

WG 14.26
HVDC STATIONS
AUDIBLE NOISE

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0. HOW TO USE THE GUIDE

The principle purpose of the Guide is to give specific recommendations to those responsible for preparing the audible noise aspects of Technical Specifications for HVDC projects, evaluating the proposed designs and monitoring the subsequent project.

The main objective is to enable future Technical Specifications to be written, and informed judgements made, such that the resulting outdoor audible noise levels fulfil applicable regulations and standards.

A diverse group including various manufacturers, utilities and consultants has written the Guide and the recommendations, which respect the interests of all parties.

Different readers can use this Guide in different ways:

- An engineer preparing a Technical Specification can find the key points, which must be considered, highlighted throughout the Guide.
- The Guide emphasises aspects where the specified requirements can, perhaps unintentionally, have a significant impact on the audible noise design and costs. A user issuing a Technical Specification should consider how these aspects apply to that Specification.
- For evaluating proposed designs and technically monitoring the project, a deeper understanding of many aspects will be required. This document contains guidance reflecting the accumulated knowledge of many HVDC projects, and so will be of value even to highly experienced users. It should help a Customer to understand the reasons for differences among audible noise designs offered by a Contractor.
- While making specific recommendations, it has also been necessary to provide a considerable amount of background material. Much of this information has never been brought together under one cover before, and so the Guide will provide a valuable source of reference.
- Additionally, the Guide contains much material, which will be of relevance in power industry applications other than HVDC, for example in the design of AC substations. Applicable parts of the Guide can also be used for the same purpose for SVC and FACTS devices.

The Guide has been clearly set-out in sections, each covering specific areas of audible noise design. For guidance on any particular subject, each section may be read individually. Cross-references to other sections are made where necessary.

The following brief description of the contents of each section is intended to assist the reader to use the Guide in the most appropriate way.

- For any reader, it is recommended to start with the short introductory sections 1 and 2, which justify the production of this document, discuss what a Technical

Specification should attempt to achieve and indicate which aspects are optional for inclusion.

- Section 3 summarises audible noise related definitions; e.g. sound pressure, sound power and sound intensity.
- Section 4 mainly deals with the performance of surveys related to the acoustic environment and the results thereof, which are specified by the Customer. The environment has been divided into three areas: background noise, topography and meteorological conditions.
- In section 5, audible noise regulations are discussed in terms of e.g. land use classification, typical limits and measurement requirements. It also includes descriptions of different boundaries where audible noise limits shall be fulfilled.
- Section 6 gives a detailed overview of sound-emitting components within an HVDC station. The mechanisms of sound generation for each component are also described.
- Possible sound reduction measures are thoroughly discussed in section 7. The different measures are divided into one group related to a component's original design and a second group dealing with remedial measures that can be taken after audible noise verification.
- Section 8 discusses the importance of specifying clearly under which operation conditions the audible noise requirements shall be fulfilled.
- In section 9, which is an essential section, focus is put on methods for modelling audible noise from whole plants as well as procedures for calculation.
- Section 10 presents verification methods for individual sound-emitting components. Both measurement and calculation methods are dealt with.
- The final aim with this Guide is to present methods for verification of the overall audible noise design of HVDC stations. In section 11 such verification techniques are thoroughly discussed.
- A summary of all the important parameters and requirements which must be specified by the Customer in a Technical Specification is given in section 12. This summary lists the key points, which have been discussed in depth elsewhere in the Guide, and makes suitable cross-references.

1. GENERAL ASPECTS OF SPECIFICATIONS

A Technical Specification has several essential purposes. Primarily it defines the technical data and features of the equipment to be purchased. In doing so, it may define in detail many aspects of the equipment design, or may restrict itself to describing the system conditions, the main constraints under which the equipment must perform, and the performance requirements. It will attempt to enforce uniformity of certain aspects of design within the converter station and its surrounding environment. It will ensure compliance with the requirements of HVDC system operation. Finally, a Specification issued for tender purposes will attempt to provide a basis on which competitive designs can be fairly evaluated and compared.

If a Technical Specification is poorly written, it can have a negative impact on a project, possibly leading to:

- overdesign or underdesign,
- different interpretations by different contractors,
- long-running discussions,
- re-design during the project,
- contractual and legal conflict.

There is therefore a strong incentive for those preparing Technical Specifications to eliminate these risks by stating precise and unambiguous definitions of their requirements, based on realistic technical knowledge.

In general, this Guide assumes that the purchase of an HVDC converter station will be made on a turn-key or similar basis; this has been the case for practically all HVDC schemes to date. The discussions herein (e.g. on provision of technical information and allocation of risks) therefore apply principally to such an all-inclusive approach. If an alternative approach of specifying and purchasing equipment item by item was adopted, then these aspects of the Guide would have to be reconsidered in the context of the particular scheme, although the purely technical content of the Guide would still be applicable.

The Technical Specification defines the technical basis for a contract between two parties, who in this Guide will be referred to as the “Customer” and the “Contractor”.

- The “Customer” is the organisation, which is purchasing the HVDC converter station. The term “Customer” is taken to cover similar terms, which may be used in specifications, such as Owner, Client, Buyer, Utility, User, Employer and Purchaser, and also covers a Consultant representing the Customer.
- The “Contractor” has the overall responsibility for delivery of the HVDC converter station as a system, and may in turn contract one or more sub-suppliers of individual items of equipment. The term “Contractor” is taken to cover similar terms, which may be used in specifications, such as Manufacturer, Supplier, Tenderer and Bidder.

1.1 Boundaries of responsibility

Before a Technical Specification enters into the detail of audible noise design requirements, it should first clearly define the boundaries of responsibility between Customer and Contractor.

In this respect, there are two extreme approaches:

- a) The Customer defines the acoustic environment, the sound level limits to be satisfied by calculation, the calculation method, and all parameters to be taken into account. The Contractor then makes studies and audible noise designs based on this information, and has the responsibility to prove, to the satisfaction of the Customer, that the proposed design complies with all the specification requirements. The risk of the HVDC station not performing according to local or regulatory requirements with respect to audible noise, under operating conditions, lies mainly with the Customer.
- b) At the other extreme, the Customer defines only that applicable regulations shall be fulfilled, i.e. there must be no audible noise problems. The Customer may also specify field tests to confirm that applicable limits are not exceeded. Most risks in this case lie with the Contractor.

In practice, most Technical Specifications adopt an approach which lies somewhere between these two extremes. The decision will depend on the strategy of each individual Customer and on the information and resources available to the Customer. The Customer should be aware that, if the Contractor has to assume risks, there might be a corresponding impact on pricing. This Guide does not recommend a particular approach, but rather provides the detailed information necessary to guide decisions in this respect.

It is strongly recommended that the Customer carefully considers this question at an early stage, and that the boundaries of responsibility and delivery are clearly defined in the Technical Specification according to the Customer's decision. The more detailed technical requirements of the Specification should then follow. Failure to make a clear definition of responsibility, and to ensure that the detailed requirements of the Specification are in accordance with the general definition of responsibility, creates risks of contractual conflict, delay and possibly unsatisfactory audible noise performance.

Most essentially, the Specification must define whether the criterion by which the audible noise performance is to be judged as satisfactory is to be:

- demonstration by calculation of performance requirements, using specified data,
- or
- measurement in the field after commissioning,
- or
- a combination of the above.

Demonstration by calculation ensures that the worst-case conditions can be taken into account, but is susceptible to erroneous data or flawed calculation methods. Measurement in the field may be considered as the definitive proof of correct design, but it may not be possible to make measurements under the most onerous environmental conditions for which

the station has been designed. Also, the effect of background noise must be taken into account by measuring background audible noise with the HVDC converters de-energised, i.e. the HVDC station stopped and isolated. Demonstration by measurement requires that the HVDC station is built, but it is more difficult to reduce noise levels retrospectively.

A combination of demonstration by calculation followed by field measurement therefore provides the Customer with the greatest assurance that the audible noise performance will be satisfactory. Furthermore, the effect of the 'actual' AC Network compared to the 'specified' one must be considered in the evaluation.

1.2 Scope of studies

Depending on the boundaries of responsibility discussed above, some investigations and measurements may need to be conducted by the Customer prior to issuing the Technical Specification, or may be the responsibility of the Contractor. These investigations/measurements would normally include:

- identifying applicable regulations,
- obtaining plans for the surrounding landscape, both today and for the future,
- measuring background audible noise levels.

The extent of system studies, factory testing and field verifications required from the Contractor should be made clear in the Technical Specification. A minimum set of studies and verifications will normally be required to ensure that the audible noise requirements are fulfilled; these comprise:

- a) overall sound level prediction;
- b) calculation or measurement of sound from individual noise sources;
- c) field verification after commissioning of the HVDC scheme

1.3 Technical data to be supplied by contractor

At the tender stage of an HVDC project, the prospective Contractors are normally required to supply technical data regarding their proposed designs to the Customer. This data is used by the Customer to qualify the proposed design technically and to allow comparisons to be made between competing Contractors. The Technical Specification should define exactly what technical data is to be supplied, otherwise there is a risk that the information supplied by different Contractors will not show possible weaknesses in design or will not enable fair comparisons to be made. Aspects where particular attention should be paid include:

- method and assumptions for audible noise calculations,
- proposed field verification method,
- under what precise conditions the audible noise requirements shall be fulfilled with respect to harmonic (either voltage or current) generation (for short duration, e.g. overload or emergency conditions, higher levels of audible noise may be permitted)

After contract award and during the design and procurement stage of the project, the Contractor will normally produce technical Study Reports and other documents covering aspects of the audible noise design. The Technical Specification (or another part of the agreement between Customer and Contractor) should make clear whether these are to be approved by the Customer and, if so, define an adequate procedure which allows time for examination of such material by the Customer, possible subsequent modification, and approval, within the intended project time schedule.

2. INTRODUCTION AND OBJECTIVES

This document is a Guide to the specification and evaluation of outdoor audible noise from HVDC stations. It is intended to be primarily for the use of the utilities and consultants who are responsible for issuing Technical Specifications for new HVDC station projects and evaluating designs proposed by prospective Contractors.

The term “Technical Specification” or “Specification” used in this Guide is taken to mean the document, which defines the overall operational system requirements for the HVDC stations. Such a document is normally issued by utilities to the prospective HVDC Contractors. It also ensures uniformity of proposals and sets guidelines for the evaluation of bids and follow-up of contract implementation.

2.1 *Introduction*

Audible noise can be defined as a series of pressure waves in air at frequencies, which can be perceived by the human ear. Noise may consist of a monofrequency acoustic signal (pure tone) or of sounds containing a distribution of frequencies.

The generation of sound by electrical components is mainly dependent on vibration in structures caused by electrical stress, either as a result of applied voltages across the component or currents through the component. Most mechanical structures have several structural resonance frequencies. 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 resonance frequencies.

As a consequence of the AC/DC conversion process, voltage and current harmonics are produced at both the AC and DC sides. These harmonics are then applied across, or through, the components within the converter station. Thus sound with different tones and magnitudes may be excited.

In practice, a number of HVDC schemes have reported problems with audible noise, normally when residential or recreation areas are located nearby. These noise problems may have occurred because recreation areas are noise-sensitive areas, or because of the added annoyance caused by pure tones.

It must also be pointed out that the science of sound, including the generation of audible noise, is “exact” only for some special cases. For most commercial software, simplifications in the modelling of noise sources, reflecting planes, etc., are always made to allow numerical solutions to acoustic problems. Furthermore, due to the impact of all the possible environmental parameters such as topography, weather conditions, atmospheric inversion layers, screening effects and ambient sound etc., it is impossible to repeat exactly a series of outdoor acoustic measurements. The reason is that the sound pressure level in any position will show both short-term and long-term fluctuations over time.

One of the fundamental problems encountered when designing an HVDC station is achieving accuracy in modelling not only the sound-emitting components within the station, but also

the landscape surrounding the station. This requires an accurate prediction tool in the design process. It is advisable to have further optional mitigation measures, even though the sound calculations indicate that the noise regulations will be fulfilled.

One final area of difficulty is the verification of the overall audible noise design. The problem is not so much related to measuring equipment, but to the method of measurement. Definition of audible ambient conditions is essential, which in many cases may lead to timing problems, e.g. the opportunity for performing correct measurements may occur within a very narrow time-frame.

2.2 Objectives

In preparing this Guide, Working Group 14.26 undertook as its scope of work to:

- examine existing audible noise specifications for HVDC stations and consider their relative merits,
- consider field experience and draw conclusions,
- take note of other relevant work in e.g. Cigré and IEEE,
- investigate modelling procedures and compare to field measurements,
- examine different field measurement methods and consider their relative merits,
- investigate the audible noise performance of known noise sources within an HVDC station,
- investigate noise mitigation measures,
- make recommendations based on all of the above,
- provide information to facilitate reasoned decisions in the preparation of future Technical Specifications, the evaluation of prospective designs and follow-up of contract implementation.

In doing so, the Working Group sought to bring together the experience, and consider the interests, of all sectors of the HVDC community and to produce a Guide which, while primarily intended for the use of utilities and consultants, will be of interest to all parties.

The Guide attempts to review all possible aspects to be covered in a specification and the subsequent design evaluation, and to give a more detailed analysis of critical or contentious points.

The technical background to each subject area is described briefly, and reference is made to further sources of information in order to provide the background and context for the decisions to be made.

Where it is possible to make clear recommendations, these are given in the Guide. In other instances, where there may be different ways to approach these aspects, then the different approaches and their consequences are described. The intention in such instances is to enhance awareness of the implications of different approaches.

The Guide gives a comprehensive treatment of most aspects of the subject. This does not imply that a Technical Specification needs to mention all the aspects included in this Guide; for example it would depend on the proposed location of the station. However, while

preparing any Specification, those responsible should at least be aware of, and consider, all the points discussed in this Guide. In the eventual design evaluation phase, most of the material included in this Guide will be of relevance.

3. DEFINITIONS

For the purpose of this Guide, the following definitions apply.

