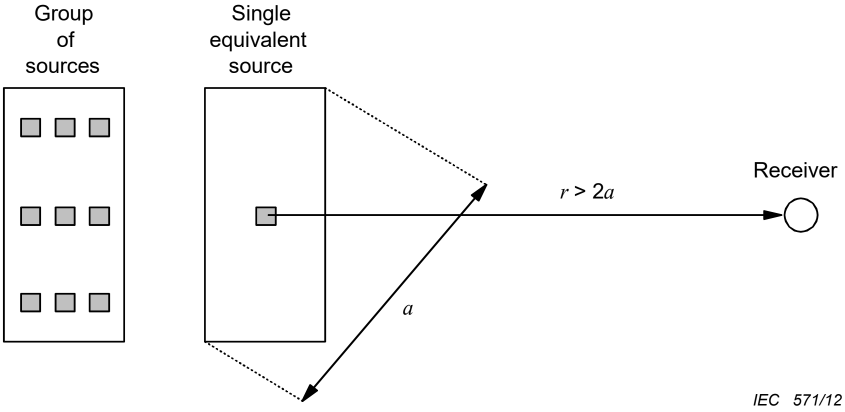


Figure 24 – Grouping of point sources to one equivalent source if the measurement distance (r) is larger than 2a

2) For each sound source (n), inclusion of its sound path from source to receiver, by calculation of the total sound pressure level in dB at the specific location for the frequency band f;

$$L_{p\text{TOT}(N)} = \sum_{n=1}^{N} \left(L_{wfi,n} - A_{fi,n} \right) \tag{17}$$

where:

$A_{fi,n}$ is the frequency dependent attenuation in dB for source n during propagation from source to receiver;

N is the total number of sound sources.

The attenuation term, $A_{fi,n}$, is given by

$$A_{fi,n} = A_{\text{div}} + A_{\text{atm}} + A_{\text{screen}} + A_{\text{reflex}} + A_{\text{ground}} + A_{\text{veg}} \tag{18}$$

where:

A_{div} is the attenuation due to geometrical divergence;

A_{atm} is the attenuation due to atmospheric absorption;

A_{screen} is the attenuation due to screening and transmission;

A_{reflex} is the attenuation due to absorption at reflecting obstacles;

A_{ground} is the attenuation due to the ground (which may include vegetation, e.g. grass);

A_{veg} is the attenuation due to sound propagation through vegetation.

3) Finally, sound pressure level summation, for each frequency band f, of different contributions L_{pTOT} (N) to the sound pressure level L_{pTOT} (dB), is performed by using the equation:

$$L_{p\mathrm{TOT}} = 10\,\lg \sum_{f=1}^{n} 10^{L_{p\mathrm{TOT}}(N)/10} \tag{19}$$

where n is the total number of frequency bands.

9.3.2 Calculation of attenuation terms

9.3.2.1 Attenuation due to geometrical divergence

A source in a free-field radiates sound in all directions equally (spherically). The surface area of this sphere increases as the diameter increases. Since the source sound power is constant, the energy expressed in W/m^2 decreases with increasing diameter. Hence:

$$A_{\mathrm{div}} = 10\,\lg\left[4\pi\left(\frac{r}{r_0}\right)^2\right] \tag{20}$$

where:

r is the distance from source to receiver, in meters;

r_0 is the reference distance (or radius) giving a sphere of surface area 1 m^2.

For r < 0,28m (resulting in $A_{\mathrm{div}} < 0$), A_{div} is set to 0 giving, if no other attenuation terms contribute, a sound pressure level that equals the sound power level, i.e. $L_p = L_w$.

9.3.2.2 Attenuation due to atmospheric absorption

The attenuation due to atmospheric absorption is given by:

$$A_{\mathrm{atm}} = \frac{(\alpha_a \times d)}{1\,000} \tag{21}$$

where:

α_a is the atmospheric attenuation coefficient, in dB/kilometer;

d is the distance of the sound path in meters.

Table 4 lists examples of atmospheric attenuation coefficients.

Table 4 – Examples of atmospheric attenuation coefficients

T	RH	Nominal octave centre frequencies Hz							
air temperature	relative humidity	63	125	250	500	1 000	2 000	4 000	8 000
°C	%	attenuation in dB per 1 000 meters							
- 20	70	0,17	0,51	1,73	5,29	11,5	16,6	20,2	27,8
- 10	70	0,15	0,33	0,83	2,65	9,19	27,8	58,5	86,2
0	70	0,15	0,39	0,76	1,61	4,64	16,1	55,5	153
10	70	0,12	0,41	1,04	1,93	3,66	9,66	32,8	117
20	70	0,09	0,34	1,13	2,80	4,98	9,02	22,9	76,6
30	70	0,07	0,26	0,96	3,14	7,41	12,7	23,1	59,3
15	20	0,27	0,65	1,22	2,70	8,17	28,2	88,8	202
15	50	0,14	0,48	1,22	2,24	4,16	10,8	36,2	129
15	80	0,09	0,34	1,07	2,40	4,15	8,31	23,7	82,8
30	> 90	0,051	0,199	0,768	2,695	7,317	13,808	23,589	53,907
NOTE See ISO 9613-1.									

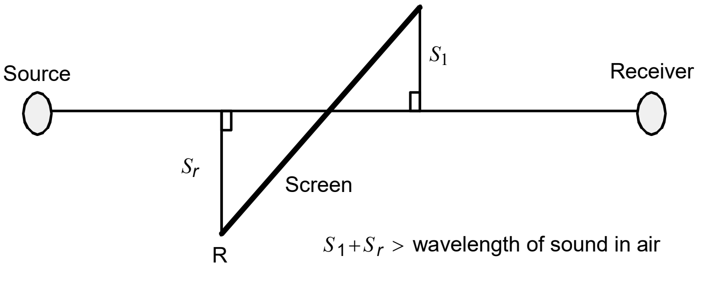
The atmospheric attenuation coefficient depends strongly on the frequency of the sound, the ambient temperature and relative humidity of the air, but only weakly on the ambient pressure. For estimates of environmental noise levels, an average attenuation coefficient should be used based on the range of ambient weather, which is typical for the locality.

9.3.2.3 Attenuation due to screening and transmission

The general principle in calculating the screening correction is to identify all screening obstacles between source and receiver. A simplifying approach is to represent each obstacle by a thin screen. The calculation procedure depends on the number of screens present. More details regarding calculation of the screening correction can be found in ISO 9613-1 and in [10].

There are three basic conditions that have to be met in order for an obstacle to qualify as an effective screen:

- The mass per unit area of the obstacle should exceed 10 kg/m^2;
- there should be no slits or openings in the obstacle;
- the horizontal dimension perpendicular to the line between the source and receiver should be greater than the wavelength of the sound in air, i.e. $s_1+s_r > \lambda_c$ (see Figure 25).

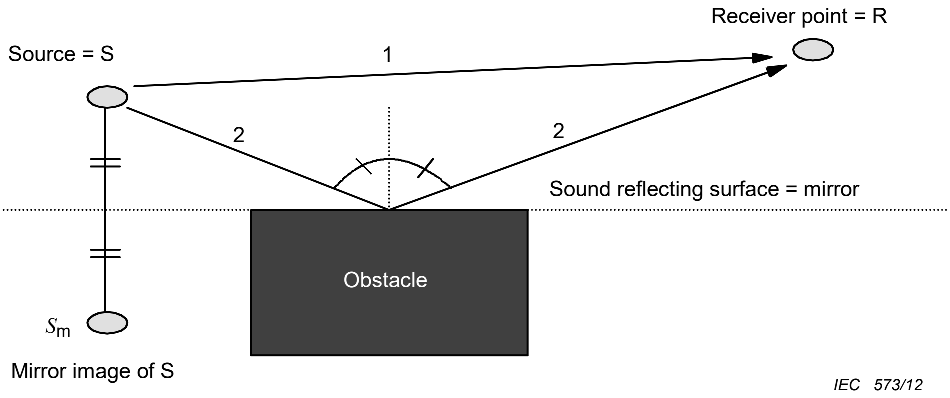


IEC 572/12

Figure 25 – Definition of the geometrical parameters used for calculation of screening

9.3.2.4 Attenuation due to reflection obstacles

In general, the effects of sound reflections from obstacle are treated in the prediction models by acoustical mirror considerations. The principle is illustrated in Figure 26 below.



Plan showing transmission paths between S and R. Note the mirror source S_m
Path 1: direct
Path 2: via reflection from building facade

Figure 26 – Reflecting obstacles are treated by mirror sources

The angle between the direction of the incident sound field and the normal to the reflecting surface is equal to the angle between this normal and the direction of the reflected sound field. The sound pressure level at the receiver can be considered to be built up by two separate individual contributions arriving via two transmission paths.

When sound hits a surface, some sound is reflected, some is transmitted and some is absorbed depending on the acoustic properties of the reflecting surface and on the properties of the sound.

The sound pressure level at the receiver can be calculated by adding the contributions from the real source, S, and the mirror source, S_m, respectively.

