



IEC 60076-10-1

Edition 2.1 2020-11  
CONSOLIDATED VERSION

# INTERNATIONAL STANDARD



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

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ELECTROTECHNICAL  
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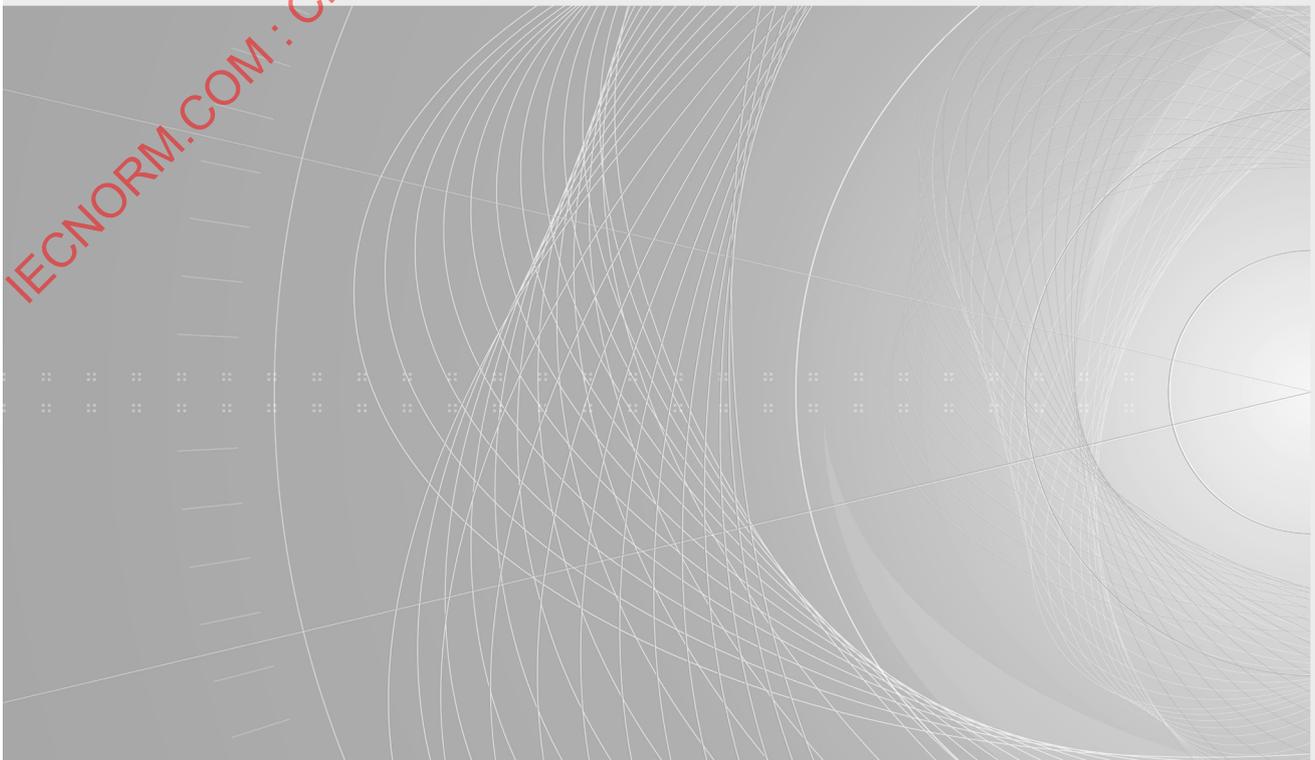
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### POWER TRANSFORMERS –

#### Part 10-1: Determination of sound levels – Application guide

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**IEC 60076-10-1 edition 2.1 contains the second edition (2016-03) [documents 14/847/FDIS and 14/850/RVD] and its amendment 1 (2020-11) [documents 14/1037/CDV and 14/1047/RVC].**

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

International Standard IEC 60076-10-1 has been prepared by technical committee 14: Power transformers.

This second edition constitutes a technical revision.

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

- a) extended information on sound fields provided;
- b) effect of current harmonics in windings enfolded;
- c) updated information on measuring methods sound pressure and sound intensity given;
- d) supporting information on measuring procedures walk-around and point-by-point given;
- e) clarification of A-weighting provided;
- f) new information on frequency bands given;
- g) background information on measurement distance provided;
- h) new annex on sound-built up due to harmonic currents in windings introduced.

This standard is to be read in conjunction with IEC 60076-10.

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

A list of all parts in the IEC 60076 series, published under the general title *Power transformers*, can be found on the IEC website.

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

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## POWER TRANSFORMERS –

### Part 10-1: Determination of sound levels – Application guide

#### 1 Scope

This part of IEC 60076 provides supporting information to help both manufacturers and purchasers to apply the measurement techniques described in IEC 60076-10. Besides the introduction of some basic acoustics, the sources and characteristics of transformer and reactor sound are described. Practical guidance on making measurements is given, and factors influencing the accuracy of the methods are discussed. This application guide also indicates why values measured in the factory may differ from those measured in service.

This application guide is applicable to transformers and reactors together with their associated cooling auxiliaries.

#### 2 Normative references

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

IEC 60076-10:2016, *Power transformers – Part 10: Determination of sound levels*

#### 3 Basic physics of sound

##### 3.1 Phenomenon

Sound is a wave of pressure variation (in air, water or other elastic media) that the human ear can detect. Pressure variations travel through the medium (for the purposes of this document, air) from the sound source to the listener's ears.