3.1 *Sound and noise*

Sound may be defined as any pressure variation in air, water or other medium (for this Guide, the medium is assumed to be air). Sound may be expressed as either sound pressure, sound intensity or sound power, see below. Noise may be defined as unwanted sound.

3.2 *Sound pressure, p*

Sound can be quantified by sound pressure, p , and can be considered as a fluctuating pressure superimposed on the static pressure. It is expressed in Pascals.

3.3 *Sound pressure level, L_p*

It is customary to express sound pressure, through the use of a decibel scale, as sound pressure level.

The sound pressure level (L_p), in decibels (dB) is defined by

$$L_p = 20 \lg \left(\frac{p}{p_0} \right) \quad (3-1)$$

where p is the measured rms (root-mean-square) sound pressure and p_0 is a reference rms pressure of 20×10^{-6} Pascal, which corresponds to the threshold of audibility. Sound pressure level is measured with sound level meters, which normally incorporate a frequency-weighting network to the measurement. Usually "A-weighting" is applied because it differentiates between sounds of different frequency in a similar way to the human ear. Measurements in dB(A) generally agree with people's assessment of "loudness". There are however other frequency weightings, e.g. "C-weighting", which takes low frequencies into account much more than the traditional A-weighting. For more information about sound level meters and A-weighting see IEC Publ. 60651, 1979, "Sound Level Meters".

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.

The average sound pressure level ($\overline{L_{pA}}$) is calculated from a number of measured values of the A-weighted sound level L_{pAi} by using the following equation:

$$\overline{L_{pA}} = 10 \lg \left(\frac{1}{N} \sum_{i=1}^N 10^{0.1 L_{pAi}} \right) \quad (3-2)$$

where

$\overline{L_{pA}}$	=	average sound level in dB(A)
L_{pAi}	=	measured sound level at location “i” in dB(A), possibly corrected for the influence of background noise
N	=	total number of measurement locations

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

$$L_{pA,TOT} = 10 \lg \left(\frac{1}{N} \sum_{j=1}^N 10^{0.1 L_{p(f_j)}} \right) \quad (3-3)$$

where

$L_{pA,TOT}$	=	total sound level in dB(A)
$L_{p(f_j)}$	=	sound level in frequency band “j” in dB(A), possibly corrected for the influence of background noise
N	=	total number of frequency components

See Section 3.10 for more information about 1/3-octave and 1/1-octave bands.

3.4 Normal sound intensity, I_n

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

$$I_n = \frac{p^2}{\rho \cdot c} \quad (3-4)$$

Here p is the rms value of the measured sound pressure in Pascals, ρ is a constant density of air in equilibrium in kg/m^3 and c is the speed of sound in air in m/s.

3.5 Normal sound intensity level, L_I

The value in decibels is equal to the ratio of the normal sound intensity to the reference sound intensity ($I_0 = 1 \times 10^{-12} \text{ Wm}^{-2}$),

$$L_I = 10 \lg \left(\frac{|I_n|}{I_0} \right) \quad (3-5)$$

N.B.! 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. Equation (3-4) however assumes a plane propagating wave in the far-field of a sound source, in the direction defined as positive.

3.6 Sound power, W

Sound power is the rate at which sound energy is radiated by a source. It is a scalar quantity and is expressed in Watts. The total sound power of a source is defined as

$$W = \oint_A \vec{I} \cdot d\vec{A} \quad (3-6)$$

Here A is a closed surface of integration and $\vec{I}$ is vector of sound intensity on an elementary surface $d\vec{A}$.

3.7 Sound power level, L_W

As for sound pressure, sound power may also be expressed in a logarithmic scale as sound power level.

The sound power level (L_W), in decibels (dB) is defined by

$$L_W = 10 \lg \left(\frac{W}{W_0} \right) \quad (3-7)$$

where W is the emitted sound power and W_0 is a reference power of 1×10^{-12} W, corresponding to the threshold of audibility.

The A-weighted sound power level (L_{WA}) of an object may be determined from the average sound pressure level L_{pA} according to

$$L_{WA} = L_{pA} + 10 \lg \left(\frac{S}{S_0} \right) \quad (3-8)$$

where S is the area of the “measurement surface” enclosing the object (in square metres) and S_0 is a reference area of 1 m^2 . The sound power within an enclosing surface is independent of the distance to the sound source.

3.8 Sound propagation

The sound pressure level at a given point depends on the distance from the source, the source sound power and the geometry involved. For hemispherical propagation over a reflecting plane the following equations apply:

$$L_p = L_w - 10 \lg(2\pi r^2) \quad (3-9)$$

or alternatively

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

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. Where the far-field begins 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 30 metres distance from the transformer. For a small reactor which radiates sound at e.g. 1 kHz, the far-field may begin at 5 metres distance.

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.

3.9 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 3.2.

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

The relation between sound power, directivity and sound pressure level is given by

$$L_p = L_w - 10 \lg \frac{4\pi r^2}{Q} \quad (3-10)$$

where

- L_p = sound pressure level at distance r from the sound source
- L_w = sound power of the sound source
- r = distance between the source and the receiver
- Q = directivity of the sound radiation, e.g.
 - $Q = 1 \Rightarrow$ spherical sound propagation (see Figure 3-1)
 - $Q = 2 \Rightarrow$ hemispherical sound propagation (see Figure 3-2)
 - $Q > 2 \Rightarrow$ non-uniform sound propagation (see Figure 3-3)

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

$$DI = 10 \lg Q \quad (3-11)$$

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

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:

$$L_p = L_w + DI - 10 \lg 4\pi r^2 \quad (3-12)$$

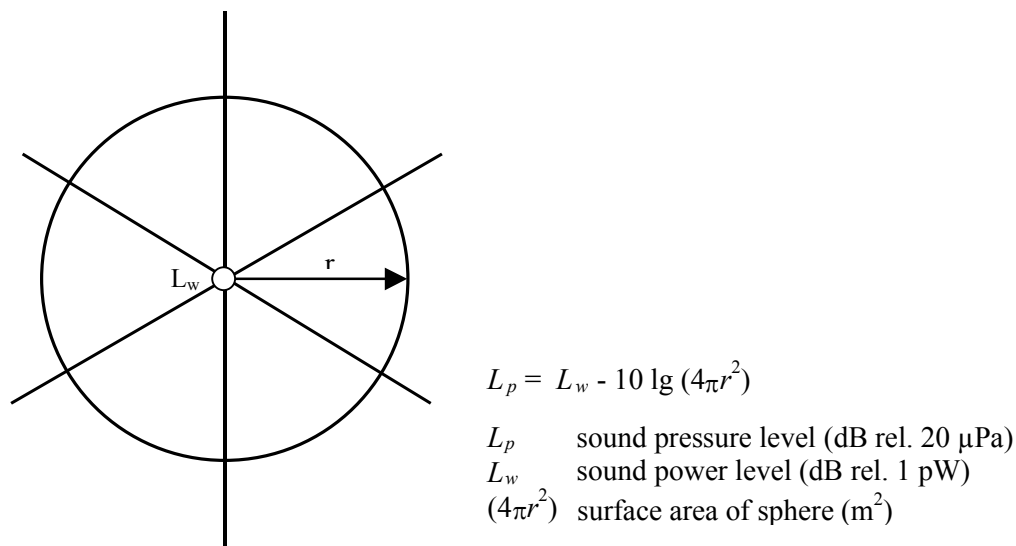


Figure 3.1. Spherical spreading in a free-field from a point source.

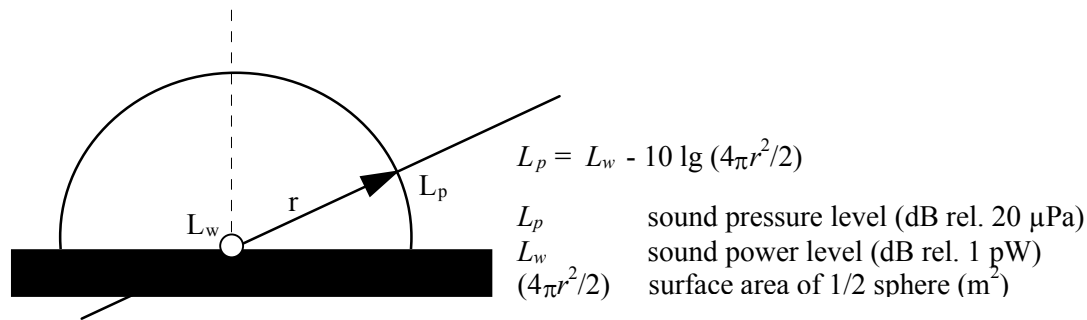


Figure 3.2. Hemispherical spreading from a point source.

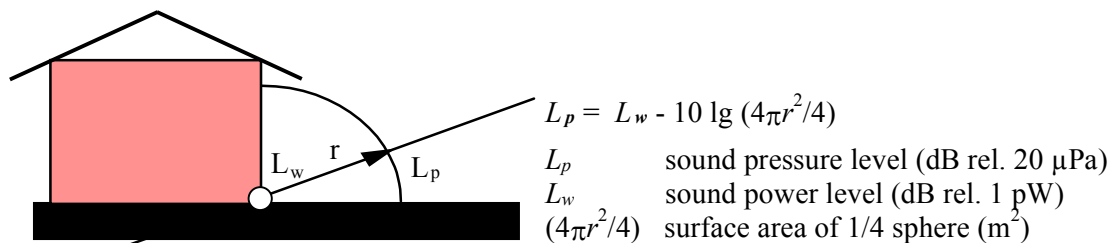


Figure 3.3. Quarter-spherical spreading from a point source.

3.10 Sound measurement filters

Standard filters used for sound measurement equipment measure the total level of sound pressure in a defined frequency band. 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 21, 31.5 and 40 Hz 1/3-octave bands.

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

$$f_2 = 2^a f_1 \quad (3-13)$$

Here $a = 1$ for the "octave" filter and $a = 1/3$ for the "1/3 octave" filter.

The centre frequencies of the filters to be used should meet applicable standards.

In accordance with ISO standard R266, IEC R266 or IEC R255 and ANSI S1.11_1966, class III the following set of centre-frequencies for the "octave" filter apply: 16, 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000, 16000. For the "1/3 octave" filter, the set of centre-frequencies is 16.0, 20.0, 25.0, 31.5... up to 17780.0, 22390.0.

3.11 Reflecting Plane

A reflecting plane is defined as any surface, which fully reflects sound.

3.12 Principal radiating surface

A principal radiating surface is a hypothetical surface surrounding the test object, which is assumed to be the surface from which sound is radiated.

3.13 Prescribed contour

A prescribed contour is a horizontal line on which the measuring positions are located spaced at a defined horizontal distance (the "measurement distance") from the principal radiating surface.

3.14 Measurement distance, X

The measurement distance X is the horizontal distance between the principal radiating surface and the "measurement surface".

3.15 Measurement surface

A measurement surface is a hypothetical surface enveloping a sound source. The measurement points are located on this surface. The measurement surface terminates on one or more reflecting planes.

3.16 Background noise

The background noise is the sound pressure level with the test object inoperative (in this case, the test object can be the whole HVDC station or a single component).

3.17 References

- [1] *IEC 60651*, 1979, Sound Level Meters with amendment No 1, 1993
- [2] *IEC 60551*, 1987, Determination of transformer and reactor sound levels
- [3] *IEC 60551*, Amendment No 1, 1995, Power transformers and reactors – Determination of sound levels
- [4] *ISO 1996*, Description and measurement of Environmental Noise

- [5] *IEEE 1127*, 1998, IEEE Guide for the Design, Construction, and Operation of Electric Power Substations for Community Acceptance and Environmental Compatibility
- [6] ANSI S1.11 1996 "Octave-Band and Fractional Octave-Band Analog and Digital Filters, Specifications"

4. ENVIRONMENTAL INFLUENCES

When sound is emitted from a source, the surrounding environment influences how the sound propagates and is perceived over distance. This section 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 metres).

4.1 Background noise

In the situation where a specific noise is heard or measured at a given measuring point, background noise is the sound still heard at the point when the specific noise stops. As shown in Figure 4.1, the specific and background noise level together give the total measured level.

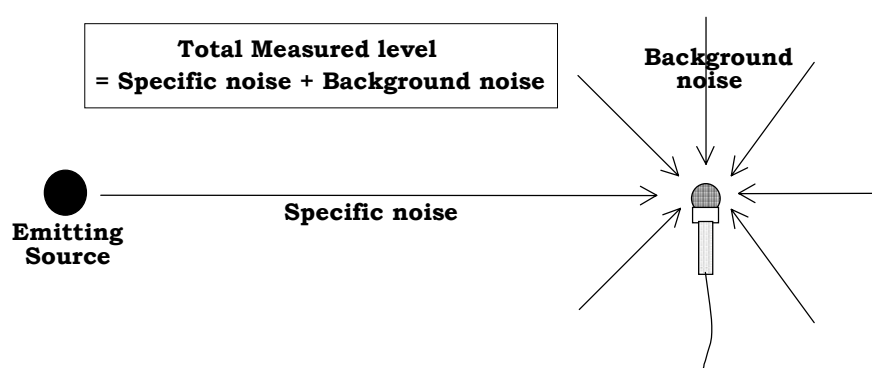


Figure 4.1. Explanation of specific and background noise.

At a proposed location for an HVDC station, there will always be existing background noise. 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 recognise 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.

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 station 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 (see Section 10.3.2.1 for details about background noise).

4.2 Topography

The topography surrounding HVDC station 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 the station 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 4.2, 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.