9.3.2.5 Attenuation due to the ground

Basically the attenuation due to the ground is calculated as the sum of three corrections (source, central and receiver), each of which is related to the properties of different regions of the ground surface between the source and the receiver (see Figure 27).

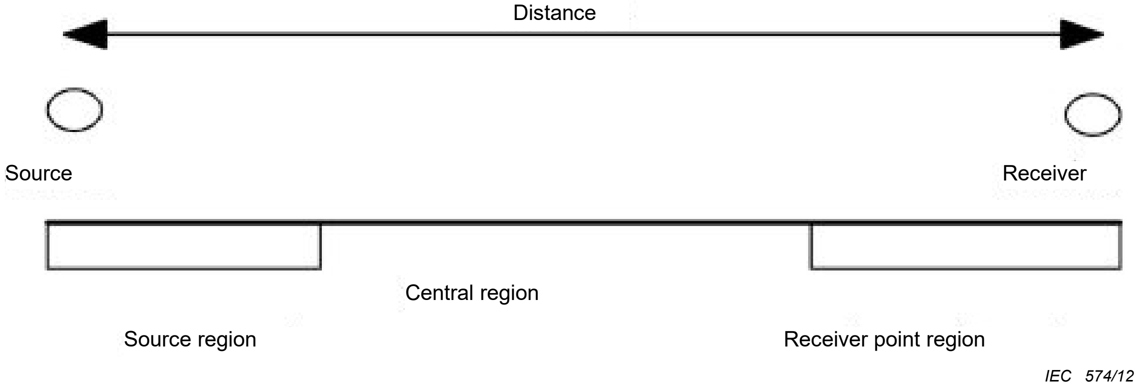


Figure 27 – Definition of parts for calculation of ground attenuation

The values of the ground correction contributions depend upon source and receiver height, type of ground surface, distance between source and receiver, and whether or not screening occurs along the transmission path. The ground correction contribution can be positive or negative, indicating amplification or attenuation.

There are two types of ground characterization. Hard ground, e.g. asphalt, pavement, concrete, water[2] and ground surfaces with many scattering obstacles are considered acoustically "hard". All surfaces on which vegetation could occur and on which only a few scattering obstacles exist are regarded as acoustically soft. Examples such as grassland, agricultural ground with and without vegetation, woods, moors and gardens can be regarded as having an acoustically porous surface.

9.3.2.6 Attenuation due to propagation through vegetation

A curved transmission path is considered, illustrated by the upper path in Figure 28. A group of trees and bushes is considered dense if – along the transmission path – it is impossible to see through the vegetation, i.e. if the transmission path is visually blocked. It must consist of a number of groups, each having a transmission path length d_v of 50 meters (see Figure 28).

Furthermore, if the transmission path passes through a number of consecutive groups of trees and bushes, and each of these groups visually blocks the transmission path, a maximum of four groups may be taken into account. The vegetation height should exceed the height of the curved transmission path by one meter or more (see Figure 28). The transmission path height, h, above the straight line between source and receiver is given by:

$$h = \frac{(d_1 \times d_2)}{16 \times d} \tag{22}$$

where:

h is the transmission path height above the straight line between source and receiver;

d_1 is the horizontal distance from source to “screen” in meters;

d_2 is the horizontal distance from receiver to “screen” in meters;

d is $d_1 + d_2$ in meters.

The attenuation due to the vegetation, A_veg, is calculated by

$$A_\mathrm{veg} = -n_\mathrm{v} \times \alpha_\mathrm{v} \tag{23}$$

where:

n_v is number of groups of vegetation;

α_v is the attenuation coefficient per group (see Table 5 below).

If $n_\mathrm{v} > 4$, n_v is set equal to 4.

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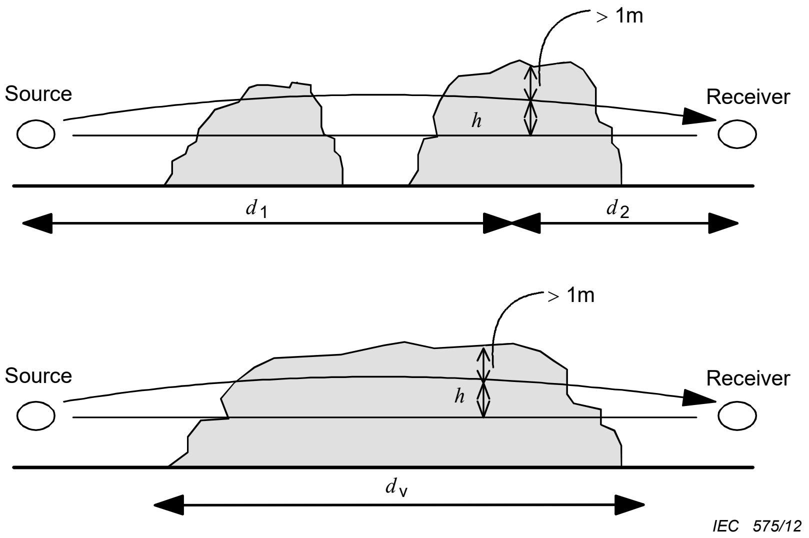
[2] When sound waves in air are incident on a water surface, the water is experienced as "hard". For sound incidence from water to air, the air is experienced as "soft".



Key

n_v = 2

$n_v = d_v/50$

Figure 28 – Definition of parameters used in Equation 22

Table 5 – Examples of attenuation coefficient values for octave bands

1/1 octave f_m [Hz]	63	125	250	500	1 000	2 000	4 000	8 000
α_v attenuation coefficient per group [dB/group]	0	0	1	1	1	1	2	3

The attenuation coefficient values are valid under both summer and winter conditions provided that the transmission path is visually blocked. Usually this is not the case in wintertime. If so, the values in the table above should be multiplied by 0,5.

As an example, a dense forest of 50 meters in depth gives a reduction of approximately one (1) dB(A).

9.3.3 Results presentation

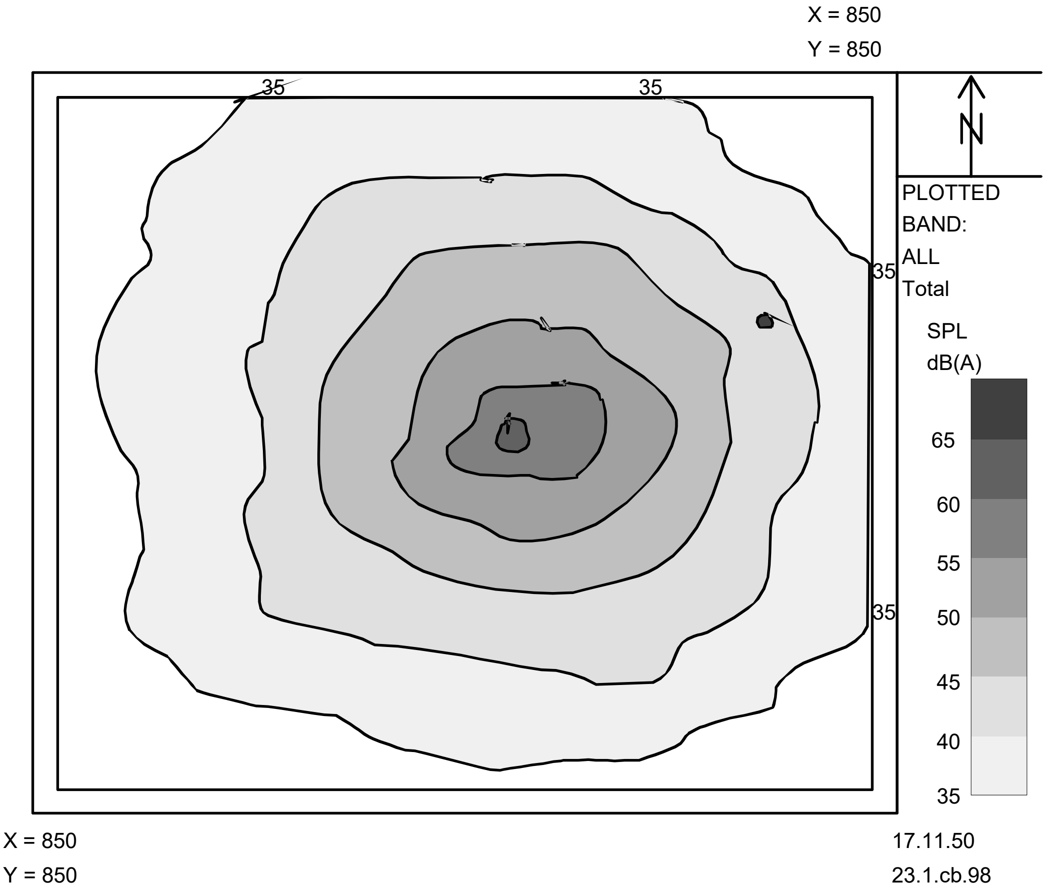
A practical and useful method for presenting and studying the results of the calculated predicted sound levels is essential. There are basically two different types of results presentation:

- graphical presentation of e.g. sound level contours with equivalent sound levels (see Figure 29);
- table with predicted sound levels at a number of receivers.