The number of cyclic pressure variations per second is called the 'frequency' of the sound measured in hertz, Hz. A specific frequency of sound is perceived as a distinctive tone or pitch. Transformer 'hum' is low in frequency, typically with fundamental frequencies of 100 Hz or 120 Hz, while a whistle is of higher frequency, typically above 3 kHz. The normal frequency range of hearing for a healthy young person extends from approximately 20 Hz to 20 kHz.

##### 3.2 Sound pressure, $p$

The root-mean-square (r.m.s.) of instantaneous sound pressures over a given time interval at a specific location is called the sound pressure. It is measured in pascal, Pa.

Sound pressure is a scalar quantity, meaning that it is characterised by magnitude only.

The lowest sound pressure that a healthy human ear can detect is strongly dependent on frequency; at 1 kHz it has a magnitude of 20  $\mu$ Pa. The threshold of pain corresponds to a sound pressure of more than a million times higher, 20 Pa. Because of this large range, to avoid the use of large numbers, the decibel scale (dB) is used in acoustics. The reference level for sound pressure for the logarithmic scale is 20  $\mu$ Pa corresponding to 0 dB and the 20 Pa threshold of pain corresponds to 120 dB.

An additional and very useful aspect of the decibel scale is that it gives a better approximation to the human perception of loudness than the linear pascal scale as the ear responds to sound logarithmically.

In the field of acoustics it is generally accepted that

- 1 dB change in level is imperceptible;
- 3 dB change in level is perceptible;
- 10 dB change in level is perceived to be twice as loud.

Human hearing is frequency dependent. The sensitivity peaks at about 1 kHz and reduces at lower and higher frequencies. An internationally standardized filter termed 'A-weighting' ensures that sound measurements reflect the human perception of sound over the whole frequency range of hearing (see 5.2).

### 3.3 Particle velocity, $u$

The root-mean-square (r.m.s.) of instantaneous particle velocity over a given time interval at a specific location is called particle velocity. It is measured in metres per second, m/s.

This quantity describes the oscillation velocity of the particles of the medium in which the sound waves are propagating. It is characterised by magnitude and direction and is therefore a vector quantity.

### 3.4 Sound intensity, $\bar{I}$

The time-averaged product of the instantaneous sound pressure and instantaneous particle velocity at a specific location is called sound intensity:

$$\bar{I} = \frac{1}{T} \int_T (p(t) \times \bar{u}(t)) dt \quad (1)$$

It is measured in watts per square metre, W/m<sup>2</sup>.

Sound intensity describes the sound power flow per unit area and is a vector quantity with magnitude and direction. The normal sound intensity is the sound power flow per unit area measured in a direction normal, i.e. at 90° to the specified unit area.

The direction of the sound power flow is determined by the phase angle of the particle velocity at the specific location.

### 3.5 Sound power, $W$

Sound power is the rate of acoustic energy radiated from a sound source. It is stated in watts.

A sound source radiates power into the surrounding air resulting in a sound field. Sound power characterises the emission of the sound source. Sound pressure and particle velocity characterise the sound at a specific location. The sound pressure which is heard or measured with a microphone is dependent on the distance from the source and the properties of the acoustic environment. Therefore, the sound power of a source cannot be quantified by simply measuring sound pressure or intensity alone. The determination of sound power requires an integration of sound pressure or sound intensity over the entire enveloping surface. Sound power is more or less independent of the environment and is therefore a unique descriptor of the sound source.

### 3.6 Sound fields

#### 3.6.1 General

A sound field is a region through which sound waves propagate. It is classified according to the manner in which the sound waves propagate.

When sound pressure and particle velocity are in phase, the corresponding sound field is said to be active. When sound pressure and particle velocity are 90° out of phase, the corresponding sound field is said to be reactive. With an active field the sound energy propagates entirely outwards from the source, as it does (approximately) in far-fields (see 3.6.5). In case of a reactive field the sound energy is travelling outwards but it will be returned at a later instant; the energy is stored as if in a spring. Examples for reactive fields are the diffuse field of a reverberant room (see 3.6.3) and standing waves (see 3.6.6). Averaged over a cycle, the net energy transfer in a reactive field is zero and hence the measured sound intensity is zero, although sound pressure and particle velocity are present.

A practical sound field is composed of both active and reactive components.

#### 3.6.2 The free field

A sound field in a homogeneous isotropic medium whose boundaries exert a negligible effect on sound waves is called a free field. It is an idealised free space where there are no disturbances and through which active sound power propagates.

These conditions hold in the open air when sufficiently far away from the ground and any walls, or in a fully anechoic chamber where all the sound striking the walls, ceiling and floor is absorbed.

Sound propagation from a theoretical point source within a free field environment is characterised by a 6 dB drop in sound pressure level and intensity level each time the distance from the source is doubled. This is also approximately correct when the distance from an area source is large enough for it to appear as a theoretical point source.

When measuring power transformer sound levels free field conditions will be approached with the exception of reflections from the floor.

IEC 60076-10 requires all sound measurements to be made over a reflecting surface. Therefore, measurements in fully anechoic chambers are not allowed.

#### 3.6.3 The diffuse field

In a diffuse field, multiple reflections result in a sound field with equal probability of direction and magnitude, hence the same sound pressure level exists at all locations and the sound intensity tends to zero. This field is approximated in a reverberant room. According to the law of conservation of energy, an equilibrium condition will occur when the sound power absorbed by or transmitted through the room boundaries equals the sound power emitted by the source. This phenomenon may result in very high sound pressure levels in environments having low sound absorption or transmission characteristics.

A practical example of a diffuse field may be the interior of a transformer sound enclosure.