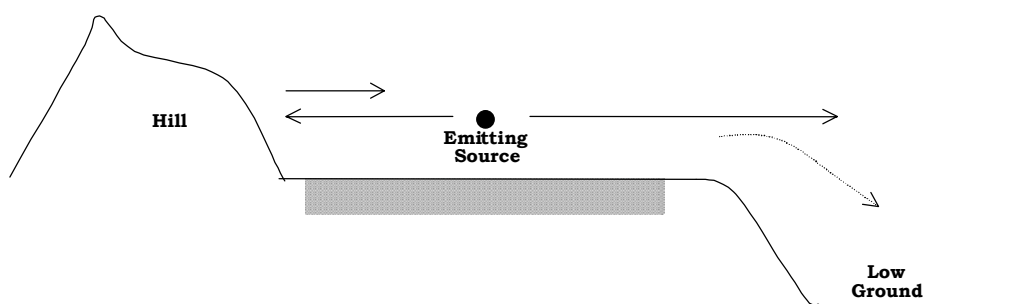


Figure 4.2. Example of reflecting hill and low ground.

Therefore, when an accurate calculation of the sound emitted by a HVDC station 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.

4.3 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 station 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 4.3 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.

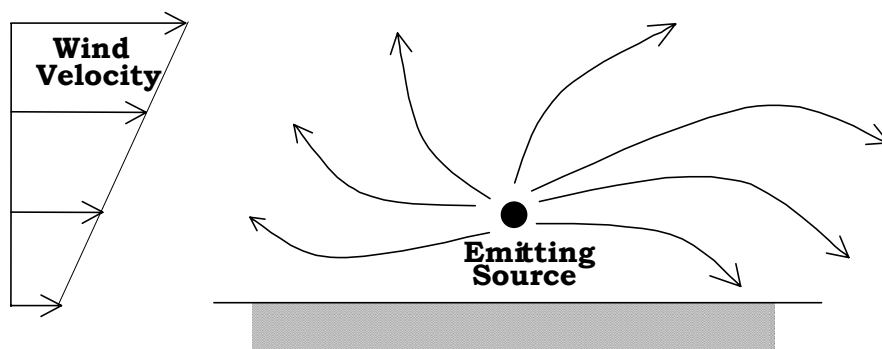


Figure 4.3. Example of sound refraction with the shown wind gradient.

For example, if there is a strong prevailing wind in the area selected for an HVDC station, sound levels will be lower on the upwind side than on the downwind side. Careful consideration of this may enable optimisation of the design of the station 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 below, Figure 4.4 and Figure 4.5). Consequently, sound attenuation for an observer at ground level is reduced for the condition shown in Figure 4.5. This phenomenon usually occurs at night.

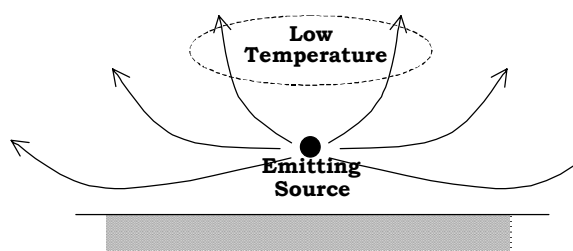


Figure 4.4. Sound travels faster near the ground.

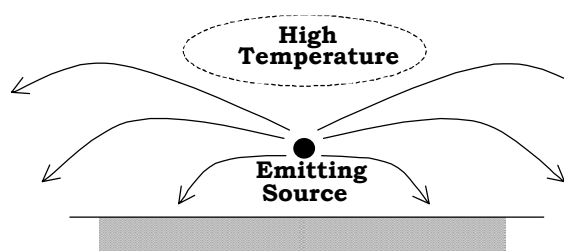


Figure 4.5. Sound travels slower near the ground.

(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 (O₂) and nitrogen (N₂) molecules mainly cause the absorption. On the whole attenuation is so small it is negligible at lower frequencies, but it becomes quite large at higher frequencies (refer to "9.2.1.2 Atmospheric absorption" for examples).

(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 Figure 4.4 and Figure 4.5). 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 [1]:

- 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.

4.4 References

- [1] *How to expand the meteorological window for noise immission*, Hans G Jonasson, Nordtest Workshop in Borås, Sweden, June 1998
- [2] *Handbook for noise and vibration*, Acoustic Materials Association of Japan, 1982 (in Japanese)

5. NOISE LEVEL LIMITS

No international standards stating noise level limits exist today. 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, see Section 3.3 and 5.1.1.

5.1 *Regulations*

The only international noise standard on environmental noise descriptions and measurement methods existing today is ISO 1996. However, standards for determining the sound level of specific equipment like power transformers (IEC 60551), standards for sound level meters (IEC 60651) and methods for determination of sound pressure and sound power levels (e.g. ISO 3746:1995) do exist.

5.1.1 Noise level limits

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 station. 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 allowable 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 don't 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.

5.1.2 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.

5.2 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 disproportionally high for the benefit gained, and it is sometimes difficult to suppress the sound at its source, e.g. mobile sources such as aeroplanes.

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 station 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 station 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 neighbours of the station. It should also be recognised that the existing background noise level may be the result of land use regulations currently in effect.

5.3 Location of required performance limits

The location where the required noise limits shall be fulfilled can be:

- at the fence surrounding the HVDC station or at the border of the Customer’s property
- at a given contour away from the HVDC station, e.g. on a circle perimeter or a property border line
- at the border of a nearby property

Advantages and disadvantages of the different approaches are listed below:

- At the fence surrounding the HVDC station or at the border of the Customer's property

Advantages	Disadvantages
• Less affected by background noise • Less impact on measurement from weather conditions • Less affected by surrounding topography and groundcover sound field	• Verification at location where nuisance typically does not affect people • May influence the station layout unnecessarily • More complicated and time consuming verification due to interference phenomena of the • 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 station

- At a given distance from the centre of the HVDC station

Advantages	Disadvantages
• Simplified prediction of the noise levels compared to predictions close to the fence. The reason is that the station may be treated as a point source, see Section 9.2	• Verification at location where nuisance may not affect people • Affected by background noise, weather conditions, topography and groundcover

- At the border of a nearby property

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

For environmental audible noise concerns the last approach is preferable as noise nuisance usually occurs where people live or work. Of course, in the future there may be houses 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 station, when planning their development layout and considering landscape options.

5.4 Relationship of performance limits to time duration

In general, noise from an HVDC station is continuous, but there are some noise sources of the station, 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 (6-13) 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 nighttime.

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

5.5 Typical noise performance limits

Before giving typical noise performance limits, it is important to mention 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 section, no international standards giving limits exist. 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.

5.5.1 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 nighttime values are given):

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

5.5.2 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 - 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.

5.6 References

- [1] *IEC 60651*, 1979, Sound Level Meters with amendment No 1, 1993
- [2] *ISO 1996*, Description and measurement of Environmental Noise
- [3] *IEC 60551*, 1993, Determination of transformer and reactor sound levels
- [4] *ISO 3746*, 1995 Acoustics - Determination of Sound Power Levels of Noise Sources Using Sound Pressure - Survey Method Using an Enveloping Measurement Surface over a Reflecting Plane - with Corrigendum
- [5] ISO Recommendation R1996 "Acoustics"

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 station. This goal is accomplished by the Contractor identifying the noise management required.

Efficient noise management requires an understanding of the acoustic behaviour 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 station 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 section, the major sound emitting sources of an HVDC station are introduced and the acoustic behaviour 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
- corona sources

This section describes the main parameters, which affect each component's sound power. The correlation between sound power and sound pressure is explained in section 3 (Definitions) and section 10 (Verification of component sound power).

6.2 *Converter transformers*

6.2.1 Noise sources in a converter transformer

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

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 also sections 6.5 and 6.6.5).

6.2.2 Comparison to AC power transformers

More is known about the mechanism of sound generation for AC power transformers, and therefore this is discussed in the following paragraphs.

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 AC 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

$$L_{WA,w} \approx 39 + 10 \lg \left(\frac{S_r}{S_p} \right) \text{ dB(A)} \quad (6-1)$$

where

$L_{WA,w}$	= A-weighted sound power level from the winding at rated current, rated frequency and impedance voltage
S_r	= rated power in MVA
S_p	= reference power of 1 MVA

The normal AC 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 = 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 [1]. Therefore the noise of a loaded AC transformer is essentially dominated by a 100 Hz tone or 120 Hz tone (according to whether the power frequency is 50 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 AC transformers of the same rated power. There are two factors, which increase the noise level:

- the load current of a converter transformer has a high harmonic content
- a converter transformer will experience a small DC bias current in the windings connected to the thyristor bridge

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

The sound spectrum generated by converter transformers contains frequencies of up to several kHz and is therefore more audible to humans (as demonstrated by A-weighting of the sound level; see also section 3). 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 DC magnetisation is not directly dependent on the load level, as the small DC 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
- the potential difference between the ground electrode and station ground for monopole ground-return operation

DC magnetization of a transformer core will increase the transformer audible noise also at moderate levels of DC content [2]. The reason is that the DC magnetisation 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 or 120 Hz, 200 or 240 Hz, 300 or 360 Hz, etc.) will be increased by the DC magnetisation.

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 a Cigré publication in *Electra* of August 1996 [3], which described the difference between the actual noise level in service and the values recorded during the standard factory 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 stations 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 item 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 field of the winding. The forces in the winding are proportional to the current multiplied by the magnetic field in the winding. The magnetic field is, however, proportional to the current, thus giving:

$$F \sim B \cdot I \sim I^2 \quad (6-2)$$

where

F	= vibrational winding force in N
B	= magnetic field density in the winding in T
I	= winding current in A

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

$$W \sim v^2 \sim (\omega \cdot x)^2 \sim F^2 \sim I^4 \quad (6-3)$$

where

W	= radiated sound power
v	= vibration velocity
x	= vibration amplitude
ω	= $2\pi f$ = 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 DC circuit of a back-to-back link to reduce the harmonics on the DC side, to reduce the current rise caused by failures in the DC system and to improve the dynamic stability in the HVDC system;
- Filter reactors installed for harmonic filtering on the AC and on the DC side;

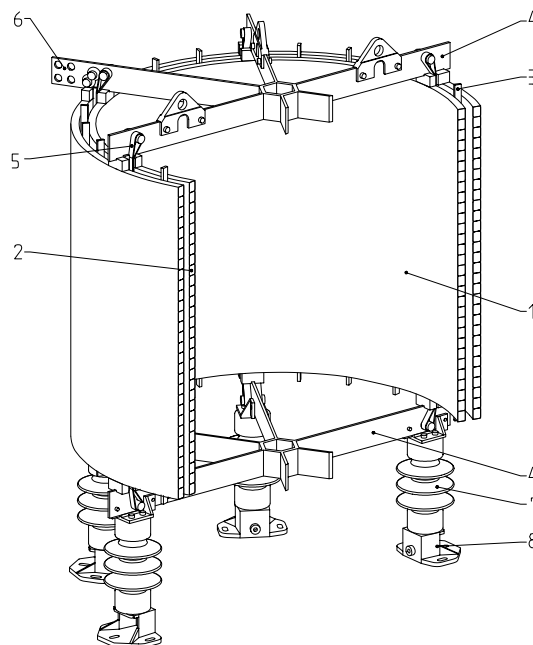
- Power line carrier- and radio interference filter reactors employed on the AC and/or DC side of the HVDC station to reduce high frequency noise propagation in the lines;
- Shunt reactors may form part of an HVDC station to provide inductive compensation for AC harmonic filters, especially under light load conditions, where a certain minimum number of harmonic filters is required to satisfy harmonic performance requirements;

When considering the impact of audible noise emanating from an HVDC station, the AC 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 iron-core oil-type HVDC smoothing reactors (e.g. at sites with extreme pollution and climatic conditions). Another exception may be reactors for self-tuned AC filters, which also contain a magnetic core. In this case, the tuning is provided by controlling the permeability of the magnetic circuit by DC magnetization.

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 item 6.2 dealing 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 6.1:



- | | | |
|----------------------|---------------------|------------------------|
| 1) winding | 2) conductor | 3) duct stick |
| 4) spider | 5) fibreglass tie | 6) electrical terminal |
| 7) support insulator | 8) mounting fitting | |

Figure 6.1. Dry-type air-core reactor.

The winding of the reactor consists of one or multiple resin-impregnated and encapsulated winding layer(s) made of insulated aluminium conductors. The concentric layers are

connected in parallel by welding their ends to metallic beam structures (spiders). Both the top and bottom spider is clamped together by several sets of fibreglass ties located along the winding. The packages are radially spaced by circumferentially arranged fibreglass-reinforced sticks, which form vertical air ducts for natural convective cooling of the windings.

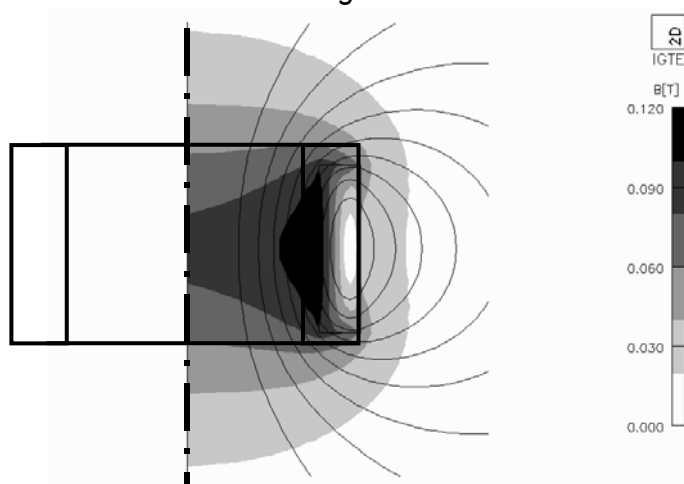
6.3.2 Mechanism of sound generation

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 field.

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.

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 6.2 shows the distribution of the magnetic field of an air-core reactor of 30 Mvar power rating.

Figure 6.2. *Magnetic field of an air-core reactor winding.*



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 AC 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 behaviour 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

- the 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 6-3) and its shape coincides with the distributed exciting electromagnetic force resulting from the axial magnetic field component.
- the "compression mode" in the axial direction where the reactor is symmetrically compressed towards the reactor midplane. This mode is excited by the radial magnetic field component.
- the "flexural modes" (bending modes) of the winding layers, characterised 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 6-4.