The graphical presentation of the calculated result gives an overall view of the predicted sound pressure levels in and around the substation, but no information about which sources are dominating the contribution at specific points.

The tabular presentation of results is especially useful if the table also contains the contribution from each source or group of sources (see Table 6) on a total level and for each frequency, forming a ranking Table 7. This presentation of results indicates on which equipment noise reduction measures should focus.

CASE No	RECEIVER	X	Y	Z	NAME
303	1	570,00	130,00	1,50	Nearest House



IEC 576/12

Figure 29 – Example of graphical presentation of sound pressure level calculation

Table 6 – Groups of noise sources

Group 1	Transformers and transformer
Group 2	Valve cooling fans
Group 3	Smoothing reactor
Group 4	PLC filter
Group 5	AC shunt capacitors
Group 6	AC shunt reactor
Group 7	11th capacitor and reactor
Group 8	13th capacitor and reactor
Group 9	24th capacitor and reactor
Group 10	36th capacitor and reactor

Table 7 – Ranking of noise sources

FREQ	All/Total		1 000	500	700	600	250	125	2 000	1 200	Other
RANK	dBA	Source	dBA	dBA	dBA	dBA	dBA	dBA	dBA	dBA	dBA
Tot:	40,6	-	35,6	34,5	29,6	29,4	27,8	27,1	26,1	25,9	25,0
1	34,3	Grp.1	29,3	29,4	7,8	8,6	23,2	21,2	23,1	-	26,1
2	32,6	Grp.10	29,8	27,4	-	-	-	-	19,7	20,2	20,7
3	32,5	Grp.9	29,9	27,6	-	1,3	-	-	19,6	19,1	17,1
4	32,0	Grp.3	26,4	25,3	-	27,7	-	-	-	23,1	12,2
5	31,1	Grp.8	20,0	17,8	29,5	19,7	-	-	9,8	-	21,3
6	29.5	Grp.7	19,5	17,2	-	22,4	-	-	9,4	-	27,5
7	28,9	Grp.6	-	21,7	-	-	25,1	24,8	-	-	4,4
8	25,7	Grp.4	23,1	22,3	-	-	-	-	-	-	-
9	23,4	Grp.5	-	18,8	-	-	17,8	19,2	-	-	-
10	12,3	Grp.2	-	9,4	-	-	4,4	-	-	-	7,4

NOTE 1 The dash symbol (-) in the table above indicates that the source does not contain this frequency.

NOTE 2 Each column in the table represents an octave or narrow frequency band. Each row represents a noise source or a group of noise sources. Reference octave band mid frequencies are used for showing the calculation result per sound source group.

10 Verification of component sound power

10.1 General

This clause describes methods for verifying the component sound power. There are three different approaches to verification:

- calculation;
- measurement:
  - sound pressure measurements in an acoustic measurement room or outdoors;
  - preferably following a standard for sound measurements;
  - sound intensity measurements;
  - vibration measurements;
- combination of calculation and measurement.

The sound requirements for HVDC substations are conventionally specified in terms of the maximum allowed sound pressure level at a specific contour or at specific points surrounding the substation. In order to meet this target, the contractor has to break down the sound requirements to the component level. The verification of the component sound power should be performed before the component is installed at site. Once all components are installed it is almost impossible to correctly determine the noise contribution of each individual component. Provided that the background noise level is low enough, it may however be possible to verify the total sound power level of a group of components at site, e.g. of an a.c. filter.

10.2 Calculation

10.2.1 General

Sound power is the most important acoustic quantity for characterization of a sound source. It is a basic parameter used for assessment and comparison of sound sources. It is a measure of the acoustic output of a source. The sound power level can be used to assess the effect of noise on the surrounding environment, which allows efficient noise management.

The calculation of sound power emitted by electrical components is conventionally divided into three steps:

a) the electrical forces are calculated:
   - electrostatic for capacitors;
   - electromagnetic for windings of reactors and transformers;
   - magnetostrictive for cores of transformers and iron-cored reactors;

b) the system response, or transfer function, is extracted;

c) the vibration amplitudes and the resulting sound power are calculated.

The procedure is outlined in Figure 30:

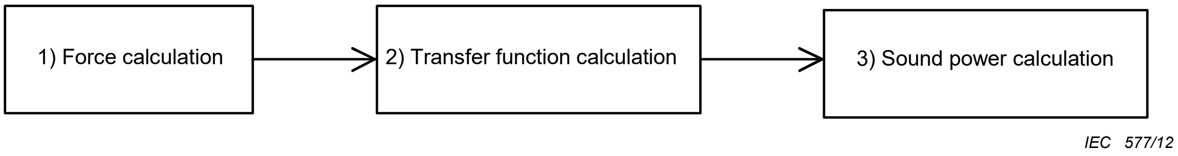


Figure 30 – Three steps to determine the sound power of HVDC components

10.2.2 Calculation of force spectrum

In the text below, the term "current" is used to describe the electrical load, but this term shall also be taken to cover "voltage". For details, see Clause 6 and in particular 6.2.4 and 6.4.2.

If a current energizes the component with a single a.c. frequency, this will result in an electromechanical force of twice the power frequency. This is however only true if no d.c. is present. With d.c. present, the power frequency will also appear in the force spectrum.

If the current consists of two frequencies, the force spectrum will contain two times the current frequencies and the sum and the difference of these frequencies. As an example, the fundamental tone 50 Hz and the 11th harmonic (550 Hz) would create force spectrum shown in Table 8.

Table 8 – Vibration force frequency spectrum resulting from the electrical fundamental frequency 50 Hz and its 11th harmonic

Force frequency Hz	**Derived from electrical frequencies** Hz
100	2 × 50
500	550 – 50
600	550 + 50
1 100	2 × 550

10.2.3 Transfer function calculation

When calculating the vibration amplitude from the applied force, the mechanical properties of a component play an important role. All electrical components are mechanical constructions, which possess natural modes of vibration; and each natural mode shape is associated with its resonance frequency and damping. The damping of the mode dominates the behavior of the response of the component close to the resonance frequency.

When a force is exciting a structure, a number of natural modes can participate in the motion. How much a mode will participate in the motion depends mainly on:

- how close the forcing frequency is to the resonance frequency of the mode;
- how large the damping of the mode is;
- the spatial force distribution has very low impact to the mode shape of vibration which is excited by the force.

The first and second reasons are obvious. Firstly, if the forcing frequency is the same as the resonance frequency, the structural vibration amplitude may be very large. Secondly, if one mode has a large damping compared to another, but both modes have resonance frequencies equal to the forcing frequency, the mode with the smallest damping will dominate the structural motion.

Thirdly, the vibration pattern, or the mode shape, of each natural mode, is very important. As an example, consider the can-type capacitor mentioned in 6.4.2. The excitation force on the capacitor is purely axial (see Figure 19). This means that the axial resonance frequencies of the capacitor will determine the radiated sound power. The resonance frequencies with mode shapes (and thus true motion) perpendicular to the exciting direction will also be excited by the electrostatic forces and will contribute to the sound power radiation, but to a much lower extent.

As an example of this discussion, consider the response between force and vibration amplitude of a mechanical system with one degree of freedom (1-DOF) in Figure 31. Near the resonance frequency, it is clear how important the damping is for the response of the system. For details about critical damping see [11].

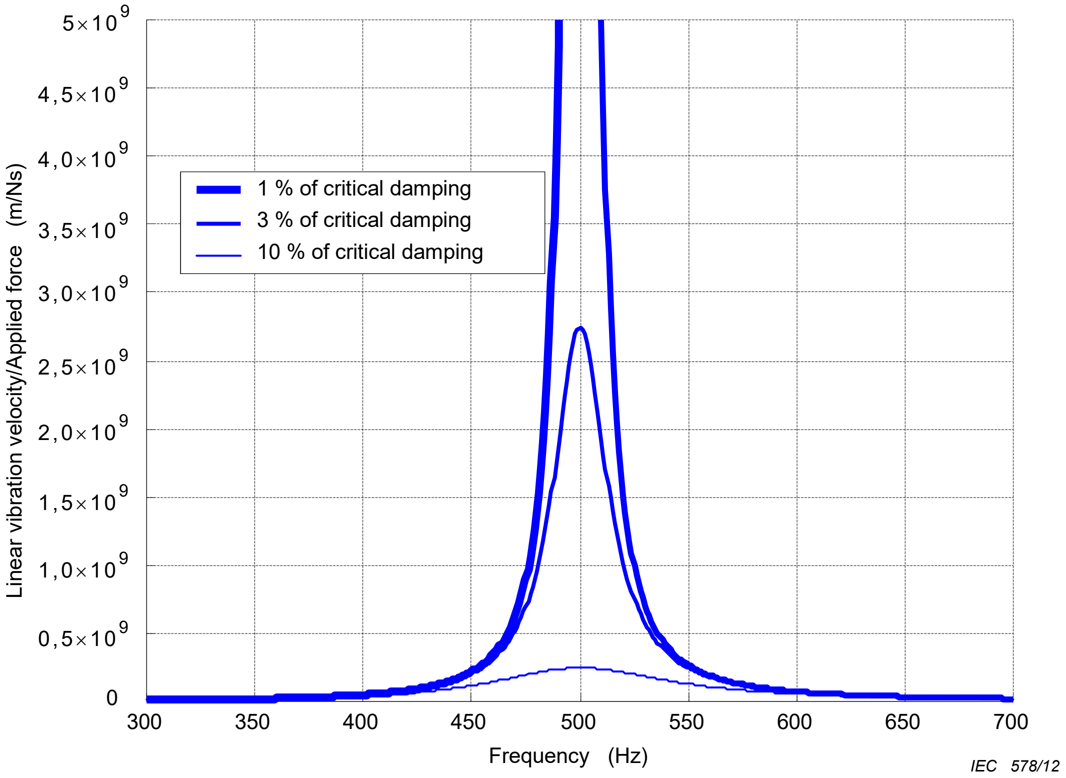


Figure 31 – Linear transfer function between e.g. force and vibration velocity for a 1-DOF system with the resonance frequency 500 Hz