#### 3.6.4 The near-field

The acoustic near-field is considered to be the region adjacent to the vibrating surface of the sound source, usually defined as being within a distance of  $\frac{1}{4}$  of the wavelength of the particular frequency of interest. This region is characterized by the existence of both active and reactive sound components. The reactive sound component decays exponentially with distance from the vibrating surface of the sound source.

Reactive sound components are created if the bending wavelength of the vibrating structure is shorter than the wavelength of the radiated sound. Sound radiation at this condition is characterised by acoustic short-circuits between adjacent regions with over-pressure and under-pressure. In such acoustic short-circuits the air acts as a mass-spring system storing and releasing energy in every cycle. As a result, a part of the sound power is always being circulated and not all of it is radiated into the far-field (see 3.6.5).

The extent of the near-field reduces with increasing frequency.

Sound pressure measurements applied in the near-field will result in a systematic overestimation (Figure 1) because of the inherent phase difference between the sound pressure and particle velocity in the near-field (see 3.6.1). As a result, spatially averaged sound pressure levels are typically 2 dB to 5 dB higher whilst spot measurements may be up to 15 dB higher than the corresponding measured sound intensity level.

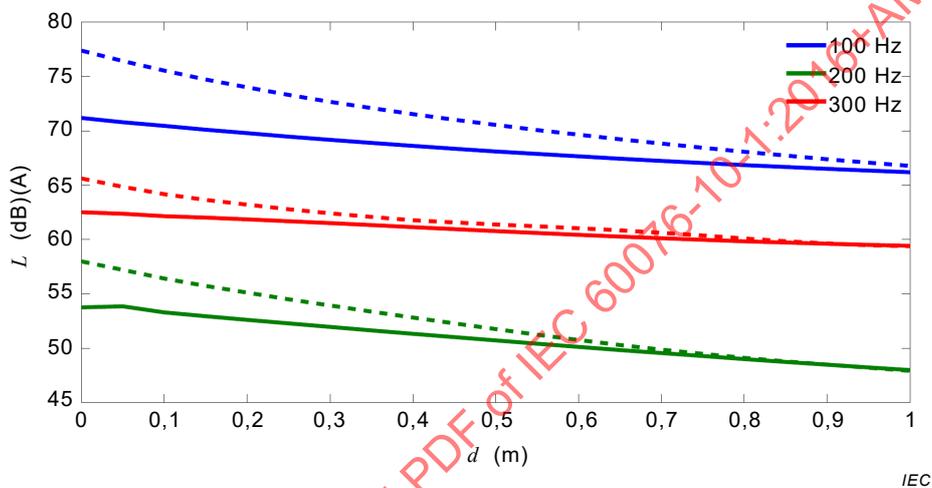


Figure 1 – Simulation of the spatially averaged sound intensity level (solid lines) and sound pressure level (dashed lines) versus measurement distance  $d$  in the near-field

### 3.6.5 The far-field

The sound field beyond a certain distance from the source where inherent disturbances due to the size and shape of the source as well as other interfering disturbances become insignificant is called the far-field. In this field the source can be treated as a theoretical point source and approximate free field conditions exist.

### 3.6.6 Standing waves

Standing waves are the result of interference between two sound waves of the same frequency travelling in opposite directions. Standing waves are formed as a result of reflections between a sound source and structural discontinuities such as the boundaries of the sound field, emphasised if the reflecting surfaces are parallel and when the relationship between sound frequency and distance meets certain conditions. The existence of standing waves of frequency  $f_v$  depends upon the distance  $d$  between the reflecting walls as follows:

$$f_v = v \frac{c}{2d} \quad (2)$$

where  $c$  is the speed of sound in air in m/s (at 20 °C,  $c = 343$  m/s),  $v = 1, 2, 3, \dots$

A standing wave does not transmit energy to the far-field; it is an example of a reactive field.

Within the region of a standing wave

- large variations in measured sound pressure will occur over small distances with the tendency to overestimate sound pressure;
- sound intensity measurements tend to be inaccurate and underestimate the actual sound intensity.

## 4 Sources and characteristics of transformer and reactor sound

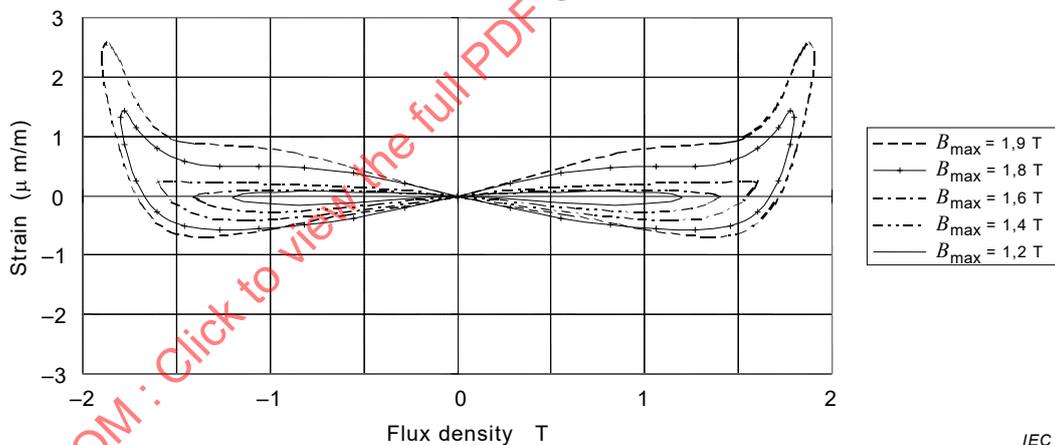
### 4.1 General

Transformer and reactor sound has several inherent physical origins. The significance of those origins of sound generation depends on the design of the equipment and its operating conditions. The design will impact the sound producing vibrations and their propagation from the origin to the transformer tank or enclosure surface and finally the sound radiation into the air.