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

$$W = \rho_0 c A_w \sigma v^2 \quad (6-4)$$

By introducing

$$v = \omega x \quad (6-5)$$

the radiated sound power at a certain acoustic frequency is defined by

$$W = \rho_0 c A_w \sigma \omega^2 x^2 \quad (6-6)$$

where

W	= radiated sound power in W
ρ_0	= air density in kg/m ³
c	= speed of sound in air in m/s
A_w	= sound radiating surface in m ²
σ	= radiation efficiency (no unit)
v	= vibration velocity in m/s
ω	= angular acoustical frequency (=2 π f)
x	= vibration amplitude in m

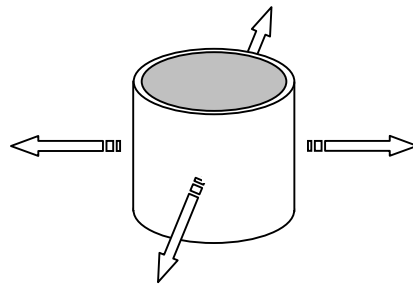


Figure 6-3. Simplified shape of the symmetrical breathing mode of a reactor winding.

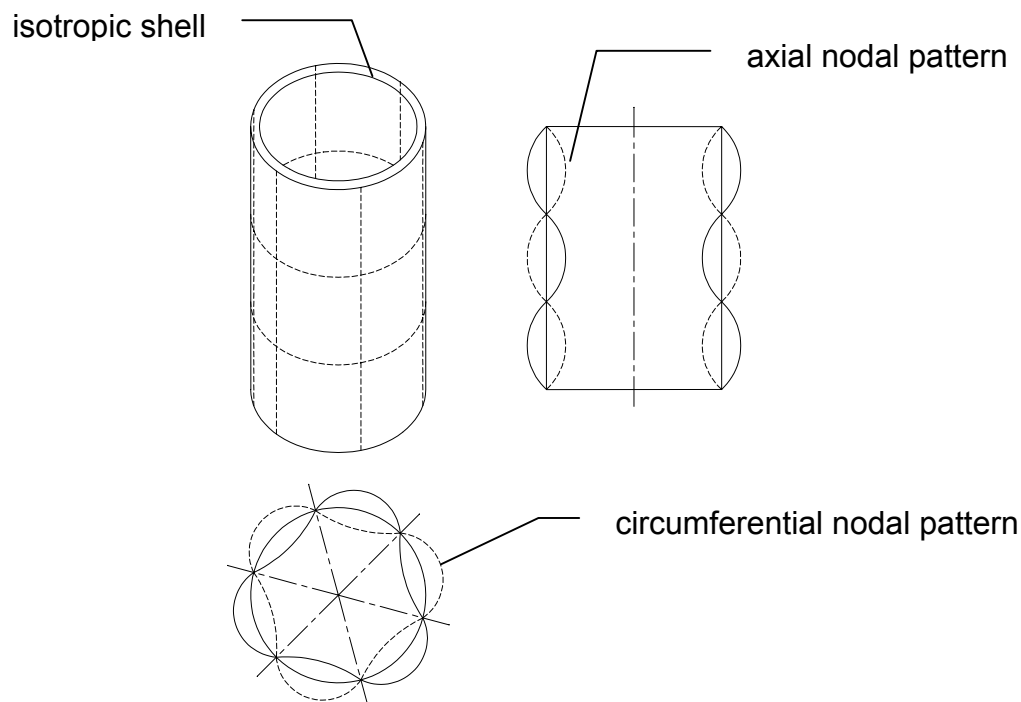


Fig. 6-4. Example of flexural modes (bending modes) for a simply supported winding layer without axial constraint (e.g.: i =number of circumferential wavelengths=3; j =number of axial half wavelengths=3).

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 in 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.

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 also section 6.2.1). For specifying sound criteria, it is therefore necessary to clearly specify

the station'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, suppose 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 the surface, even outside the immediate vicinity of the surface. Thus $\sigma = 1$. If the situation is the opposite, $\sigma < 1$. At frequencies where the wavelength of the vibrating structure is about the same as the wavelength in air, σ can get larger than 1. See also section 10.2.3.

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:

$$L_{W2} = L_{W1} + 40 \lg \left(\frac{I_2}{I_1} \right) \quad (6-7)$$

where

$$\begin{aligned} L_{W1} &= \text{sound power level in dB at current load } I_1 \\ L_{W2} &= \text{sound power level in dB at current load } I_2 \end{aligned}$$

The total sound power level, including all acoustic frequencies, is derived by logarithmic summation (see section 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 6.5 shows the simplified current spectrum of an AC 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.

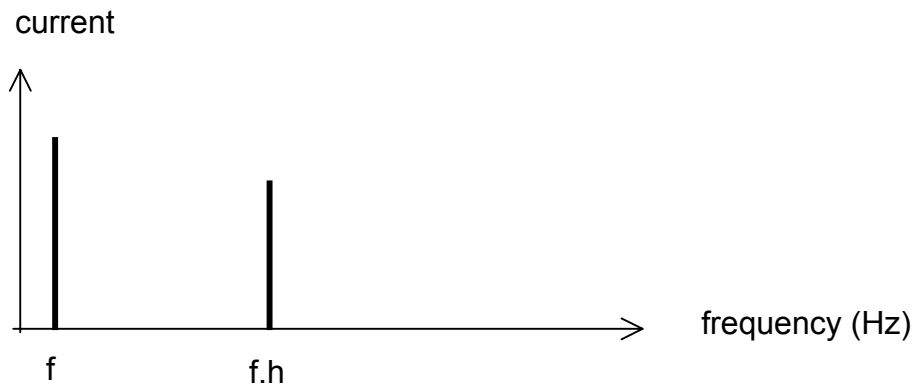


Figure 6.5. Example of spectrum of currents through AC filter reactor.

Figure 6.6 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 $2fh$. Only the vibration force components are generating noise; the static pre-load does not affect the sound power.

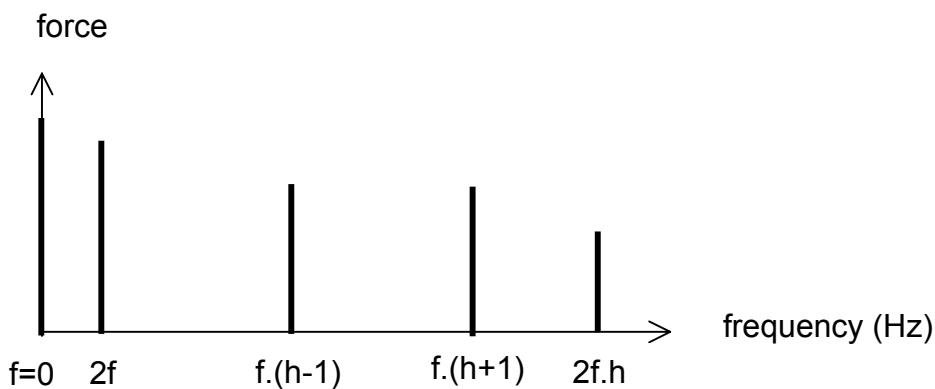


Figure 6.6. Example of spectrum of forces acting on the reactor winding.

When going from electrical load to electrical force, a frequency shift occurs and the number of force components is equal to the number of load components squared. 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 behaviour of the filter reactors, it is therefore necessary to include both the fundamental and the harmonic content of the current.

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 DC current with the harmonic currents. Since modern converter stations generally operate with 12-pulse bridges, the main harmonics are the 12th and the 24th. Therefore for 50 Hz AC systems, the main noise of the smoothing reactor is generated at 600 Hz and 1200 Hz; for 60 Hz systems the corresponding frequencies are 720 Hz and 1440 Hz.

As an example, Figure 6.7 shows the simplified current spectrum of an HVDC smoothing reactor. It is assumed that the current consists of a DC 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 6.7. Example of spectrum of currents through an HVDC smoothing reactor.

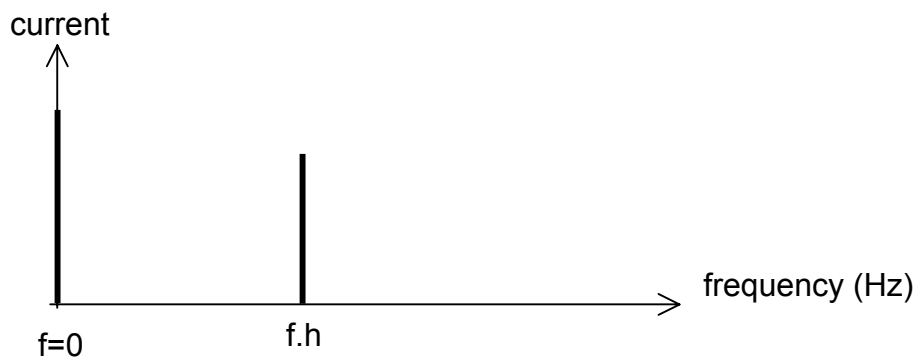
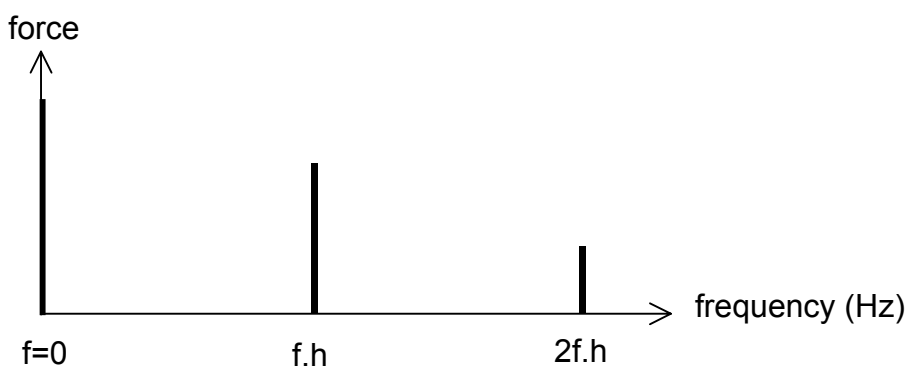


Figure 6.8 depicts the force components acting on the winding of the reactor. The force consists of a static pre-load and vibration components with frequencies fh and $2fh$.

Figure 6.8. 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 6.9. A DC current in the control winding affects the permeability of the core and changes the inductance of the reactor. The AC cable is wound on a fibreglass 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 AC current. The *DC current* in combination with the AC current creates forces at the AC frequency as shown in Figure 6.8. A change of the DC current thus only affects the sound at the AC frequency (and e.g. not double the AC frequency). There will be no sound radiation at the frequency zero Hz.

Radial vibrations of the fibreglass cylinder seem to determine the radiated sound power, and not as has been found on air-cored reactors, the radial vibrations of the (AC) winding. See also section 9 and 10.

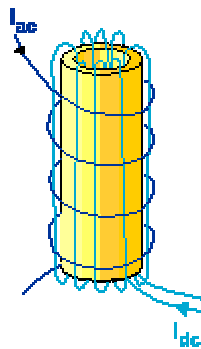


Figure 6.9. Reactor for self-tuned filter applications.

6.4 Capacitors

6.4.1 Type and design of capacitors

After transformers and reactors, capacitors are the main noise sources in an HVDC station. Capacitors are used for various functions in an HVDC scheme, such as for AC- and DC 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 porcelain 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 6.10), which are connected in series or parallel. The capacitor element is made by winding two aluminium foils and a number of plastic or paper films of a specific length.

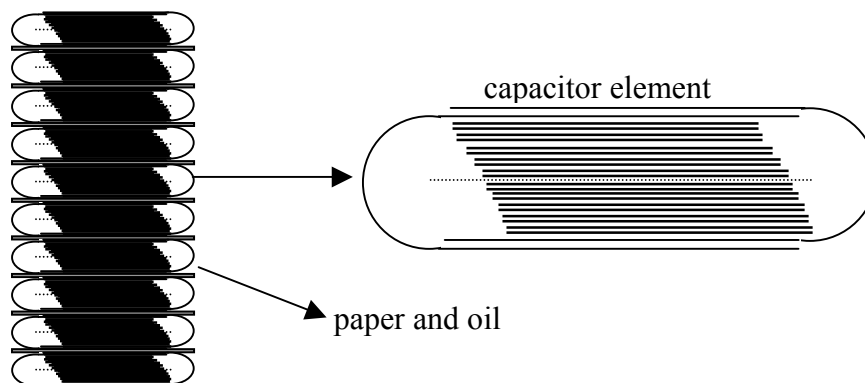


Figure 6.10. Capacitor element package with capacitor elements.

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 energised capacitor element (see Figure 6.11) shows that most of the charge-carrying aluminium 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.

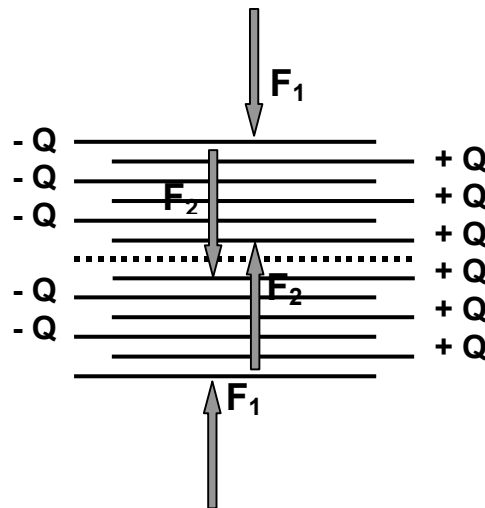


Figure 6.11. Forces in a capacitor element.

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).

$$F = \frac{dW}{dx} \quad (6-8)$$

where

W = energy stored in the capacitor in W
 x = distance between the capacitor plates in m

By introducing the formula for the energy stored in a capacitor

$$W = \frac{U^2 C}{2} \quad (6-9)$$

where

U = rms voltage across the capacitor in V
C = capacitance in F

the force can then be calculated by:

$$F = -\frac{U^2 C}{2x} \quad (6-10)$$

If U is a sinusoidal voltage

$$U(t) = \sqrt{2} U \sin(\omega t) \quad (6-11)$$

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 6.11 shows the simplified voltage spectrum of an AC 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.