10.2.4 Sound power calculation

Given a structural vibration velocity, v, the Equation (24) often gives a good estimation of the sound power in dB:

$$L_w = 10\,\lg\left(\frac{\rho c \times A \times \sigma \times \left\langle \tilde{v}^2 \right\rangle}{1 \times 10^{-12}}\right) \qquad (24)$$

where:

ρc	is the impedance of the surrounding fluid in Ns/m^3 (ρc = 410 Ns/m^3 for air);
A	is the area of the vibrating surface in m^2;
σ	is the radiation factor, or radiation efficiency (no unit);
$\left\langle \bar{v}^{2} \right\rangle$	is the squared and time averaged r.m.s vibration velocity of the vibrating surface in (m/s)^2;
1×10^{-12}	is reference level for sound power in W.

What sometimes makes Equation (24) uncertain is the radiation factor σ, as briefly described in 6.3.2. For example, for bending waves the radiation factor generally is in the range from $\sim 10^{-4}$ to 1. However for the breathing mode σ = 1 unless the wavelength of the sound is of the same order as the height of the reactor which decreases σ.

To achieve better accuracy of the radiation factor, BE (boundary element) or FE (finite element) methods could be used.

10.3 Measurement

10.3.1 General aspects on sound power determination

10.3.1.1 General

As mentioned in the introduction of this clause, sound power is the most important acoustic quantity for characterisation of a sound source. However, sound power cannot be measured directly with an instrument. There are several different methods to determine the sound power of an object. Each method has its benefits and drawbacks.

10.3.1.2 Classification of methods

The simplest and therefore the most common method to determine sound power is to use sound pressure measurements. Most of the standards are based on the measurement of sound pressure. This requires a sound level meter, which should have the capability to analyze the frequency content of the measured sound. One way to achieve this is to use a Fast Fourier Transformation (FFT) analyzer; another is to use real-time filters. The method either requires a measurement room (not necessarily an acoustic laboratory, though) or free field conditions and the use of an acoustic standard. ISO 3743-2 specifies a relatively simple engineering method for determining the sound power levels of small, movable noise sources. In this direct method the A-weighted sound power level of the source under test is determined from a single A-weighted sound pressure level measurement at each microphone position, rather than from a summation of octave-band levels. This method eliminates the need for a reference sound source, but requires the use of a special reverberation test room. ISO 3744 specifies methods for determining the sound power level or sound energy level of a noise source from sound pressure levels measured on a surface enveloping the noise source (machinery or equipment) in an environment that approximates to an acoustic free field near one or more reflecting planes. The sound power level (or, in the case of noise bursts or transient noise emission, the sound energy level) produced by the noise source, in frequency bands or with frequency A-weighting applied, is calculated using those measurements. ISO 3745 specifies methods for measuring the sound pressure levels on a measurement surface enveloping a noise source in anechoic and hemi-anechoic rooms, in order to determine the sound power level or sound energy level produced by the noise source. It gives requirements for the test environment and instrumentation, as well as techniques for obtaining the surface sound pressure level from which the sound power level or sound energy level is calculated, leading to results which have a grade 1 accuracy. ISO 3746 specifies methods for determining the sound power level or sound energy level of a noise source from sound pressure levels measured on a surface enveloping a noise source (machinery or equipment) in a test environment for which requirements are given. The sound power level (or, in the case of noise bursts or transient noise emission, the sound energy level) produced by the noise source with frequency A-weighting applied is calculated using those measurements. Although having the benefit of being simple, sound pressure measurements can be sensitive to background noise and reflections. Furthermore, the safety of personnel must be considered when using any measurement technique, which involves working in the proximity of energized equipment.

The sound intensity method reduces the influence of background noise provided that it is constant during the measurement. This makes it possible to perform measurements in an environment, which would not be ideal for sound pressure measurements. ISO 9614-1 and ISO 9614-2 specify a method for measuring the component of sound intensity normal to a measurement surface which is chosen so as to enclose the noise source(s) of which the sound power level is to be determined. The one-octave, one-third-octave or band-limited weighted sound power level is calculated from the measured value. The method is applicable in situ or in special purpose test environments to any source for which a physically stationary measurement surface can be defined, and on which the noise generated by the source is stationary in time. The method is more time consuming and requires more experienced personnel to give an accurate result. Correctly performed though, the intensity measurement is a very accurate way to determine the sound power, but is for safety reasons great care has to be taken if audible noise measurements are done in HVDC substations.

10.3.1.3 Directivity

Vibration patterns on sound emitting components often create noise radiation with a spatial non-symmetry – the noise radiation is said to have directivity. These directivity effects cause maxima and minima of the sound in some directions. When sound pressure measurements are performed, it is important that a sufficient number of measurement points are used to get a good average of the spatial variations of the sound pressure level. Otherwise large errors in sound power determination may be the result. The same principles regarding the number of measurement points hold for vibration and sound intensity measurements as well. Recommendations are given in the acoustic standards, for example, ISO 3744.

Another example of directivity is the result of the actual placement of the noise source in relation to reflecting surfaces. This is explained in 3.2.1 and is of course very important to bear in mind when sound power determinations are performed.

10.3.1.4 Test environment

Sound power verifications at a manufacturer's works may be complicated due to space limitations. Firstly, the manufacturer may not have a special test area designated for acoustic measurements. Secondly, high background levels may make sound pressure measurements hard to perform. However, it is usually possible to find a test location at the factory, which fulfils the requirements of an acoustic standard, even if is outside in the car park or involves working at night when background levels are reduced. Requirements for acoustic test environments are given in the acoustic standards (see ISO 3745, ISO 3744 and ISO 3740).

Furthermore, in a test laboratory it not always possible to produce the high currents and/or voltages which exist at site. Also, on site, the load spectrum consists of several harmonics. In the test laboratories, it is more practical to excite a component with one frequency at a time and at a smaller load than will occur in normal operation. The sound power at normal, full load can then be calculated according to scaling laws (see e.g. Equation (9)). For this procedure to work, the test load must give sound levels higher than the background noise levels (recommendations are given in relevant standards).

If it is necessary to verify the sound power of an object with very high accuracy, it may be necessary to use specially designated acoustic test rooms, e.g. anechoic chambers or reverberation rooms. In these cases, the manufacturer could work with acoustic consultants and/or universities. These kinds of measurements should be exceptions though, as it is impractical, time consuming and expensive to use such acoustic test rooms.

10.3.2 Sound pressure measurement

As already mentioned, the sound pressure measurement is a simple method for measuring radiated sound, and is therefore most commonly used. However, sound pressure measurements are sensitive to noise produced by sources other than the object to be measured and to reflections. To avoid ambient influences, sound pressure measurements are usually performed in test laboratories or in special outside test areas at the component manufacturers [12].

Since the sound level distribution measured around sound sources is usually non-uniform, it is necessary to assess noise levels on spatial average figures gained from several measurement positions rather than from one single position. The measurement positions should be located on the surface of a hypothetical envelope enclosing the source. The average sound pressure level ($\overline{L}_{p\mathrm{A}}$) is calculated from the measured values of the A-weighted sound level ($L_{p\mathrm{A}i}$) in dB by using the following equation:

$$\overline{L}_{p\mathrm{A}} = 10\,\lg\left(\frac{1}{N}\sum_{i=1}^{N}10^{0{,}1L_{p\mathrm{A}i}}\right) \qquad (25)$$

where:

N is total number of measurement points.

The A-weighted sound power level ($L_{W\mathrm{A}}$) of an object (in dB) may be determined from the average sound pressure level, $L_{p\mathrm{A}}$, according to the following equation;

$$L_{W\mathrm{A}} = L_{p\mathrm{A}} + 10\,\lg\left(\frac{S}{S_0}\right) \qquad (26)$$

where:

S is the area of the envelope in square meters and S_0 is a reference area of 1 m^2 (see Figure 32).