### 4.2 Sound sources

#### 4.2.1 Core

Magnetostriction is the change in dimension observed in ferromagnetic materials when they are subjected to a change in magnetic flux density (induction). In electrical core steel this dimensional change is in the range of 0,1  $\mu\text{m}$  to 10  $\mu\text{m}$  per metre length ( $\mu\text{m}/\text{m}$ ) at typical induction levels. Figure 2 shows magnetostriction versus flux density for one type of core lamination measured at five different flux densities. Each loop describes one 50 Hz cycle with flux density  $B_{\text{max}}$ .

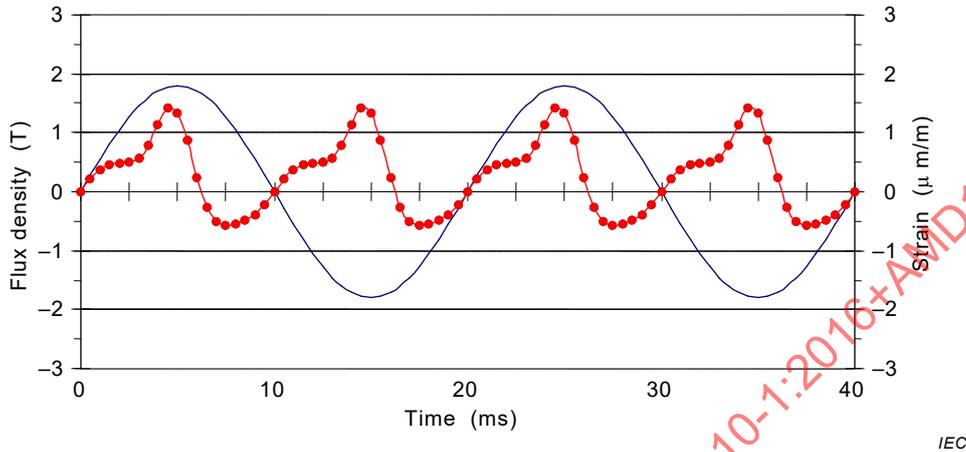


**Figure 2 – Example curves showing relative change in lamination length of electrical core steel during complete cycles of applied 50 Hz a.c. induction up to peak flux densities  $B_{\text{max}}$  in the range of 1,2 T to 1,9 T**

NOTE 1 Mechanical stresses in core laminations will have a strong influence on magnetostriction.

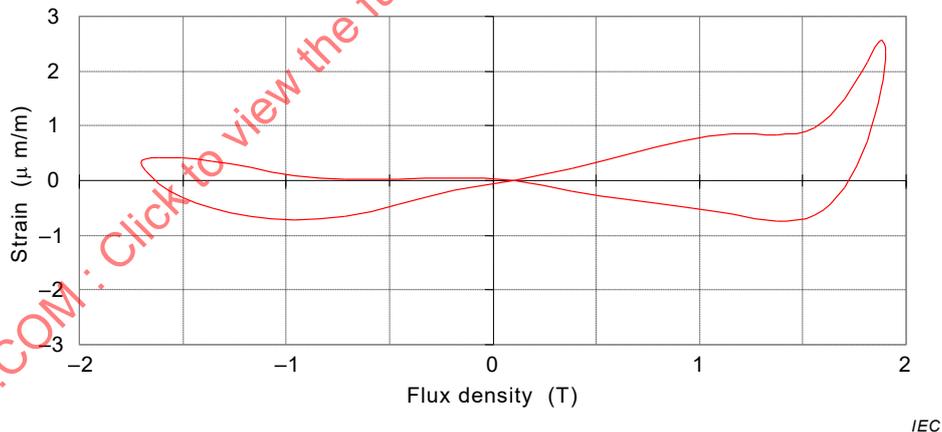
The strain does not depend on the sign of the flux density, only on its magnitude and orientation relative to certain crystallographic axes of the material. Therefore, when excited by a sinusoidal flux, the fundamental frequency of the dimensional change will be twice the exciting frequency. The effect is highly non-linear, especially at induction levels near saturation. This non-linearity will result in a significant harmonic content of the strain and this causes the vibration spectrum of the core. Figure 3 shows the magnetostriction for a sinusoidal induction with  $B_{\text{max}} = 1,8 \text{ T}$  and a frequency of 50 Hz. It has a periodicity of double the exciting frequency with peaks at 5 ms and 15 ms which are indistinguishable.

The sound emitted by transformer cores depends on the velocity of the vibrations, i.e. the rate of change of the magnetostriction (dotted line in Figure 3). This results in an amplification of the harmonics (distortion) in relation to the fundamental which is at double the exciting frequency. Several even multiples of the exciting frequency will be seen in the spectrum; in such cases the fundamental component at double the exciting frequency is seldom the dominant frequency component of the A-weighted sound.