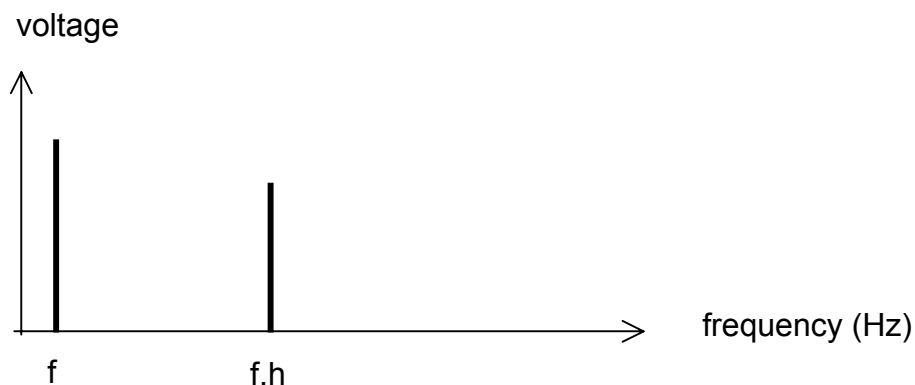


Figure 6.11. Example of spectrum of voltages across the capacitor.

Figure 6.12 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 $2fh$.

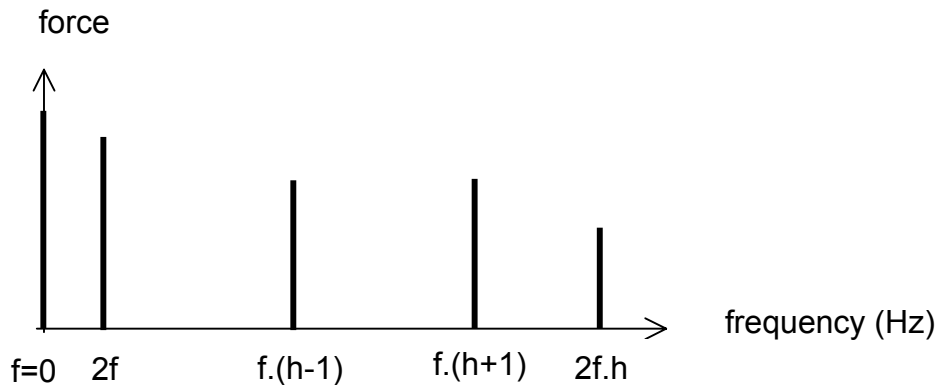


Figure 6.12. Example of spectrum of electrostatic forces in a capacitor.

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 item 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.

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

$$L_W^{stack} = L_W^{unit} + 10 \lg(n) \quad (6-12)$$

where

L_{Wstack}	=	sound power level of the complete capacitor stack in dB
L_{Wunit}	=	sound power level of a capacitor unit in dB
n	=	number of capacitor units

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

- fundamental and harmonic AC 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

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 section 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 1000 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 emitted noise levels. Two-speed motors or motors with frequency control for speed regulation may be employed. The manufacturers are able to optimise the acoustic design of the coolers by combining adequate standardised 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 (6-13). There are 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 section 7.2.6.

$$L_{WAeq} = 10 \lg \left[\left(\frac{1}{T} \right) \sum T_i 10^{0.1 L_{WAeq, T_i}} \right] \text{ (dB)} \quad (6-13)$$

where

L_{WAeq}	=	equivalent continuous A-weighted sound power level in dB over time interval T (rel. 1 pW)
T	=	total time interval ($T = \sum T_i$) in s
L_{WAeq, T_i}	=	equivalent continuous A-weighted sound power level in dB during period T_i (rel. 1 pW)
T_i	=	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 station 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, oil- and SF₆ 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 SF₆ breakers produce a relatively low level of sound.

Air break disconnectors and earth switches can produce significant sound levels for up to 10 seconds, depending on the voltage across the gap being created or closed.

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, slipring/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

As a diesel generator is unlikely to operate for extended periods, and is almost always enclosed in a building, 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 or 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 louvre noises and residual noise from the air-handling plant, although acoustic louvres 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 Outdoor valves

As this section only describes those components emitting sound into the area surrounding an HVDC station, the acoustic behaviour 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 (snubber reactors). The coolers of the thyristor valves, however, are generally installed outdoors and are discussed under item 6.5.

In the rare case of tanked valves installed outdoors, the fans of the cooling equipment may also be a dominant sound-emitting source and therefore the measures related to fan noise will apply again.

6.6.7 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 high levels of corona should trigger remedial actions.

In particularly sensitive sites it may be necessary to suppress corona levels by methods such as:

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

6.7 Typical sound power levels of sound emitting sources

The figures stated below 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.

Sound emitting source	Component sound power $L_{W(A)}$ in dB(A)
HVDC converter transformer	
• nominal load	100-125
• no load	90-110
HVDC smoothing reactor	85-100
Self tuned filter reactors	90-100
AC filter reactor	70-90
AC filter capacitor stack (can-type capacitors)	60-105
Cooling fans (forced air coolers for valve cooling)	
• fan speed approx. 300 rpm cooling capacity 30kW/300kW	approx. 55/85
• fan speed approx. 900 rpm cooling capacity 500kW/1300kW	approx. 90/105
Switching device	(impulsive noise!)
• air blast circuit-breaker	150-160
• oil- and SF6 circuit-breaker	105-130

Table 6-1. Examples of component sound power levels.

6.8 References

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7. SOUND REDUCTION MEASURES

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

Ideally sound reduction should be part of the original design and is a combination of station layout techniques and component design measures. The aim is to use these 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 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 - see References 1 and 2.

7.1 *Station Layout*

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 station. 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

7.1.1 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 buildings and converter transformers, and even the entire converter station, to shield a sound-sensitive area from transformer noise.

For converter transformers and tanked DC 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 higher 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.

7.1.2 Air-cored reactors

Air cored reactors can be significant sound producers, particularly those in filters. Unlike transformers, they cannot be easily enclosed, as they require free movement of air for cooling.

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.

7.1.3 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 and screening technique can be optimised with respect to the acoustic layout of the HVDC station.

7.1.4 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 orientate the fans in a direction in which the sound levels are less of a nuisance.

7.1.5 Diesel generators

For a diesel generator, the main noise source is usually the exhaust vent (as described in section 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 other buildings.

7.1.6 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.

7.1.7 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 louvre noises (remembering that “acoustic louvres” are available) and residual noise from the air handling plant, the same concepts that apply to fans generally apply.

7.1.8 Corona sources

All practical high voltage connections emit a level of corona. For reasons other than audible noise, corona should be limited to low levels and high levels of corona should trigger remedial action.

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 busbar

7.1.9 Synchronous compensators

As described in 6.6.2, 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.

7.2 **Component Design**

Low-noise designs of equipment normally seek to minimise the vibrational 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 section 6; this section 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, this limits the spread of low frequency sound.

7.2.1 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;
- utilising modern core-joint technologies;
- avoiding critical mechanical resonances;
- provision of mechanical damping both in the tank and in the installation;
- utilising advanced winding designs to minimise impedance tolerances;
- better control of manufacturing tolerances;
- use of low noise fans (see section 7.2.4 below);
- use of separate cooler banks may reduce the requirement for forced cooling and ease the enclosure of the transformer.

7.2.2 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 vibrational 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 approximately maximum 6 dB.

7.2.3 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 vibrational forces;
- the 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.

7.2.4 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.

7.2.5 Pumps and Diesel generators

Although 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.

7.2.6 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 modern 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.

Air break disconnectors and earth switches can produce significant levels of noise for up to 10 seconds. This is entirely dependent on the voltage across the gap being created or closed. 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

7.2.7 Air-Conditioning Plant

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

7.2.8 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.

7.3 *Sound Enclosures*

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 (see e.g. Ref. [3]) and hence the wall height necessary to protect the receiver location.

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

7.3.1 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 by Reference 2.

7.3.2 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 fibreglass 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-BIL reactors in wet and polluted conditions. Typical maximum attainable noise reductions are:

- top hat and bottom baffles 5 dB(A)
- + outside cylinder 10 dB(A)
- + complete enclosure 15 dB(A)

7.3.3 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.

7.4 *Retrofittable techniques*

7.4.1 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.

7.4.2 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.

7.4.3 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 modelling of all structures.

Active Noise and Vibration Control (ANVC) is most practical for low frequency noise. Effective installations in operation today on electric 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 minimises 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.

7.5 References

- [1] *Transformer Noise Attenuation in Substations*, Cigré report 23.10, August 1980
- [2] *IEEE C57.136*, Draft 9, January 1999 - Guide for Sound Level Abatement & Determination for liquid-immersed Power Transformers and Shunt Reactors over 500 kVA
- [3] *Theoretical Acoustics*, Morse & Ingard, Princeton University Press, 1986

8. OPERATING CONDITIONS

8.1 *Introduction*

This chapter 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 station. These factors include:

- HVDC station 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
- External AC parameters influences such as:
 - AC system voltage and frequency
 - background harmonics
 - other converters and SVCs
- Environmental influences such as (see also section 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 AC harmonic filters) are dependent on the operating conditions.

When looking at the operating conditions for a complete HVDC station, 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 AC-related equipment and harmonics related to the AC network.

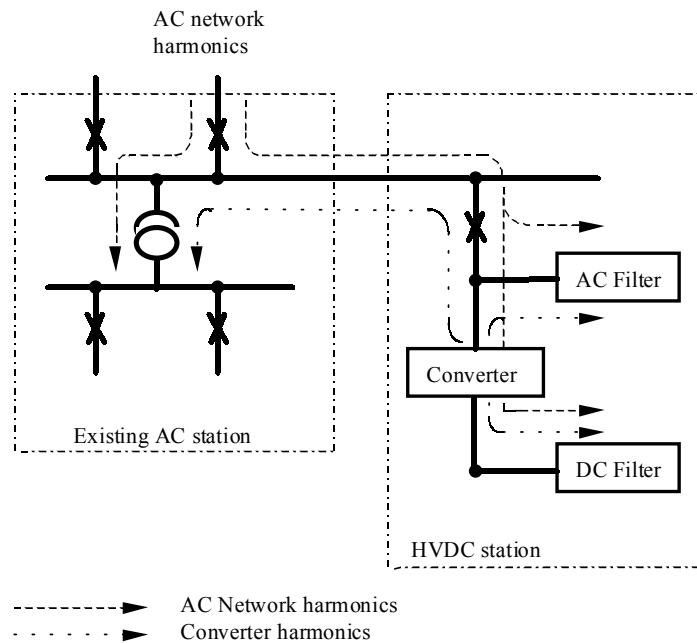


Figure 8.1. Explanation of AC network harmonics and converter harmonics.

The AC harmonics on the AC network will contribute to the total noise level of an HVDC station. These harmonics are an external contribution, and the Customer has to include data on harmonics on the AC network in the technical specification, so that the Contractor can take it into account when making calculations for the complete station.

In practice, it is of most interest to the Customer to look at the total station noise level, but when specifying it is important to 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 to the Customer that he get qualified verification of the noise level of the HVDC station 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:

Power range	From minimum to nominal
DC Voltage range	Nominal (for long distance transmission systems)
AC Voltage & Frequency	Normal continuous
Filter configuration	Corresponding to power levels
Control strategy	Normal
Redundancy	Operation without redundant equipment

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 AC filters and AC network deviation. Exceptional operating conditions include:

Power range	From minimum power to maximum possible power
DC Voltage range	Full operating range (for long distance transmission systems)
AC Voltage & Frequency	Normal continuous
Filter configuration	Corresponding to power levels
Control strategy	For example, using increased firing angles and/or reduced DC voltage
Redundancy	All redundant equipment in operation (e.g. thyristor and transformer cooling)

If the sound levels must 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.

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

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 section 4 for further details).

The prediction of sound levels in the vicinity of an HVDC station is based on the sound generated by equipment at site. Thus, such predictions only include the contribution from the HVDC station 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 station, however it has a significant influence on measurements of the sound level.

The accuracy of predicting sound levels in or around a converter station 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 station affects the sound propagation.

9.1 *Modelling of plant*

Modelling 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 station normally consists of AC and DC 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 station, should include the dominant sound sources, and also the most important buildings. In addition, the station layout and the transmission paths should be considered.

9.1.1 Layout

The converter station layout defines the location and orientation of all equipment at site. Buildings and the site area are also included in the model of the station. 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.

9.1.2 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

9.1.3 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. Sound energy arriving from each of these paths has to be added to obtain the total sound pressure level at the receiver.

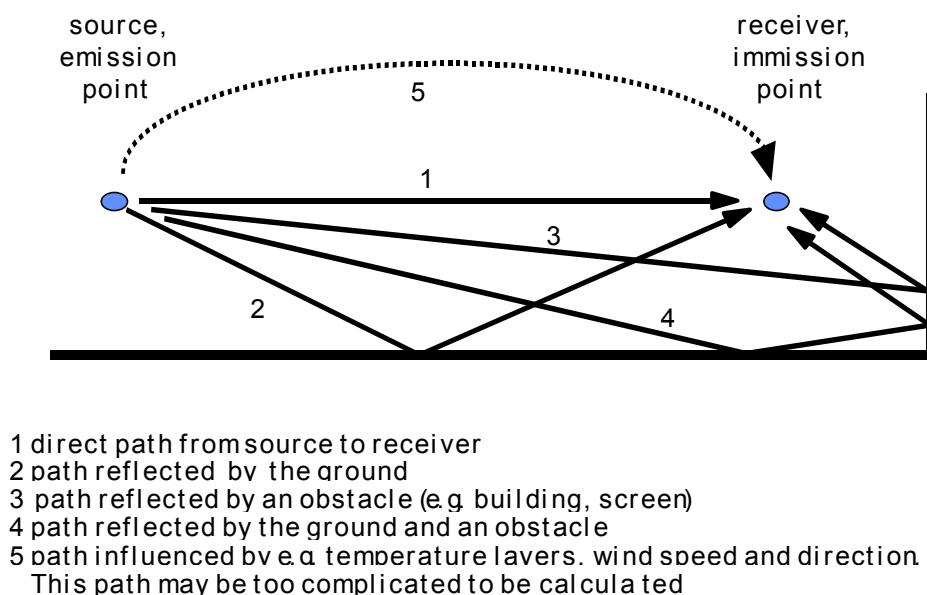


Figure 9.1. Examples of transmission paths from source to receiver.