This procedure is valid only if the measurement points are located at approximately the same distance from the acoustical centre of the sound source. If however, the background noise level is too high to allow an accurate determination of the sound power of the test object, the sound pressure method will not give reliable results. However, under these circumstances, the sound pressure method will always give a value for sound power, which is too high. If this high value of sound power still meets the required limit (guarantee value), then it may not be necessary to make further measurements. If a more accurate value is required, measurements should be performed closer to the sound source and another measuring method should be used.

Specific noise level is defined here as the "true" noise level of a measured object. If the background noise level is within 10 dB of the total measured noise level, it is necessary to correct the total noise level for the influence of background noise. Theoretically this is possible, as long as the background noise level does not exceed the specific noise level, but in practice the correction will be very uncertain if the difference is small, i.e. only a few dBs. Some ISO standards set this lower limit to 6 dB.

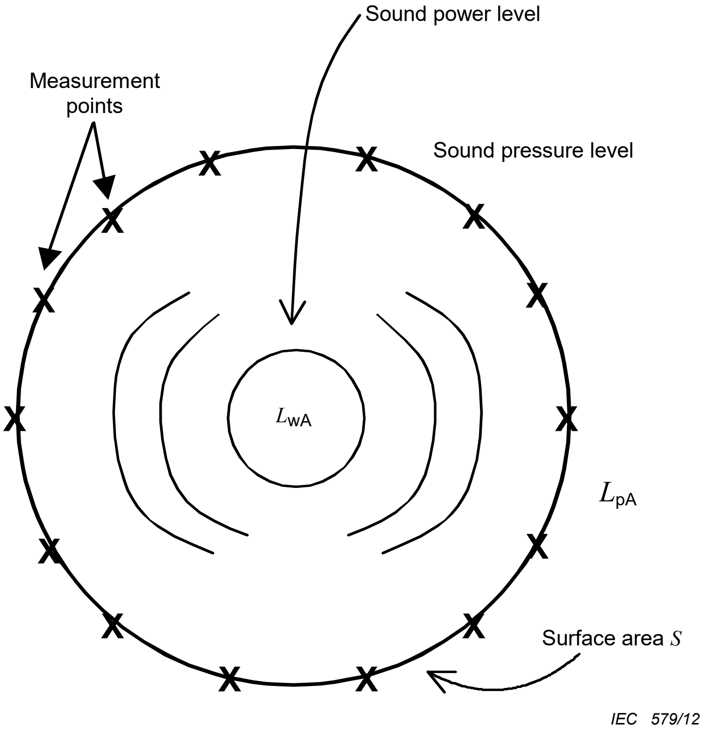


Figure 32 – Definitions of the parameters used in Equation (26)

10.3.3 Corrections for background noise

Equation (27) gives the relationship between the total measured noise level $L_{p,\mathrm{t}}$, the background noise level $L_{p,\mathrm{b}}$ and the (true) specific noise level $L_{p,\mathrm{s}}$ (dB).

$$L_{p,\mathrm{s}} = 10\,\lg\left(10^{(L_{p,\mathrm{t}}/10)} - 10^{(L_{p,\mathrm{b}}/10)}\right) \tag{27}$$

10.3.4 Sound intensity measurement

Sound intensity is defined as sound energy emitted by a sound per unit time flowing through unit area in a direction perpendicular to that area. It is computed as a vector quantity equal to the time-averaged product of the instantaneous sound pressure and its corresponding instantaneous particle velocity. The component of intensity in the direction r is given by

$$\vec{I}_r = \langle p(t) \times v_r(t) \rangle \tag{28}$$

where:

$\vec{I}_r$ is sound intensity in direction r;

$p(t)$ is instantaneous sound pressure;

$v_r(t)$ is instantaneous particle velocity in direction r.

NOTE Symbol < > implies a time average.

In contrast to sound pressure, which as a scalar quantity has only magnitude, sound intensity is a vector quantity with both magnitude and direction.

The sound pressure of Equation (28) can be measured by a simple method using one or several microphones. It is however difficult to measure the particle velocity directly, but it can be determined by measuring the sound pressures p_1 and p_2 with two microphones along the vector r at r_1 and r_2 ($r_1 > r_2$).

Sound intensity can then be determined from the following expression:

$$\vec{I}_r = \frac{1}{2\rho\Delta r}\left\langle (p_1 + p_2)\int_0^t (p_1 - p_2)dt \right\rangle \tag{29}$$

where:

p_1, p_2 is the sound pressure measured at r_1, r_2;

Δr is the distance between the two microphones (= $r_1 - r_2$);

ρ is the mass density of the environment (for air, ρ is 1,2 kg/m^3 at 20 °C).

Sound power can be calculated by integrating the sound intensity around an enclosing surface (imaginary contour), which completely surrounds the sound source:

$$W = \oint_A \vec{I}\,\overrightarrow{dA} \tag{30}$$

where:

W is total sound power;

$\vec{I}$ is intensity vector measured by the sound intensity meter;

$\overrightarrow{dA}$ is element of surface area A.

The sound radiated by the sound source always travels out from the source through the imaginary contour. Sound radiated by external sources (including sound from reflecting obstacles), i.e. those outside the imaginary contour, will flow into this hypothetical volume and then out of the region on another side. Hence, this "external" sound will not contribute to the total integral. Consequently, sound intensity measurement allows discrimination between the test object sound power and that produced by other constant sound sources.

In practice, an enclosing surface of integration has to be chosen which is close to the sound source in order to increase the signal-to-noise ratio for the sound intensity measurement. One has to spatially average over the entire surface by sweeping the sound intensity probe over a region of surface for an adequate time, or to measure at a number of discrete measuring points. During the measurement period, the background noise has to be constant. Otherwise there will be a difference in ambient energy entering and leaving the surface of integration, because all the measurement points on this surface are not measured at the same time.

To conclude this subclause, sound intensity measurement can be a useful tool in some cases, but requires more experience from the personnel.

10.4 Combination of calculation and measurement

10.4.1 General

The sound power of a component must be determined for the full, normal operational loading, which means the correct voltage for capacitors and the correct current for reactors. The power frequency of the test load must be correct. Based on the relationship between load and sound power for an electric component, it is however possible to use a test load during the measurement and to scale the sound power to correspond to the operational loading. For capacitors, the sound power level is proportional to voltage to a power of four, (U^4) and for air-cored reactors it is proportional to current to a power of four, (I^4).

To illustrate the procedure, an example is given. Assume that sound pressure measurements have yielded a sound power for a capacitor of 56 dB(A). The test voltage used was 1/5 of the planned operating voltage. The sound power under real operating conditions will therefore be $56 + 10\lg(5^4)$ dB(A) = $56 + 40\lg(5)$ dB(A) = 83 dB(A).

For transformer cores, there is a linear relationship between voltage and sound power up to a certain value of the magnetic flux density. For flux densities greater than this value, the relationship is extremely non-linear. Sound power determination at flux densities other than the ones where linear conditions prevail would therefore be subject to errors. In these cases, it is necessary to rely on measurements.

Two methods for sound power determination are summarized: the verification of individual components (at the manufacturer's) and the verification (of several components) at site. See 10.3 for further details.

10.4.2 Verification of key components

The two general methods for determining the sound power of individual components are summarized in Table 9.

Table 9 – Summary of different methods for sound power determination

Method	Required equipment	Benefits	Drawbacks
Sound pressure	Sound level meter, preferably together with an Fast Fourier Transformation (FFT) analyzer or real-time filters	– simple and relatively fast – less expensive measuring equipment – physically correct measurement of sound power if measured in the acoustic near field	– requires sound kind of measurement room or free-field conditions – sensitive to background noise and reflections – overestimates the sound power level systematically if measured in the acoustic near field
Sound intensity	Sound intensity equipment	– when correctly performed, probably the most accurate method – not sensitive to constant background noise – a good tool for diagnostic purposes	– time consuming – needs two microphones and special software, more expensive equipment than for sound pressure measurement – for safety reasons not applicable to HVDC substations

10.4.3 Verification of key components at site

The most common method to use for sound power verification at site is the sound pressure measurement. It might however be very difficult, if not impossible, to verify the sound power of an individual component, e.g. the components of an a.c. filter. One exception may be the smoothing reactor, which normally dominates the noise in its vicinity. Vibration measurements can however give a fair estimation of a component's sound power.

When the verification measurements at site are performed, the actual values of the current I, voltage U, etc., should be recorded. These values should be compared with the ones used for noise predictions for the site. If there are large discrepancies between the current and/or voltage values used for predictions and the values during verification measurements, the predictions might be repeated with the updated values of the voltage and/or current.

When measuring sound pressure on an object, which generates tonal noise, it is important to use a rotating boom or to measure the noise at a great number of points in order to get a good spatial average. Otherwise the sound power determination will be subject to errors due to interference effects of the tonal sound field. Recommendations can be found in ISO 3744.

11 Verification of sound levels from the HVDC substation

11.1 General

Depending on electric load, background harmonics related to the a.c. network, meteorological variations and irregularities in the measurement environment (e.g. reflecting obstacles), the sound level at any point around a site will fluctuate considerably during a period of 24 hours. This is important to bear in mind, both for those defining the noise requirements and for those who perform sound level measurements.