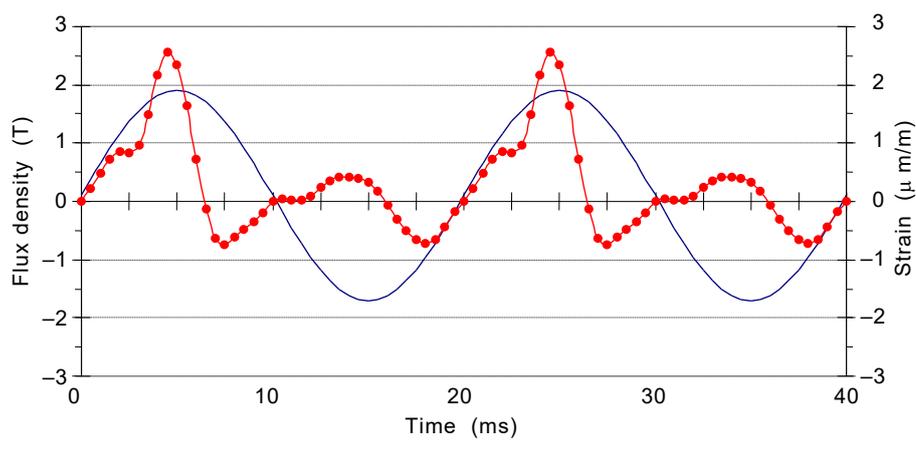
**Figure 3 – Induction (smooth line) and relative change in lamination length (dotted line) as a function of time due to applied 50 Hz a.c. induction at 1,8 T – no d.c. bias**

If the flux has a d.c. bias, for example due to remanence in the core from preceding testing of the windings' resistance, or due to a d.c. component in the current, the strong non-linearity of magnetostriction causes a significant increase in vibration amplitudes. With a d.c. bias on the induction, the peaks in magnetostriction at the positive and negative peak flux density differ significantly; obvious in the magnetostriction loop in Figure 4.



**Figure 4 – Example curve showing relative change in lamination length during one complete cycle of applied 50 Hz a.c. induction at 1,8 T with a small d.c. bias of 0,1 T**

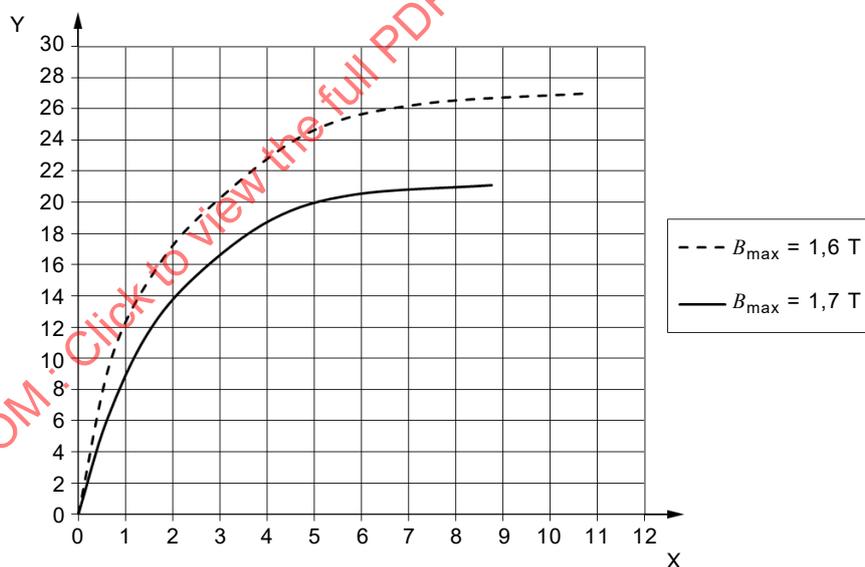
The vibration pattern is now repeated every cycle, that is every 20 ms in a 50 Hz system, indicating a magnetostriction at exciting frequency (see Figure 5). The presence of odd harmonics in the sound spectrum is a clear indication of d.c. bias in the induction.



**Figure 5 – Induction (smooth line) and relative change in lamination length (dotted line) as a function of time due to applied 50 Hz a.c. induction at 1,8 T with a small d.c. bias of 0,1 T**

A d.c. bias in magnetization can significantly affect the sound level of a transformer. Therefore, a transformer undergoing sound tests shall be energised until the temporary effects of inrush currents and remanence have decayed and the sound levels have stabilised.

The ratio between the d.c. bias current and the r.m.s. no-load current is a useful parameter for predicting the increase in sound power due to the d.c. bias current. The relationship between d.c. bias current over no-load current and sound level increase has been measured on a number of large power transformers; Figure 6 shows one set of this data.



**Key**

- X axis d.c. bias current as per unit of a.c. no-load current (r.m.s.)
- Y axis increase in total sound level in dB(A)

**Figure 6 – Sound level increase due to d.c. current in windings**

NOTE 2 Figure 6 shows the results for a certain design of large power transformers with a core having a path for flux return and the core made from high permeable electrical steel. For other constructions, for example with different core form or different electrical steel type, the curve can deviate in detail but will contain the same upward trend.

### 4.2.2 Windings

Load currents in transformer and reactor windings generate a magnetic field that oscillates at the excitation frequency. The resultant electromagnetic forces on the windings act both axially and radially. The magnitude of these forces depends on the magnitude of the load current and on the magnetic field, which itself is a function of the load current. Thus, the magnetic forces on the windings are proportional to the square of the load current while their frequency is twice the excitation frequency. The resulting vibration amplitudes depend on the elastic properties of the conductor, those of the electrical insulation and the proximity of the mechanical eigenfrequencies (natural frequencies of the windings) to the vibration frequency. In a well clamped and tightly wound winding, the elastic properties of the insulating material are almost linear in the range of displacements occurring under normal operating currents. Metals have very linear elastic moduli. Therefore harmonic vibration is normally minimal and the fundamental frequency (double the exciting frequency) dominates the vibration spectrum of windings (see Figure 7).

Winding deflections and their vibrational velocities are proportional to the excitation force which is proportional to the square of the load current. The sound power radiated from a vibrating body is proportional to the square of the vibration velocity (see 4.4). Consequently, the sound power generated by windings varies with the fourth power of the load current.