9.2 Calculation Procedure

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. There are several publications describing calculation procedures for the attenuation of sound during propagation outdoors, see for example Reference [1] and [2].

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 formulae 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;
- the same propagation conditions to the point of reception;
- a distance from the single equivalent point source to the receiver exceeding two times the largest diameter of the relevant area of the sources.

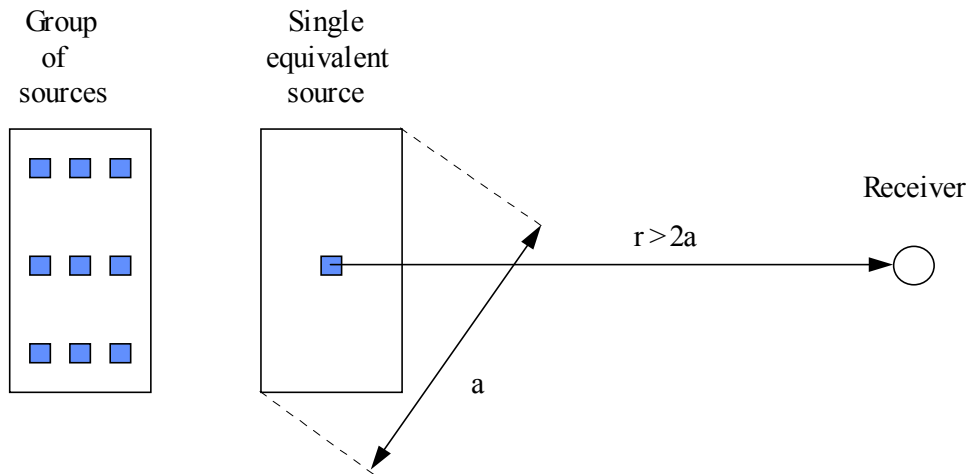


Figure 9.2. Grouping of point sources to one equivalent source if the measurement distance (r) is larger than $2 \cdot a$.

If the measurement distance is smaller than described in Figure 9.2, 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. The basic calculation procedure for each source, mid-band frequency and sound path is described in three steps (the order of the procedure may differ between calculation programs):

1. Calculate 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} ;

$$L_{wfi} = L_{wf} + D I \text{ (dB)} \quad (9-1)$$

DI is the directivity index in dB, see section 3.9. 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.

2. For each sound source (n), including its sound path from source to receiver, calculate the total sound pressure level at the specific location for the frequency band f ;

$$L_{pTOT}(N) = \sum_{n=1}^N L_{wfi,n} - A_{fi,n} \text{ (dB)} \quad (9-2)$$

where

$$\begin{aligned} A_{fi,n} &= \text{frequency dependent attenuation in dB for source } n \text{ during} \\ &\quad \text{propagation from source to receiver} \\ N &= \text{total number of sound sources} \end{aligned}$$

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

$$A_{fi,n} = A_{div} + A_{atm} + A_{screen} + A_{reflex} + A_{ground} + A_{veg} \quad (9-3)$$

where

$$\begin{aligned} A_{div} &= \text{attenuation due to geometrical divergence} \\ A_{atm} &= \text{attenuation due to atmospheric absorption} \\ A_{screen} &= \text{attenuation due to screening and transmission} \\ A_{reflex} &= \text{attenuation due to absorption at reflecting obstacles} \\ A_{ground} &= \text{attenuation due to the ground (which may include vegetation, e.g. grass)} \\ A_{veg} &= \text{attenuation due to sound propagation through vegetation} \end{aligned}$$

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

$$L_{pTOT} = 10 \lg \sum_{f=1}^n 10^{L_{pTOT}(N)/10} \text{ (dB)} \quad (9-4)$$

where n is the total number of frequency bands.

9.2.1 Calculation of attenuation terms

9.2.1.1 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;

$$A_{div} = 10 \lg \left[4\pi \left(\frac{r}{r_0} \right)^2 \right] \quad (9-5)$$

where

r = distance from source to receiver, in metres
 r_0 = reference distance (or radius) giving a sphere of surface area 1 m^2

For $r < 0,28\text{m}$ (resulting in $A_{div} < 0$), then 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. $L_p = L_w$.

9.2.1.2 Attenuation due to atmospheric absorption

The attenuation due to atmospheric absorption is given by

$$A_{atm} = \frac{(\alpha_a \cdot d)}{1000} \quad (9-6)$$

where

α_a = atmospheric attenuation coefficient, in dB/kilometre
 d = distance of the sound path in metres

T	RH	Nominal octave centre frequencies, Hz							
Air temperature	Relative humidity	63	125	250	500	1000	2000	4000	8000
(C)	(%)	Attenuation in dB per 1000 metres							
-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

Table 9.1. Examples of atmospheric attenuation coefficients.

Table 9.1 lists examples of atmospheric attenuation coefficients. For more detailed information see Reference [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.

9.2.1.3 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 Reference [2] and [3].

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. $s_l + s_r > \lambda_c$. See Figure 9.3.

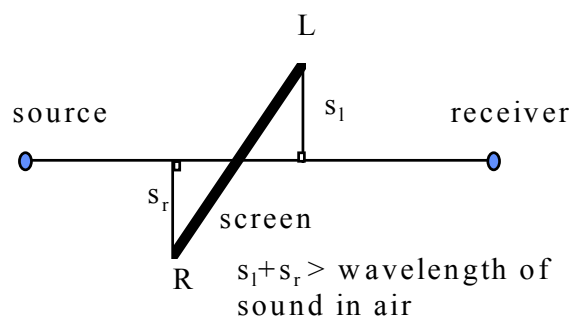


Figure 9.3. Definition of geometrical parameters used for calculation of screening.

9.2.1.4 Attenuation due to reflecting 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 9.4:

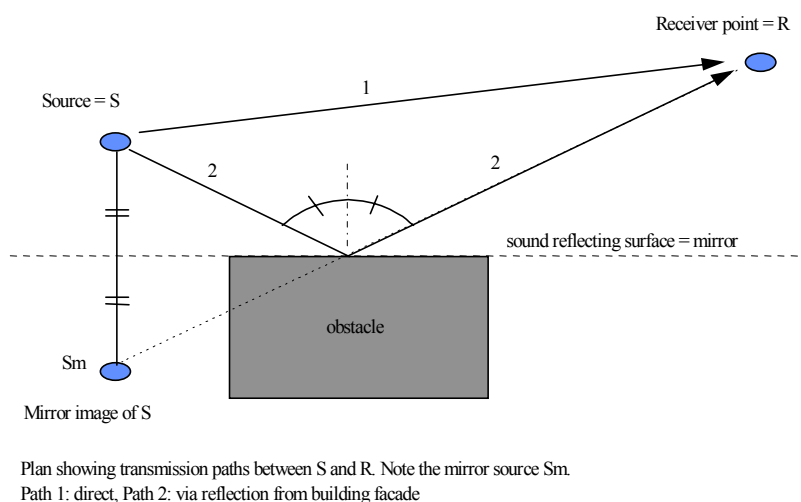


Figure 9.4. Reflecting obstacles are treated by mirror sources.

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.

9.2.1.5 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.

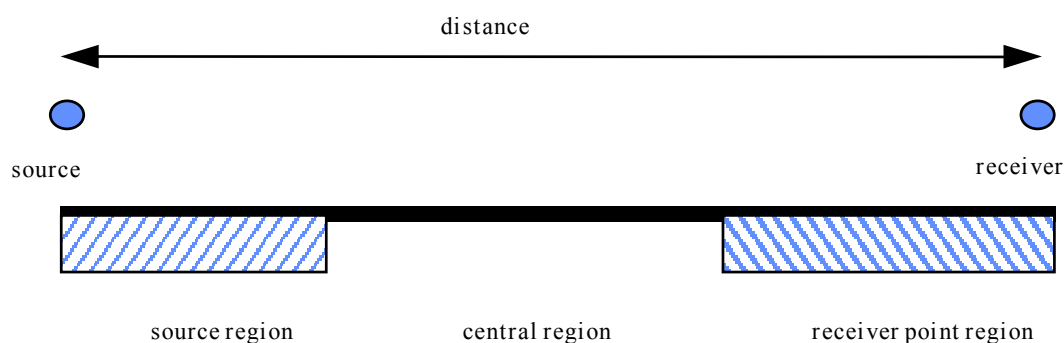


Figure 9.5. Definition of parts for calculation of ground attenuation.

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 characterisation. Hard ground, e.g. asphalt, pavement, concrete, water¹ 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.

9.2.1.6 Attenuation due to propagation through vegetation

A curved transmission path is considered, illustrated by the upper path in figure 9.6. 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 9.6.

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 9.6). The transmission path height, h , above the straight line between source and receiver is given by:

¹ 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".

$$h = \frac{(d_1 \cdot d_2)}{16 \cdot d} \quad (9-7)$$

where

- h = transmission path height above the straight line between source and receiver
 d_1 = horizontal distance from source to “screen” in metres
 d_2 = horizontal distance from receiver to “screen” in metres
 d = $d_1 + d_2$ in metres

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

$$A_{veg} = -n_v \cdot \alpha_v \quad (9-8)$$

where

- n_v = number of groups of vegetation
 α_v = attenuation coefficient per group, see table 9.2 below

If $n_v > 4$, n_v is set equal to 4

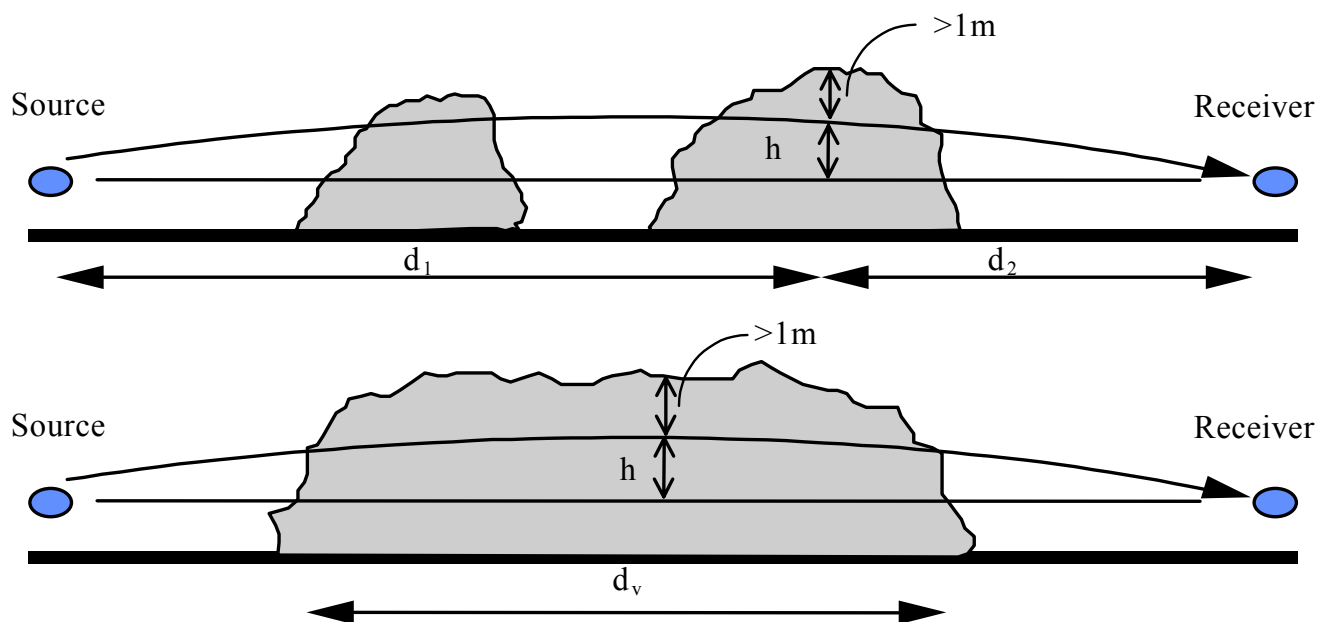


Figure 9.6. Definition of parameters used in equation (9.7). Figure a, $n_v = 2$, Figure b, $n_v = d_v/50$.

1/1 octave f_m [Hz]	63	125	250	500	1000	2000	4000	8000
α_v attenuation coefficient per group [dB/group]	0	0	1	1	1	1	2	3

Table 9.2. Examples of attenuation coefficient values for octave bands.

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 metres in depth gives a reduction of approximately one (1) dB(A).

9.3 Result 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 result presentation:

- a graphical presentation of e.g. sound level contours with equivalent sound levels, see Figure 9.7
- a table with predicted sound levels at a number of receivers, see Table 9.3

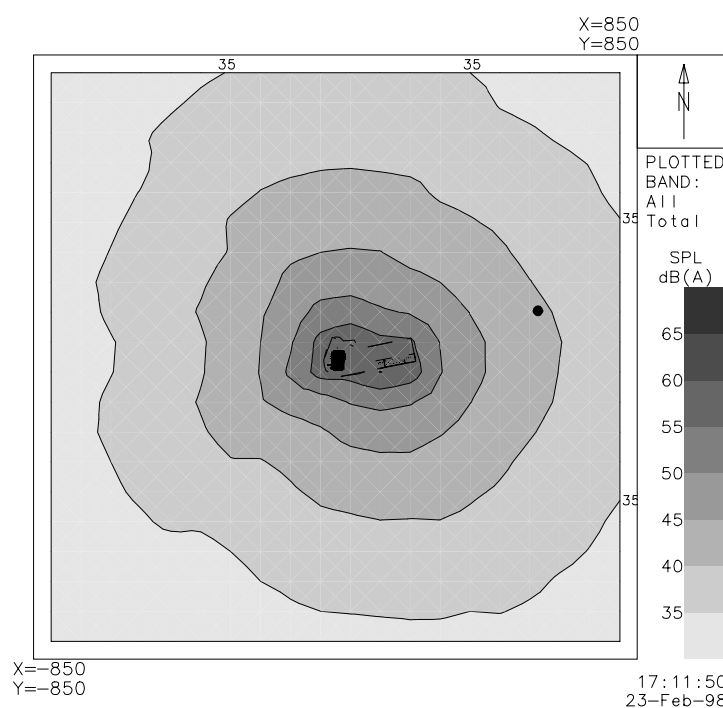


Figure 9.7. Example of graphical presentation of sound pressure level calculation.