The verification of specified sound levels is normally performed by measurements at the receiver location, often corresponding to the nearest inhabited house. In cases when the background noise level at the receiver locations is high, perhaps higher than the allowed contribution from the HVDC substation, measurements at the receiver will not give the required information (see 10.3.2 for details about background noise). In such cases, sound level measurements closer to the HVDC substation are necessary. These results allow the expected sound level at the receiver location to be calculated by considering the additional attenuation over distance (see 9.3.2 and 3.2).

If a suitable measurement point between the nearest inhabited houses and the substation cannot be found, sound pressure measurements close to or within the substation are necessary. These measurements are used to determine the sound power level of the multi-source plant, and hence to evaluate the sound pressure levels outside the substation. Such measurements may however suffer from interference phenomena due to the complexity of the sound field. If a simple measuring method has been used, e.g. a stationary microphone at just a few locations, the measured sound pressure levels may contain great variations depending on the spatial location of the microphone. This problem may be solved by using a rotating microphone with a radius of at least half the wavelength of the lowest frequency of interest.

There are in practice two approaches to sound measurements in HVDC substations. The first approach is to verify the result (in terms of Sound Pressure Level) of the customer requirements directly and the second is to determine the sound power (in terms of Sound Power Level) of the sound sources. The first type of measurement is often made at some distance from the HVDC substation. In this case the problem is how to extract the sound from the plant from the background sound. Often these measurements have to be performed over longer periods of time to get a good time average where the influences of meteorological influences are averaged out. The difficulty with the second type of measurements is that there are several sound sources and also high voltages which make it impossible to get close to the sound source. The solution may be to measure at different distances from the sources, as the law of distance then can be used (see also 9.3.2).

One further method for evaluating the overall sound power level of multi-source industrial areas is given in ISO 8297.

11.2 Acoustic environment

When measuring sound inside or near an HVDC substation, there will normally be pure tones and electromagnetic fields present. The sound measuring equipment thus has to be suitable for this environment. Condenser microphones should be used because dynamic microphones are influenced by the magnetic fields. Therefore it may be necessary to use a measuring technique that evaluates the sound sources from a distance. Also, the analysis instruments should be of two types: real time analyzers for sound level information and frequency analyzers for quantifying the total content and identifying individual noise sources.

The sound field outdoors, in the substation and in the vicinity, may be similar to the standing wave pattern of discrete tones indoors in a reverberation room. There are many different sound sources emitting sound at discrete frequencies. When many sources emit the same frequency, or when there are reflecting obstacles adjacent to a source – thus acting like "mirror sources" – an interference pattern is formed. At one point, the contribution from several sources, at the same frequency, will be in phase resulting in a high sound level whereas at another point the level will be lower because of destructive interference. The distance between these minima and maxima depends on the wavelength in air of the sound involved. Therefore sound measurements always have to be performed with rotation or translation of the microphone, or a sufficient number of measurement positions has to be used. In practice this is achieved either by moving a hand-held sound level meter in a circular motion during the measurement or by using a microphone mounted on a rotating boom. At larger distances from the substation, of the order of hundreds of meters, the microphone may be substationary because the transmission path attenuation fluctuates due to variations in meteorological conditions. Over long distances, the intensity of the interference patterns decreases due to ground reflections, wind, temperature gradients etc.

11.3 Conditions for verification

There are four main factors, which affect the sound pressure level measured at a specific point and these are:

- operating conditions of the sound sources (see Clause 8);
- meteorological conditions (see Clause 4);
- type of ground and topography included (see Clauses 4 and 9);
- background noise (see Clauses 4 and 10).

The operational state of the sound sources is important because the sound radiated from the sources is dependent on the currents and voltages present in the sources during the measurement. Weather conditions can affect the measured sound levels in a complicated way, as described in Clause 4. When verification measurements are performed, special meteorological conditions normally have to be fulfilled (see ISO 1996-2):

- wind direction within an angle of ± 45 degrees of the direction connecting the centre of the dominant sound source and the receiver, with wind blowing from source to receiver;
- wind velocity of between 1 m/s and 5 m/s, measured at a height off to 10 m above ground, or equivalently, propagation under a well-developed, ground-based temperature inversion.

Among the meteorological parameters temperature, humidity, pressure, cloudiness precipitation and wind, wind is the most important parameter. See Clause 4 for details.

11.4 Calculation

Calculations are very helpful tools when designing and planning HVDC substations. They give indications of the acoustic performance of the substation. Very often it is however necessary to rely on calculations combined with measurements as described in 11.6.

11.5 Measurement

Sound level measurements, for the purpose of verifying if a specified sound level requirement is fulfilled, has to involve several measurements over time. One single short measurement will not give a correct representative result. The measurement time for each single measurement of the equivalent sound pressure level L_{eq} from a constant sound source shall be at least 1 minute. For night-time measurements, at least three such measurements, with at least one hour between the measurements, shall be used to form an energy equivalent average. For daytime measurements, five different single measurement periods shall be used.

The measurement time is chosen to fit the meteorological conditions for moderately downwind sound propagation. It will normally be long enough to average out the effects of a varying wind velocity over several gusts with a measurement time in the range of 10 minutes to one hour.

11.6 Combination of calculation and measurement

In some cases, measurements of the sound level originating from the converter substation may be impossible at a remote receiver location, e.g. due to high background sound levels. In such a case measurements can be performed closer to the substation, between the source and the receiver. The expected sound level at the receiver location can then be calculated based on the measured level at a point between the source and receiver. This method can give reasonably accurate results provided the landscape is fairly smooth and there are no obstacles in the transmission paths.

The sound pressure level is measured at point A and is then calculated at point B by using the measurements at point A. For example, in Figure 33 if the sound pressure level measured at point A is 50 dB(A) the calculated pressure level at point B is equal to $L_B = L_A - 20 \lg (b/a)$, i.e. $L_B = 50 - 20 \lg(500/200) = 42$ dB(A).

Sometimes measurements between the source and receiver, as described above, may be impossible to perform due to e.g. difficult terrain, dense traffic on nearby roads or other circumstances disturbing the sound level measurements. Then measurements close to the different sources at site can be done and the source sound power level calculated. These calculated source sound power levels are then used for predicting the expected sound pressure levels at the receiver points by calculation alone. Calculation is then performed as described in Clause 9.

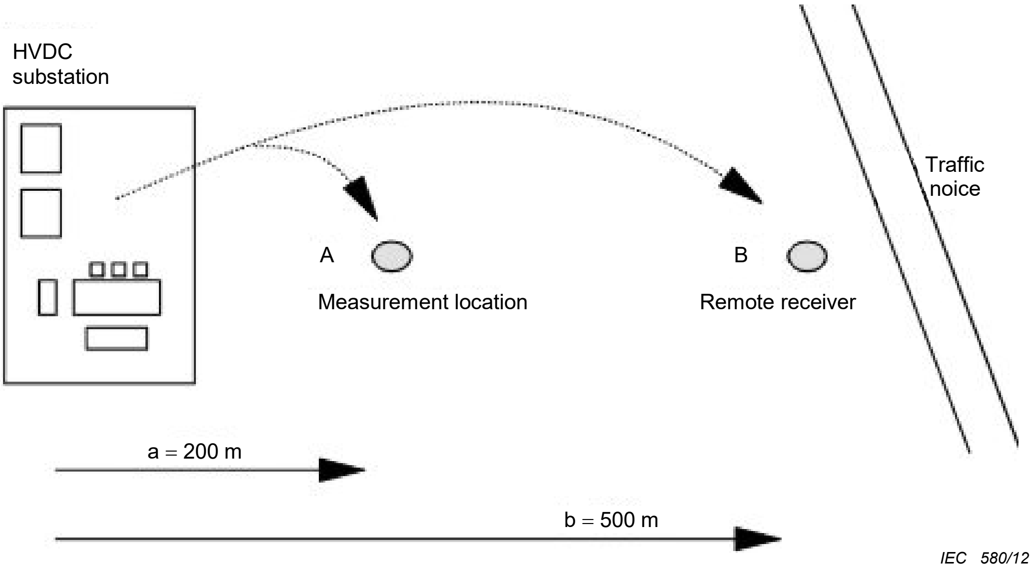
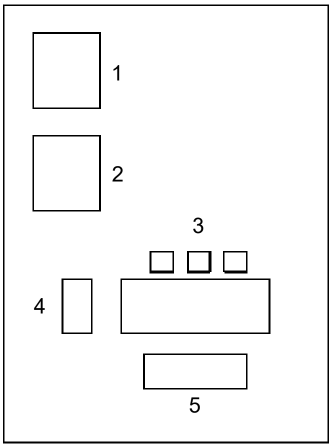


Figure 33 – Combination of calculation and measurement in determining the sound pressure level

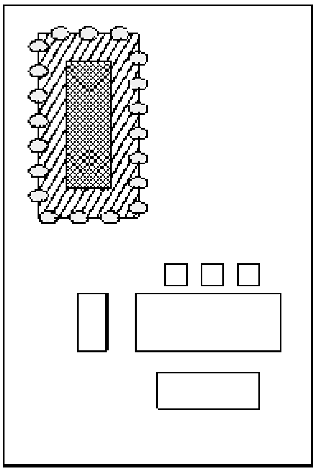
Practical limitations often make it impossible to study one single source by this measuring technique. Instead the substation can be divided in larger sub-sources, e.g. a.c. filter, transformers, valve cooling fans, d.c. filter (see typical layout in Figure 34). Suitable measurement methods can then be chosen for sound level measurements around these different parts of the substation. Also for these measurements around larger groups of sound sources there are often limitations for the microphone height, for example due to overhead buswork. Sometimes a desired microphone location is not accessible due to fences or safety regulations at site. In each different case a practical method has to be found, based on specific circumstances at site. Figure 35 shows an example of measurement positions around the a.c. filters for sound pressure level measurements for determining the sound power of the complete filters.