Harmonics in the load current appear in the sound spectrum at twice their electrical frequency and at the sum and difference of all their frequencies. They can contribute significantly to the transformer or reactor sound level. For more details see 4.2.5.

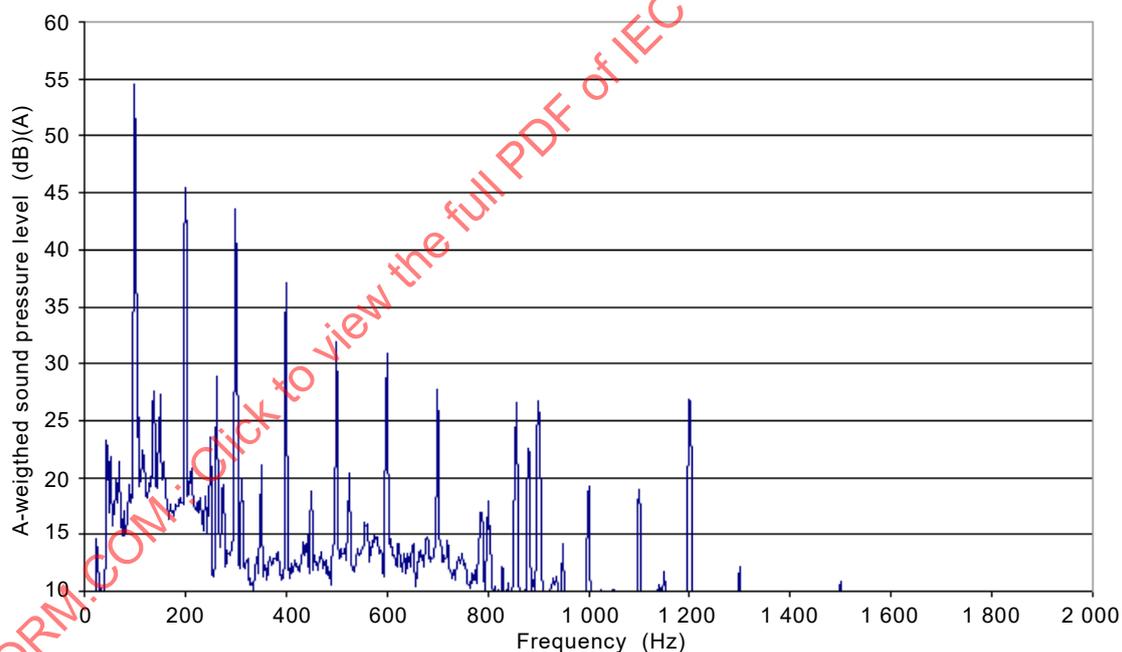


Figure 7 – Typical sound spectrum due to load current

### 4.2.3 Stray flux control elements

Magnetic stray flux in loaded transformers is linked to windings and connection leads. This stray flux shall be controlled to avoid the overheating of inactive metal parts such as the tank by reducing eddy current losses. There are in principle three possibilities to control magnetic stray flux:

- by application of laminated electrical steel the stray flux is guided in a controlled way. Elements providing this guidance are commonly called ‘shunts’ or ‘tank shunts’;

- by application of copper or aluminium shields the stray flux is repelled by eddy current loops in the shield;
- by sizing the tank such that stray flux control is not necessary.

Elements used for stray flux control as well as the tank itself are also sources of vibration due to electromagnetic forces and magnetostriction and they impact the overall sound power level.

The method of attachment of stray flux control elements may influence the sound power level.

#### 4.2.4 Sound sources in reactors

There are several types of single-phase and three-phase reactors, generally utilising two different technologies in their design.

- In air-core reactors, the sound power produced by the winding due to the load current is dominant. The interaction of the current flowing through the winding and its magnetic field lead to vibrational winding forces. While the oscillating forces can be clearly determined, the vibrational response of the winding structure is complex. The vibrational amplitude, the size of the sound radiating surface and its radiation efficiency determine the sound power. The sound power is governed by the magnitude of the winding vibration in the radial direction (because 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 power is usually low.
- In magnetically-shielded reactors (with or without gapped cores), the magnetic force between the yokes tends to close the gap as the flux increases; the cyclic displacement thus produced is the dominant sound source. This force mechanically excites the entire magnetic circuit of the reactor, resulting in a sound spectrum dominated by double the excitation frequency and its first few harmonics. Magnetostriction, winding vibrations and stray flux control elements are also contributing factors to sound power radiation.

NOTE See IEC 60076-6 for definitions of different types of reactor.

#### 4.2.5 Effect of current harmonics in transformer and reactor windings

##### 4.2.5.1 General

As indicated in 7.6 of this standard, power electronic devices can be a source of current harmonics. This effect on the overall sound power level can be significant.

The spectrum of harmonic currents in magnitude and phase shall be specified by the purchaser or the manufacturer of the power electronic device in order to predict a realistic in service sound power level. Where phase angles are not available a statistical approach may be applied.

More detailed information of the theory and engineering practice of additional sound produced by harmonic currents in windings is given in Annex A of this standard.

Radiated sound power from a transformer/reactor depends on the current at all frequencies but usually it is only the fundamental and the most significant harmonic currents out of the current spectrum that contribute significantly.

The determination of the additional sound power due to harmonic currents can be performed with two different approaches:

- by exciting and measuring individual frequencies (usually applicable only for special reactors, such as filter reactors);
- by calculation of the individual frequency contributions.

#### 4.2.5.2 Measuring sound levels of individual frequency components

A set of harmonic exciting currents has to be determined for this test, representing the significant sound harmonics.