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

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

CASENO	RECEIVER	X	Y	Z	NAME
303	1	570.00	130.00	1.50	Nearest House

Ranking of sources by total values and contribution by frequency.

		1	2	3	4	5	6	7	8	9
FREQ	All/Total	1000	500	700	600	250	125	2000	1200	Other
RANK	dBa	Source	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
1	34.3	Grp.1	29.3	29.4	7.8	8.6	23.2	21.2	23.1	-
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: - The source does not contain this frequency.

NOTE: * The source has this frequency but it is below ranking.

RANK	dBa	Source	PRODID	DESCRIPTION	X [m]	Y [m]	Z [m]
1	34.3	Grp.1	<Group>	Transformers and transfor	23.0	1.0	2.8
2	32.6	Grp.10	<Group>	36th Capacitor and Reacto	168.5	-7.0	4.5
3	32.5	Grp.9	<Group>	24th Capacitor and Reacto	163.5	-15.0	4.5
4	32.0	Grp.3	<Group>	Smoothing reactor	5.0	26.0	8.0
5	31.1	Grp.8	<Group>	13th Capacitor and Reacto	170.0	-13.3	4.5
6	29.5	Grp.7	<Group>	11th Capacitor and Reacto	162.0	-8.3	4.5
7	28.9	Grp.6	<Group>	AC Shunt Reactor	166.5	-12.5	1.5
8	25.7	Grp.4	<Group>	PLC Filter	-41.0	-12.2	18.4
9	23.4	Grp.5	<Group>	AC Shuntcapacitors	165.5	-8.5	5.0
10	12.3	Grp.2	<Group>	Valve Cooling Fans	-16.3	-25.3	2.0

Table 9.3. Ranking of noise sources. Each column in the upper table represents an octave or narrow frequency band. Each row represents a noise source or a group of noise sources.

9.4 References

- [1] *ISO 9613-1*, Acoustics - Attenuation of sound during propagation outdoors - Part 1: Calculation of the absorption of sound by the atmosphere
- [2] *ISO 9613-2*, Acoustics - Attenuation of sound during propagation outdoors - Part 2: A general method of calculation
- [3] *Technical report #32*, Danish Acoustical Laboratory, March 1982, Environmental Noise from Industrial Plants. General Prediction Method

10. VERIFICATION OF COMPONENT SOUND POWER

In this section, methods for verifying the component sound power are described. 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

10.1 General

The sound requirements for HVDC stations are conventionally specified in terms of the maximum allowed sound pressure level at a specific contour or at specific points surrounding the station. 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 AC-filter.

10.2 Calculation

Sound power is the most important acoustic quantity for characterisation 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:

- Firstly, the electrical forces are calculated
 - Electrostatic for capacitors
 - Electromagnetic for windings of reactors and transformers
 - Magnetostrictive for cores of transformers and iron-cored reactors
- Secondly, the system response, or transfer function, is extracted
- Thirdly, the vibration amplitudes and the resulting sound power are calculated

The procedure is outlined in Figure 10.1:

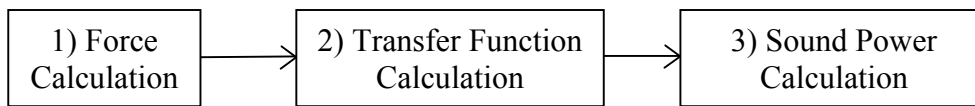


Figure 10.1. Three steps to determine the sound power of HVDC components.

10.2.1 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 section 6 and in particular sections 6.2.4 and 6.4.2.

If a current energises the component with a single AC frequency, this will result in an electro-mechanical force of twice the power frequency. This is however only true if no DC is present. With DC 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 the following force spectrum:

<i>Force frequency (Hz)</i>	<i>Derived from electrical frequencies (Hz)</i>
100	2*50
500	550-50
600	550+50
1100	2*550

Table 10.1. The electrical frequency 50 Hz and the harmonic 550 Hz give vibration forces of frequency 100, 500, 600 and 1100 Hz.

10.2.2 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 determines the behaviour 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;
- how similar the spatial shape of the natural mode is to the shape of 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 modeshape, of each natural mode, is very important. As an example, consider the can-type capacitor mentioned in section 6.4.2. The excitation force on the capacitor is purely axial, see Figure 6.10. This means that the axial resonance frequencies of the capacitor will determine the radiated sound power. The resonance frequencies with mode shapes (and thus a motion) perpendicular to the axial direction will not be excited by the electrostatic forces and will not contribute to the sound power radiation.

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 10.2. Near the resonance frequency, it is clear how important the damping is for the response of the system. For details about critical damping, see Ref. [8].

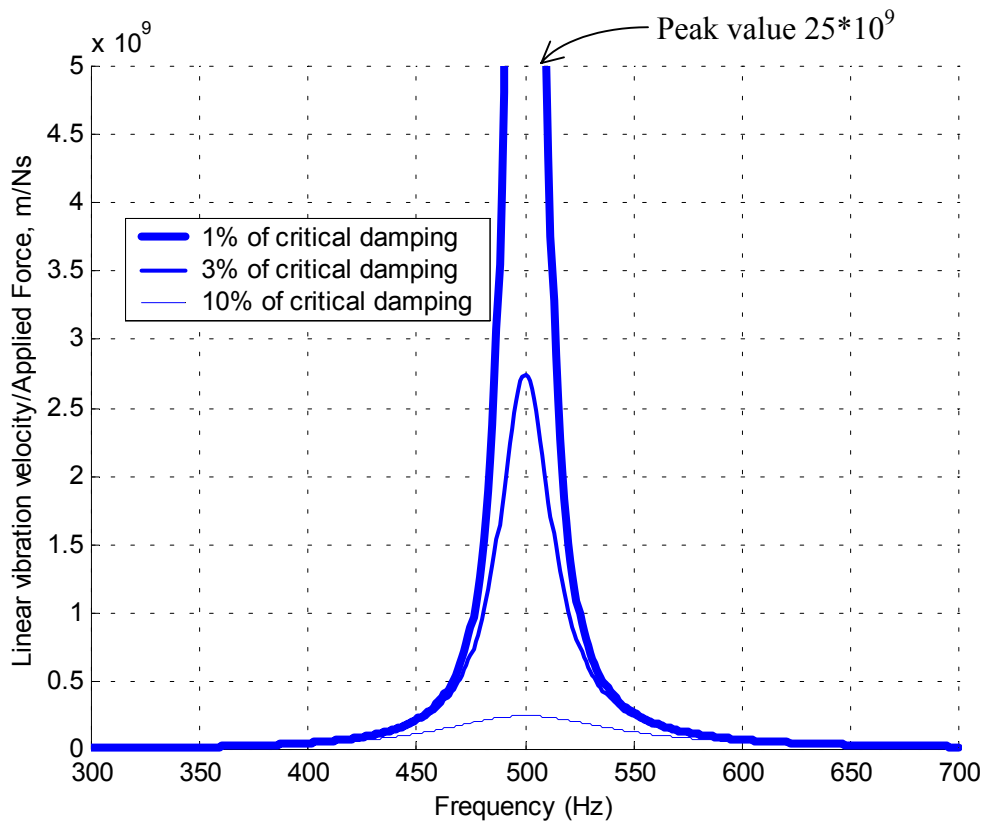


Figure 10.2. Linear transfer function between e.g. force and vibration velocity for a 1-DOF system with the resonance frequency 500 Hz. The effects are shown for different values of critical damping.

10.2.3 Sound power calculation

Given a structural vibration velocity, v , the formula (10-3) often gives a good estimation of the sound power in dB:

$$L_w = 10 \lg \left(\frac{\rho c \cdot A \cdot \sigma \cdot \langle \tilde{v}^2 \rangle}{1 \cdot 10^{-12}} \right) \text{ (dB)} \quad (10-3)$$

where

ρc	=	impedance of the surrounding fluid in Ns/m^3 ($\rho c = 410 \text{ Ns/m}^3$ for air)
A	=	area of the vibrating surface in m^2
σ	=	radiation factor, or radiation efficiency (no unit)
$\langle \tilde{v}^2 \rangle$	=	squared and time averaged rms vibration velocity of the vibrating surface in $(\text{m/s})^2$
$1 \cdot 10^{-12}$	=	reference level for sound power in W

What sometimes makes equation (10-3) uncertain is *the radiation factor* σ , which is briefly described in Section 6.3.2. For example, for bending waves the radiation factor generally is in the range of $\sim 10^{-4}$ -1 for the breathing mode however, $\sigma = 1$ unless the wavelength of the sound is of the same order as the height of the reactor: this 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

As mentioned in the introduction of this section, 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.

10.3.1.1 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 analyse the frequency content of the measured sound. One way to achieve this is to use an FFT analyser; 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. Examples of acoustic standards are ISO 3743, ISO 3744, ISO 3746 and IEC 60551. 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 energised equipment.

Another method uses sound intensity measurements. 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. The method is 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.

As a final alternative, measurement of the vibration amplitude of a vibrating structure can give a reasonable estimate of sound power. Two factors, which provide uncertainties, are the estimation of the radiation factor, σ , and the risk that too few measuring points are chosen to get a good spatial average of the vibration velocity. Additionally, it might be necessary to use a laser device to avoid high voltages on and/or currents in an object, as vibration transducers, when mounted directly on an energised object, can be destroyed. Vibration measurements do not require special laboratory, but may be expensive if a laser device is needed.

These three methods (sound pressure measurement, sound intensity measurement and vibration measurement) are summarised in section 10.5, where benefits and drawbacks are listed for each measurement method.

10.3.1.2 *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, see e.g. Ref. [12].

Another example of directivity is the result of the actual *placement* of the noise source in relation to reflecting surfaces. This is explained in section 3.9, and is of course very important to bear in mind when sound power determinations are performed.

10.3.1.3 *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 it 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 e.g. Ref. [14].

Furthermore, in a test laboratory it is not always possible to produce the high currents and/or voltages which exist at site. Also, at 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 6-7). 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.

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 (L_{pA}) is calculated from the measured values of the A-weighted sound level (L_{pAi}) by using the following equation;

$$\overline{L}_{pA} = 10 \lg \left(\frac{1}{N} \sum_{i=1}^N 10^{0.1 L_{pAi}} \right) \text{ (dB)} \quad (10-4)$$

where N = total number of measurement points.

The A-weighted sound power level (L_{WA}) of an object may be determined from the average sound pressure level, L_{pA} , according to the following equation;

$$L_{WA} = \overline{L}_{pA} + 10 \lg \left(\frac{S}{S_0} \right) \text{ (dB)} \quad (10-5)$$

where S is the area of the envelope in square metres and S_0 is a reference area of 1 m^2 (see Figure 10.3).

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.

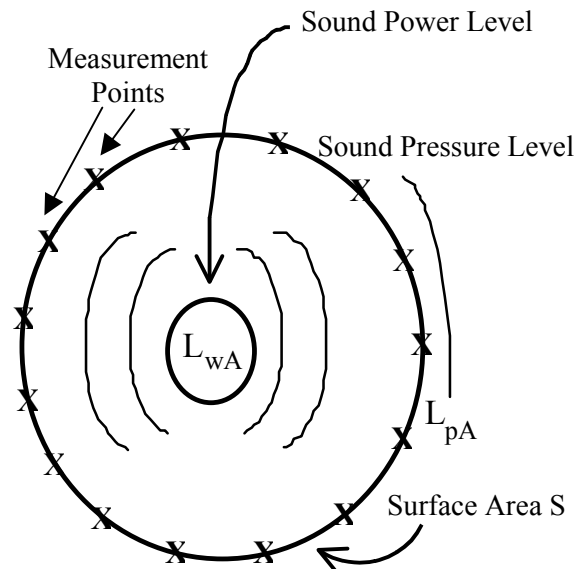


Figure 10.3. Definitions of the parameters used in equation 10-5.

10.3.3 Corrections for background noise

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.

Equation (10-6) gives the relationship between the *total* measured noise level $L_{p,t}$, the *background* noise level $L_{p,b}$ and the (true) *specific* noise level $L_{p,s}$

$$L_{p,s} = 10 \lg(10^{(L_{p,t}/10)} - 10^{(L_{p,b}/10)}) \text{ (dB)} \quad (10-6)$$

10.3.4 Sound intensity measurement

Sound intensity is defined as sound energy emitted by a sound source 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

$$\vec{I}_r = \langle p(t) \cdot v_r(t) \rangle \quad (10-7)$$

where

$$\begin{aligned} \vec{I}_r &= \text{sound intensity in direction } r \\ p(t) &= \text{instantaneous rms sound pressure} \\ v_r(t) &= \text{instantaneous rms particle velocity in direction } r \\ &\text{symbol } \langle \rangle \text{ implies a time average} \end{aligned}$$

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 (10-7) 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 ($r_2 > r_1$).