1 AC filter 1
2 AC filter 2
3 Converter transformers
4 Cooling system fans
5 DC yard

IEC 581/12

Figure 34 – Example of layout of noise sources of an HVDC substation



○ Microphone positions
▩ Area covering sources
▨ Measurement area

IEC 582/12

Figure 35 – HVDC substation and example of microphone positions for determination of sound power levels

There are instructions (see ISO 8297 and [10]) defining the area of the measurement surface depending on the area covering the sound sources, defining the distance from source area to the measurements points, number of measurement points, microphone height and how to use the results of the sound pressure level measurements to determine the sound power level of the source.

12 Parameters to be specified

12.1 General

This clause deals with data and information required for the acoustic design of an HVDC substation. The clause also covers the subsequent verification of the sound levels in and around the substation. Examples are given of the specification data, which is required for audible noise concerns. The data can be used as a checklist for an HVDC substation for the design of audible noise. The list intends to contribute to more rational acoustic design of HVDC substations.

For planning the HVDC substation in the given situation, it is often helpful to get an acoustical report about the current situation at site containing actual background measurements.

12.2 Noise level measurement

Existing regulations specify applicable conditions for an acceptable measurement. The following requirements may be specified:

- number and duration of measurements at single points required to secure a representative description of the sound level;
- measuring equipment to be used;
- allowable distances between obstacles and microphones;
- weather conditions, e.g. wind direction and maximum allowable wind speed.

In addition to these conditions, it is important that the "measurement accuracy" is described, i.e. the measurement uncertainty. An example of how this may be written is 45±3 dB.

12.3 Data to be presented by customers, or to be investigated by contractors

12.3.1 Land-use classification, noise regulation and limits

a) Land-use classification of the site for the HVDC substation

A map shall be presented, preferably a topographical map of the area which defines the classification of the land where the substation will be located (see Table 10). This map shall also define the type of surrounding areas as well as the location of the nearest neighbors, commercial, public or industrial. See also Clauses 4, 5 and 11.

Table 10 – Land use classification

	industrial area		commercial area		residential area
	recreation area		other area		

NOTE 1 Enclose the land-use classification map if a border with other land-use classification exists near the site.

b) Noise limits for the site for each time of day

Reference to applicable noise regulations shall be given, as well as the location of the points where these regulations shall be met. Also specific requirements during different hours of the day, if applicable, shall be noted (see Table 11). The presence of other acoustic regulations, e.g. corrections for tonal components or short-term noise shall be defined (see Table 12).

Table 11 – Existence different noise limits at different times

Noise limit, dB(X)/dB(A)	Time of day

NOTE 2 Limits in terms of sound power level or sound pressure level dB(X) could be e.g. dB(L) or dB(C), where L means Linear (no weighting) and C means C-weighting

Table 12 – Existence of noise limits due to further regulation

Item	yes	no
Existence of another regulation for single or special frequency		
Existence of another regulation for short time noise		

Identify all applicable noise regulations. Indicate from what regulation the limits have been derived.

c) Location for the noise limit(s) (see Table 13)

Table 13 – Definition of noise limits at different locations

	At the fence surrounding the substation		At the border of customer's property
	At a given distance from the centre of the substation		At the border of a nearby property
	At a given distance from the fence surrounding the substation		Other point

Illustrate the location point on the map.

12.3.2 Environmental condition

a) Existing background noise levels during verification measurements

Existing background noise levels influence the results of the subsequent verification measurements of the HVDC substation, as they are present at the area where the substation will be located (see Table 14). The levels of background noise sources, e.g. existing installations, road noise or air traffic noise, are usually depending of the time of day. Such noise sources should be acoustically mapped and the information submitted in the specification. If the background noise levels cannot, or have not, been determined in advance, they have to be presumed during the verification measurements.

Table 14 – Existence of background noise limits at different locations and different times

Maximum background noise, dB(X)/dB(A)	Location	Time of day

b) Topography (see Table 15)

Table 15 – Compilation of relevant topographical features

Item	yes	no
existence of reflective mountain or hill		
existence of high undulation		

NOTE 1 Attach the contour map if marking "yes".

c) Meteorological condition for verification of audible noise requirements (see Tables 16 and 17)

Table 16 – Compilation of relevant meteorological conditions

Maximum temperature (°C)	Minimum temperature (°C)
Maximum humidity (%)	Minimum humidity (%)

Table 17 – Compilation of further noise related weather conditions

Item	yes	no
existence of a strong wind*		
existence of heavy snow*		

NOTE 2 Explain the contents if marking "yes". These factors may have a significant impact on sound propagation.

d) Neighbors (see Tables 18 and 19)

Table 18 – Existence of additional locations with relevant noise limits

Location of nearest neighbor (commercial, public or industrial) where noise requirements must be fulfilled

Table 19 – Possibility of future development

Item	yes	no
high possibility of a nearer neighbor in future		

NOTE 3 Applicable if sound requirements are specified at adjacent properties. Attach a sketch, drawing or map.

e) Others (see Table 20)

Table 20 – Other sources of audible noise

Item	yes	no
existence of a substation or a power substation nearby		
existence of corona noise from the transmission line		
existence of a significant noise source nearby		

12.3.3 Operation condition of HVDC substation

a) Normal operating conditions

The operating conditions for the substation, during the acoustic verification measurements, need to be specified in detail (see Tables 21 and 22).

NOTE Clause 8 contains information regarding conditions to consider.

Table 21 – Definition of operating condition during audible noise measurement

Maximum power %	Minimum power %	Maximum voltage kV	Minimum voltage kV	Negative Phase Sequence(NPS) %
Harmonics in a.c. voltage (%)	3rd	5th	7th	others
Maximum frequency Hz	Minimum frequency Hz			

Table 22 – Further conditions relevant for audible noise measurement

Power system condition to be considered

b) Operating conditions for noise control design

List the parameters, which are to be considered outside normal operating conditions.

12.4 Data to be clarified by contractors

12.4.1 Noise of components

The list of audible noise sources planned to be installed should be prepared (see Table 23).

Table 23 – List of audible noise sources to be installed

Component’s name				
Noise level, dB (X) / dB (A)				
Sound reduction measures				
Method of sound measurement				
Method of sound correction (e.g. "scaling", see 10.4)				
Voltage and current condition				
Note				

12.4.2 Noise prediction of the HVDC substation

The acoustic design includes predicting the contribution from the substation to the surrounding area. The results of this process are normally presented in a report describing the calculation method, sources included, the results and possible noise reduction measures necessary (see Table 24).

Table 24 – Contents of an audible noise prediction report

Operating conditions and other assumptions	
Method of sound calculation	
Substation layout	Show on the map
Result of sound calculation dB (X) / dB (A)	Show on the map or as a table

12.4.3 Noise measurement on the site

Verification measurements normally follow existing rules and regulations. The results of all the work is presented in a report describing the measurement method, instrumentation, operating conditions, weather conditions and measured levels (see Table 25). An assessment regarding the fulfillment of the requirements is also done in this report as well as suggestions about possibly necessary reduction measures.

Table 25 – Contents of an audible noise measurement report

Date and time					
Method of sound measurement					
Measuring instruments					
Measuring location points (show on the map)					
Measured noise levels, dB (X) / dB (A)					
Weather condition					
Operation condition					
Note					

Annex A
(normative)

Procedure to correct for background noise in HVDC and SVC plants

Sound sources in electrical power plants such as HVDC and SVC are mainly transformers, air core reactors, shunt reactors and capacitors. The total sound power emission is characterized by discrete tonal contribution starting with the fundamental frequency at double the main electrical frequency (100/120 Hz for 50/60 Hz systems). Power control circuits, with the thyristor switching combined with different tuned electrical filters causes multiple harmonics up to 1 kHz for SVC and 2 kHz for HVDC.

A-weighted logarithmic addition of all tonal contributions constitutes the total sound impact from a plant.

Background sound level, in a traditional measurement situation, is the sound level without the plant contribution. Sound from HVDC/SVC-plants is normally very stable with variations only related to the voltage/current circulating in the circuits. Background noise, on the other hand, can change very fast in an uncontrolled manner.