Since currents at power frequency and at other frequencies usually cannot be applied simultaneously for testing, the transformer/reactor may be successively tested with power frequency current and currents at other harmonic frequencies. In this case the transformer/reactor shall be tested at currents and frequencies which reflect the current harmonics but also the interaction of currents having different frequencies.

For a transformer/reactor current spectrum with currents  $I_1, I_2, I_3, I_4, I_5 \dots$  the sound significant currents are for example determined to be  $I_1, I_2, I_3$ . These currents result in the following sound components:

Amplitude of currents	Frequency of currents	Sound frequencies
$I_1$	$f_1$	$2 f_1$
$I_2$	$f_2$	$2 f_2$
$I_3$	$f_3$	$2 f_3$

$f_1, f_2, f_3$  are the frequencies of the transformer/reactor r.m.s. currents  $I_1, I_2, I_3$ . Usually  $f_1$  is the power frequency and  $f_2, f_3$  are the frequencies of the significant currents of the current spectrum (significant harmonics).

Pairs of transformer/reactor currents in the table above, for instance  $I_1$  and  $I_2$ , result in two additional frequency components due to interactive effects.

Amplitude of a pair	Frequencies of a pair	Sound frequencies
$(2 I_1 I_2)^{1/2}$	$(f_2 + f_1)/2$	$f_2 + f_1$
$(2 I_1 I_2)^{1/2}$	$(f_2 - f_1)/2$	$f_2 - f_1$

All harmonics and pairs with the same frequency have to be summed and the derived value forms the test current at this frequency. For a correct summation it is necessary to consider the phase correlation, see Annex A for detailed information. Where this is unavailable a statistical approach may be taken by calculating the square root of the sum of squares (SRSS) of the individual current components. If for example  $f_1$  is the power frequency and  $f_2$  and  $f_3$  are the frequencies of the significant harmonics then the following components would usually be taken into account for the derivation of the test currents.

Contributing amplitude	Contributing frequency	Sound frequency
$I_1$	$f_1$	$2 f_1$
$(2 I_1 I_2)^{1/2}$	$(f_2 + f_1)/2$	$f_2 + f_1$
$(2 I_1 I_2)^{1/2}$	$(f_2 - f_1)/2$	$f_2 - f_1$
$(2 I_1 I_3)^{1/2}$	$(f_3 + f_1)/2$	$f_3 + f_1$
$(2 I_1 I_3)^{1/2}$	$(f_3 - f_1)/2$	$f_3 - f_1$

Note that the harmonics themselves and the sum and difference frequency pairs of harmonics usually do not significantly contribute to the radiated sound power. Significant components always involve the excitation frequency current and such pairs require consideration.

When applying the SRSS approach to the above considered current components  $I_1, I_2, I_3$  the following test currents would then be derived for a typical current spectrum comprising the current at excitation frequency  $f_1$  and the significant harmonics at frequencies  $f_2$  and  $f_3$  ( $f_2$  and  $f_3$  are commonly the harmonics of 5<sup>th</sup> and 7<sup>th</sup> order):

Amplitude of test current	Frequency of test current	Sound frequency
$I_{1T} = (I_1 I_1)^{1/2}$	$f_1$	$2 f_1$
$I_{2T} = (2 I_1 I_2)^{1/2}$	$(f_2 - f_1)/2$	$f_2 - f_1$
$I_{3T} = \{[(2 I_1 I_2)^2 + (2 I_1 I_3)^2]^{1/2}\}^{1/2}$	$(f_2 + f_1)/2 \equiv (f_3 - f_1)/2$	$f_2 + f_1$
$I_{4T} = (2 I_1 I_3)^{1/2}$	$(f_3 + f_1)/2$	$f_3 + f_1$

Where the full test current at a harmonic frequency  $f_i$  cannot be applied due to test lab limitations the test can be performed at reduced currents and the sound power at full test current shall then be derived by calculation based on Equation (7) of IEC 60076-10:2016 to

$$L_{iT} = L_{ired} + 40 \times \lg \frac{I_{iT}}{I_{ired}}$$

where

$L_{iT}$  sound level at harmonic frequency  $f_i$  at full test current  $I_{iT}$

$L_{ired}$  sound level at harmonic frequency  $f_i$  at reduced test current  $I_{ired}$

The total sound power level shall then be calculated using the following Equation (3):

$$L_{tot} = 10 \times \lg \left( \sum_i 10^{L_i/10} \right) \quad (3)$$

where

$L_{tot}$  is the total sound power level and

$L_i$  is the sound power level of the individually tested harmonic component  $i$ .

NOTE For power converter transformers, such as industrial and HVDC transformers, application of harmonic test currents is usually impracticable due to unavailability of test equipment.

#### 4.2.5.3 Calculation of the predicted sound level increase due to harmonics

This method of calculation is relative to the known sound level for excitation at fundamental frequency. Calculation steps are as follows:

- Calculate the relative amplitude of forces for harmonics  $I_n$  by applying  $(I_n/I_1)^2$  resulting in components with frequencies of  $(2 f_n)$
- Calculate the relative amplitude of forces for harmonic pairs  $I_n, I_m$  by applying  $(2 I_n I_m)/I_1^2$  resulting in two components per pair with frequencies  $(f_m + f_n)$  and  $(f_m - f_n)$
- Summation of all relative force components per frequency using the given phase relation. If this is not available a statistical approach may be considered (SRSS = square root of the sum of the squares)
- Application of a logarithmic approach per frequency for the dynamic response of winding displacement to the forces (consideration of winding transfer function)
- Conversion of force components per frequency into a logarithmic figure relative to the fundamental force
- Conversion of circular frequency into a logarithmic figure relative to the fundamental frequency
- Application of a logarithmic approach per frequency for the radiation efficiency relative to the fundamental radiation efficiency
- Application of A-weighting per frequency relative to the A-weighting of the fundamental
- Summation of all components d) to h) expressed in dB(A) to derive the total sound power level increase.