Sound intensity can then be determined from the following expression:

$$\vec{I}_r = \frac{1}{2\rho\Delta r} \left\langle (p_1 + p_2) \int_0^t (p_1 - p_2) dt \right\rangle \quad (10-8)$$

where

$$\begin{aligned} p_1, p_2 &= \text{rms sound pressure measured at } r_1, r_2 \\ \Delta r &= \text{distance between the two microphones } (= r_2 - r_1) \\ \rho &= \text{mass density of the environment (for air, } \rho = 1.2 \text{ kg/m}^3 \text{ at } 20 \text{ degrees Celsius)} \end{aligned}$$

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

$$W = \int_A \vec{I} \cdot d\vec{A} \quad (10-9)$$

where

$$\begin{aligned} W &= \text{total sound power} \\ \vec{I} &= \text{intensity vector measured by the sound intensity meter} \\ d\vec{A} &= \text{element of surface area } A \end{aligned}$$

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

10.3.5 Vibration measurement

In some cases when sound (pressure or intensity) measurements can not be used to determine the sound power of an object, measurement of the vibration amplitude can give a good, or at least fair, sound power estimation. One important factor, which has to be taken into account, is the vibration pattern of the measurement object. At least four to six measurement points per structural wavelength should be used to provide a good spatial average of the vibration amplitudes. It is thus important to ‘map’ the vibration pattern before any vibration amplitude measurements are started. As also mentioned in section 10.3.1, the radiation factor, σ , can introduce uncertainties to the sound power estimation, as it can vary between e.g. 10^{-4} and 1.

10.4 Combination of calculation and measurement

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.

10.5 Verification

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

10.5.1 Verification of key components

The three general methods for determining the sound power of individual components are summarised in Table 10.2.

Method	Required equipment	Benefits	Drawbacks
Sound Pressure	Sound level meter, preferably together with an FFT analyser or real-time filters	- Simple and relatively fast - Less expensive measuring equipment	- Requires some kind of measurement room or free-field conditions - Sensitive to background noise and reflections
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 measurements
Vibration	Vibration transducers or laser	Easy to 'scan' a surface and achieve a relatively fast sound power estimation	- Can give quite large errors due to poor estimates of radiation factor or of the average vibration amplitude - Might require a laser device, which is expensive

Table 10.2. Summary of different methods for sound power determination.

10.5.2 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 AC-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 the standards, see e.g. Ref. [12].

10.6 References

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11. VERIFICATION OF SOUND LEVELS FROM THE HVDC STATION

11.1 Introduction

Depending on electric load, background harmonics related to the AC 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 station, measurements at the receiver will not give the required information (see section 10.3.2.1 for details about background noise). In such cases, sound level measurements closer to the HVDC station are necessary. These results allow the expected sound level at the receiver location to be calculated by considering the additional attenuation over distance (see section 3.8 and 3.9).

If a suitable measurement point between the nearest inhabited houses and the station can not be found, sound pressure measurements close to or within the station 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 station. 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 stations. 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 Station. 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 influence 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 section 3.8).

11.2 Acoustic environment

When measuring sound inside or near an HVDC station, 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 analysers for quantifying the tonal content and identifying individual noise sources.

The sound field outdoors, in the station 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 station, of the order of hundreds of metres, the microphone may be stationary 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 section 8],
- meteorological conditions [see section 4],
- type of ground and topography included [see sections 4 and 9],
- background noise [see sections 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 section 4. When verification measurements are performed, special meteorological conditions normally have to be fulfilled. Examples of such conditions may be (see also Ref. [3]):

- 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 and 5 m/s, measured at a height of 3 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 section 4 for details.

11.4 Calculation

Calculations are very helpful tools when designing and planning HVDC stations. They give indications of the acoustic performance of the station. Very often it is however necessary to rely on calculations combined with measurements as described in section 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 10 minutes. 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.

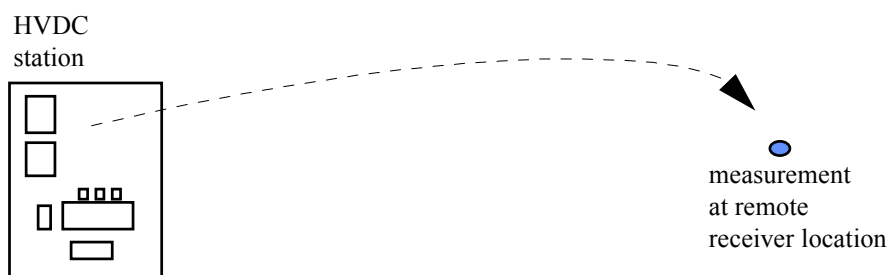


Figure 11.1. Simple sketch of HVDC station and receiver location for measurement of acoustic noise.

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 station 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 station, 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.

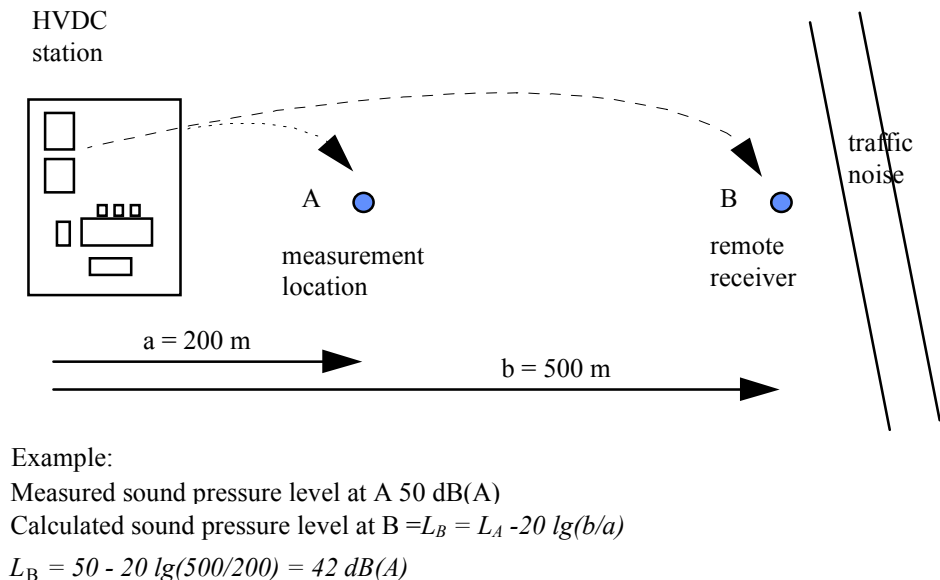


Figure 11.2. The sound pressure level is measured at point A and is then calculated at point B by using the measurements at point A.

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 section 9.

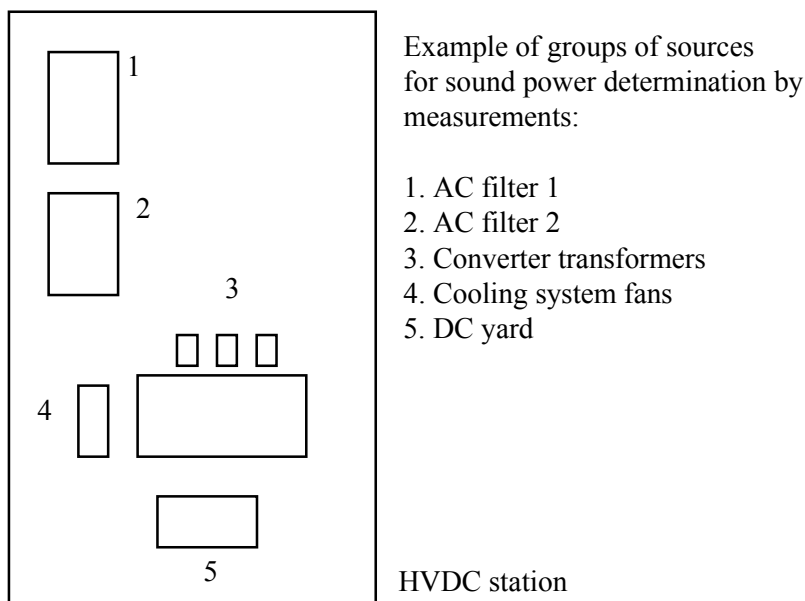


Figure 11.3. Examples of groups of noise sources.

Practical limitations often make it impossible to study one single source by this measuring technique. Instead the station can be divided in larger sub-sources, e.g. ac-filter, transformers, valve cooling fans, dc-filter. Suitable measurement methods can then be chosen for sound level measurements around these different parts of the station. 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 11.4 shows an example of measurement positions around the AC filters for sound pressure level measurements for determining the sound power of the complete filters.

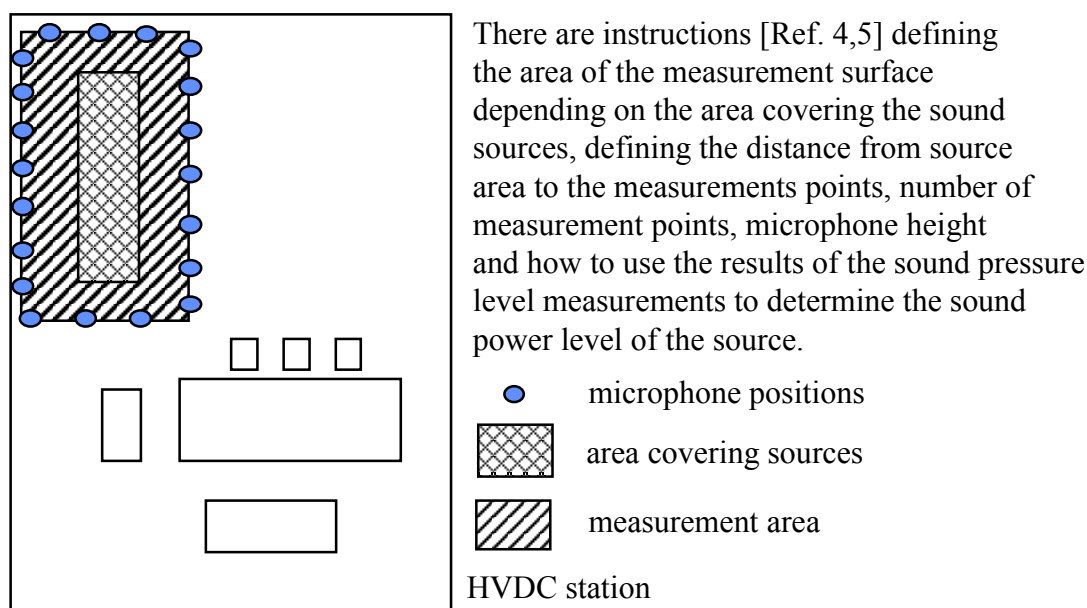


Figure 11.4. HVDC station and example of microphone positions for determination of sound power levels.

11.7 References

- [1] *Prediction And Verification of Tonal Noise From High Voltage Components Considering Interference Effects*. Samuelsson et. al. Published at INTERNOISE99, December 1999
- [2] *ISO 1996-1*, Acoustics - Description and measurement of environmental noise Part 1: Basic quantities and procedures
- [3] *ISO 1996-2*, Acoustics - Description and measurement of environmental noise Part 2: Acquisition of data pertinent to land use
- [4] *ISO 8297*, Acoustics - Determination of Sound Power Levels of Multi Source Industrial Plants for the Evaluation of the Sound Pressure Levels in the Environment
- [5] *Velledning fra Miljøstyrelsen - Beregning af ekstern støj fra virksomheder* (Danish Ministry of Environment - Calculation of External Noise from Industrial Plants. In Danish), Nr. 5 1993
- [6] *ISO 9613-2*. Acoustics - Attenuation of sound during propagation outdoors - Part 2: A general method of calculation
- [7] *ISO 3744*, 1995, Determination of sound power levels of noise sources using sound pressure

12. PARAMETERS TO BE SPECIFIED

This section deals with data and information required for the acoustic design of an HVDC station. The section also covers the subsequent verification of the sound levels in and around the station. 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 station for the design of audible noise. The list intends to contribute to more rational acoustic design of HVDC stations.

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

12.1.1 Land-use classification, noise regulation and limits

(a) Land-use classification of the site for the HVDC station*

A map shall be presented, preferably a topographical map of the area which defines the classification of the land where the station will be located. This map shall also define the type of surrounding areas as well as the location of the nearest neighbours, commercial, public or industrial. See also Section 4, 5 and 11.

☐	Industrial area	☐	Commercial area	☐	Residential area
☐	Recreation area	☐	Other area	☐	

*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. The presence of other acoustic regulations, e.g. corrections for tonal components or short-term noise shall be defined. See also Section 4, 5 and 11.

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

**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.

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)*

☐	At the fence surrounding the station	☐	At the border of customer's property
☐	At a given distance from the centre of the station	☐	At the border of a nearby property
☐	At a given distance from the fence surrounding the station	☐	Other point

*Illustrate the location point on the map. See also Section 4, 5 and 11.

12.1.2 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 station, as they are present at the area where the station will be located. The level 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. This is not a recommended method. See also Section 4, 10 and 11.

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

(b) Topography**

Item	yes	no
Existence of reflective mountain or hill	☐	☐
Existence of high undulations	☐	☐

**Attach the contour map if marking yes. See also Section 4 and 11.

(c) Meteorological condition for verification of audible noise requirements

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

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

*Explain the contents if marking yes. These factors may have a significant impact on sound propagation. See also Section 4 and 11.

(d) Neighbours**

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

Item	yes	no
High possibility of a nearer neighbour in future		

**Applicable if sound requirements are specified at adjacent properties. Attach a sketch, drawing or map. See also Section 5.

(e) Others**

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

**Explain the details if marking yes.

12.1.3 Operation condition of HVDC station

(a) Normal operating conditions

The operating conditions for the station, during the acoustic verification measurements, need to be specified in detail. Please refer to Section 8 regarding conditions to consider.

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

Power system condition to be considered

(b) Operating conditions for noise control design

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

12.2 Data to be clarified by contractors

12.2.1 Noise of components

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

12.2.2 Noise prediction of the HVDC station

The acoustic design includes predicting the contribution from the station 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 also Section 9.

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

12.2.3 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. An assessment regarding the fulfilment of the requirements is also done in this report as well as suggestions about possibly necessary reduction measures. See also Section

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					

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