If a measurement is made in narrow band the correction for the background can be done frequency by frequency. Highest accuracy, in the correction procedure, is achieved when each tonal contribution is corrected for the background level on both sides of the measured tone taken during the same measurement during the same time sequence.

The same procedure is also possible for a frequency resolution up to 1/24 –octave bands when the highest harmonic frequency is < 2kHz. If a measurement is made in 1/3 – octave band the correction for the background can only be done by switching the plant on/off. There is no clear visual information of the tonal contribution in a 1/3 octave spectrum. A change in the background level, between "on and off", will be unknown and the correction accuracy becomes very uncertain.

Illustrating case

Sound contribution from an SVC:

$$\overline{L}_{pA} = 10 \lg \left(10^{0,1\overline{L_{pA0}}} - 10^{0,1\overline{L_{bA}}}\right) \qquad \text{(A.1)}$$

where;

L_{pA0} is the measured sound pressure level at an identified tone;

L_{bA} is the measured background sound noise to the left/right of the zone.

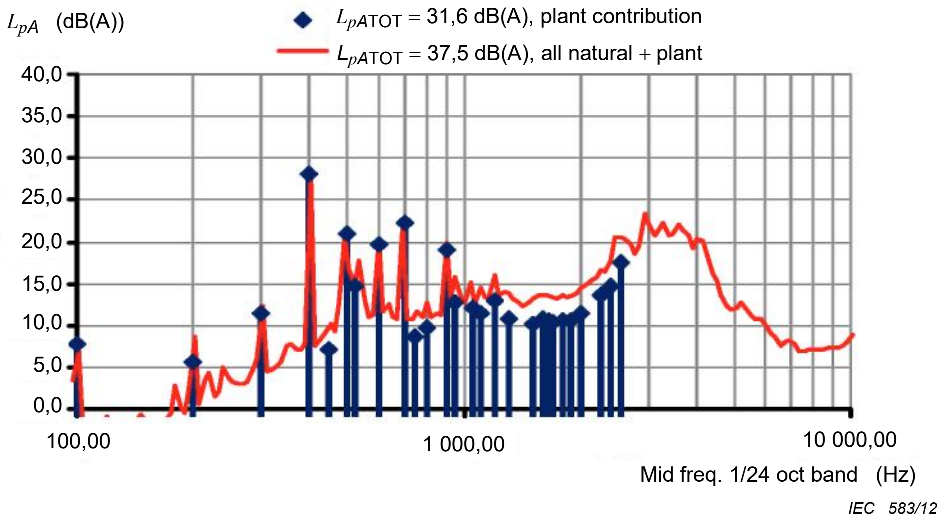


Figure A.1 – Example of a background correction at 1/24 octave band resolution

Example of a background correction at 1/24 octave band resolution (Figure A.1) gives the opportunity to distinguish tonal source (SVC) from a real background measured during the same conditions. A contribution from a fan must be treated separately – first measured on/off – and then added back into the total spectrum before summing up the total 1/3 octave band plot.

Table A.1 – Total sound level for the SVC example

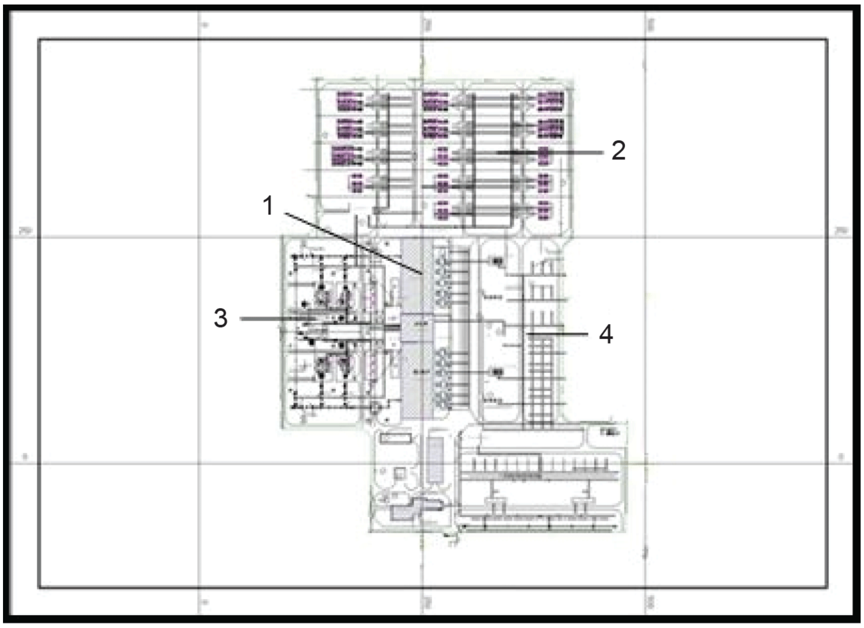
Frequency: Hz	Plant contribution L_{nA} dB (A)	All Natural + Plant L_{nA} dB (A)
100	7,9	6,9
200	5,6	8,6
300	11,4	12,3
400	28,0	28,1
450	7,1	10,1
500	20,9	21,1
525	14,6	17,6
600	19,6	20,2
700	22,4	22,7
750	8,7	11,7
800	9,8	12,8
900	19,1	19,9
950	12,7	15,7
1 050	12,1	15,1
1100	11,5	14,5
1 200	13,0	16,0
1 300	10,9	13,9
1 500	10,2	13,2
1 600	10,7	13,7
1 650	10,6	13,6
1 700	10,4	13,4
1 800	10,5	13,5
1 900	10,5	13,5
2 000	11,4	14,4
2 250	13,6	16,6
2 400	14,8	17,8
2 550	17,5	20,5
L_{nAtot} [dB (A)]	< 31,6	37,5

Total sound level is measured to 37,5 dB (A) and the plant contribution is < 31,6 dB (A).

Annex B
(informative)

Typical twelve-pulse and dual twelve-pulse HVDC substation layouts

The converter valve hall is the largest building in the HVDC substation, so its layout is very important. The typical twelve-pulse HVDC substation layout is shown in Figure B.1.



IEC

Key

1 valve hall and transformer

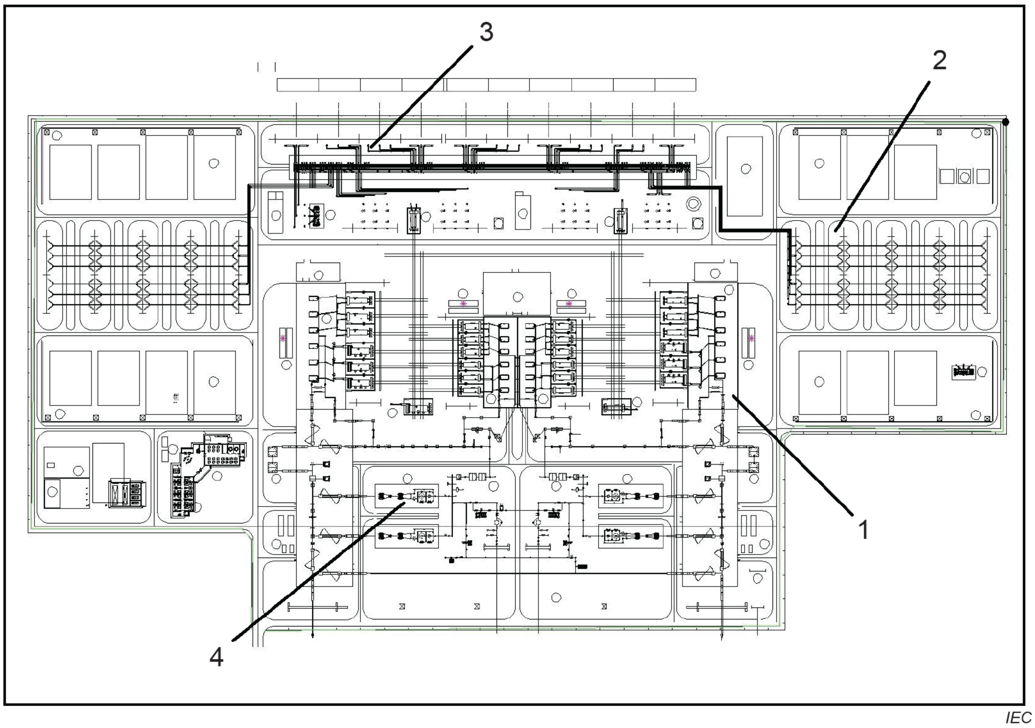
2 AC filter

3 DC switch yard

4 AC switch yard

Figure B.1 – Example of typical twelve-pulse HVDC substation layout

For the dual twelve-pulse forms, the valve hall can be arranged in face-to-face form, the converter transformers arranged on the inside of the buildings, which have significance for controlling the noise of the HVDC substation. The typical dual twelve-pulse HVDC substation layout is shown in Figure B.2.



Key

1 valve hall and transformer

2 AC filter

3 AC switch yard

4 DC switch yard

Figure B.2 – Example of dual twelve-pulse HVDC substation layout

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