Annex A provides more details of this method.

#### 4.2.6 Fan noise

The origin of fan noise is the turbulent flow of air, resulting in pressure fluctuations with a wide range of frequencies, i.e. it is a broadband noise mainly in the range of 300 Hz to 2 kHz. The sound power level of fans is predominantly ruled by the tip speed of the blades, this being a function of blade diameter and rotational speed. By adjusting the angle of attack of the blades the noise and airflow can be influenced.

NOTE A reduction in airflow can invalidate the temperature rise test.

#### 4.2.7 Pump noise

Pump noise and oil flow in general do not contribute significantly to sound power except at very high flow rates or on extremely low-noise transformers. In case of an unexpected pump noise the direction of rotation may be incorrect.

#### 4.2.8 Relative importance of sound sources

Historically, sound level measurements on transformers have been made in the no-load condition with only the magnetising current flowing in the windings. This was acceptable because the magnetostrictive deformation of the core was the primary source of the transformer sound. However, present day transformer designs utilizing high quality electrical steel and having low induction levels often result in a low no-load sound power level to the extent that the sound due to load currents, mainly caused by the windings, becomes significant.

A rough indication, based on empirical data, as to whether a measurement under load conditions may be relevant is given by Equations (5) and (6) of IEC 60076-10:2016 together with an indication of the significance of the result. A general rule of acoustics is that when a sound signal is 10 dB below another signal its contribution to the total (of the two) is insignificant.

The sound power of cooling devices assumes greater significance with low-noise transformer designs or for transformers intended to be used within an enclosure, to the extent that in certain circumstances cooling may be specified without fans (ONAN, ODAN).

### 4.3 Vibration transmission

The magnetic circuit, windings, tank and acoustic enclosure (where provided) are all mechanical structures with their own mechanical resonance frequencies. If the frequency of one of the exciting forces coincides with a structural resonance, a significant amplification of this frequency may occur. Resonances should be eliminated at the design stage, or sufficient damping provided to control the vibration amplitude.

In liquid-filled transformers, vibrations from both the core and windings are transmitted to the tank through the structural supports of the core and coil assemblies and through the incompressible liquid.

If the insulating fluid is a gas, as in the case of dry-type transformers with enclosure or SF<sub>6</sub> transformers, the excitation of vibrations is dominated by the structural supports of the active part.

Vibration isolators beneath core supports inside the tank reduce the transmission of vibrations to the tank and hence decrease the radiated sound power.

Vibration isolators beneath the tank or enclosure are intended to reduce the vibration transmitted to the foundation. Whilst such isolators are intended to minimize vibration propagation they do not significantly influence the sound power of the transformer itself.

NOTE It is noted that the scope of IEC 60076-10 is sound power radiation only and vibration transmission is not included.

In some applications, the transmission of structural vibration may be significant enough to cause problems to the support structure, for instance if a transformer is installed in a building or an offshore platform.

Similarly, transformers mounted on bedrock can cause problems in other buildings mounted on the same bedrock at remote locations.

#### 4.4 Sound radiation

The r.m.s. sound power radiated into the far-field depends on the square of the vibration velocity, the area of the radiating surface and the radiation efficiency of that surface as given in Equation (4)

$$W = \rho_0 c S \sigma \omega^2 x^2 \quad (4)$$

where

- $W$  is the radiated sound power in W;
- $\rho_0$  is the air density in kg/m<sup>3</sup>;
- $c$  is the speed of sound in air in m/s;
- $S$  is the area of the sound radiating surface in m<sup>2</sup>;
- $\sigma$  is the radiation efficiency in per unit, a function of frequency and geometrical and structural properties of the radiating surface;
- $\omega = 2\pi f$  is the acoustic angular velocity in s<sup>-1</sup> for each frequency under consideration;
- $x$  is the r.m.s. vibrational amplitude in m;
- $\rho_0 c$  is the acoustic impedance of air;
- $\omega x$  is the r.m.s. vibration velocity in m/s.

Vibrating objects with dimensions small relative to the wavelength of the radiating frequency have low radiation efficiency; where the dimension of the vibrating object is approaching or larger than the wavelength the radiation efficiency approaches unity. Where acoustic resonances are present the radiation efficiency can exceed unity. Such resonances may occur for example in an open void between tank base and floor or also within the air volume enclosed by the winding of an air core reactor.

NOTE Large, flexible plates with complex vibration patterns radiate less sound than stiff plates with simpler vibration patterns when the vibration amplitudes are equal.

#### 4.5 Sound field characteristics

Transformer sound radiation is mainly caused by bending waves of the tank walls. With reference to Figure 8 it can be seen that the resulting sound radiation around the tank is non-uniform. The distinct patterns result from constructive and destructive interference of sound waves originating from different parts of tank surfaces vibrating with different amplitude and phase.

Non-uniform sound field patterns apply to all tanked transformers but also to dry-type transformers and reactors, whether enclosed or not.

In Figure 8 it is also noted that the distinct pattern of sound intensity is present at all distances which emphasises the fundamental importance of obtaining spatially averaged sound level measurements.

The radiation patterns of higher order sound harmonics show an increased number of interference structures due to the shorter acoustic wavelength.

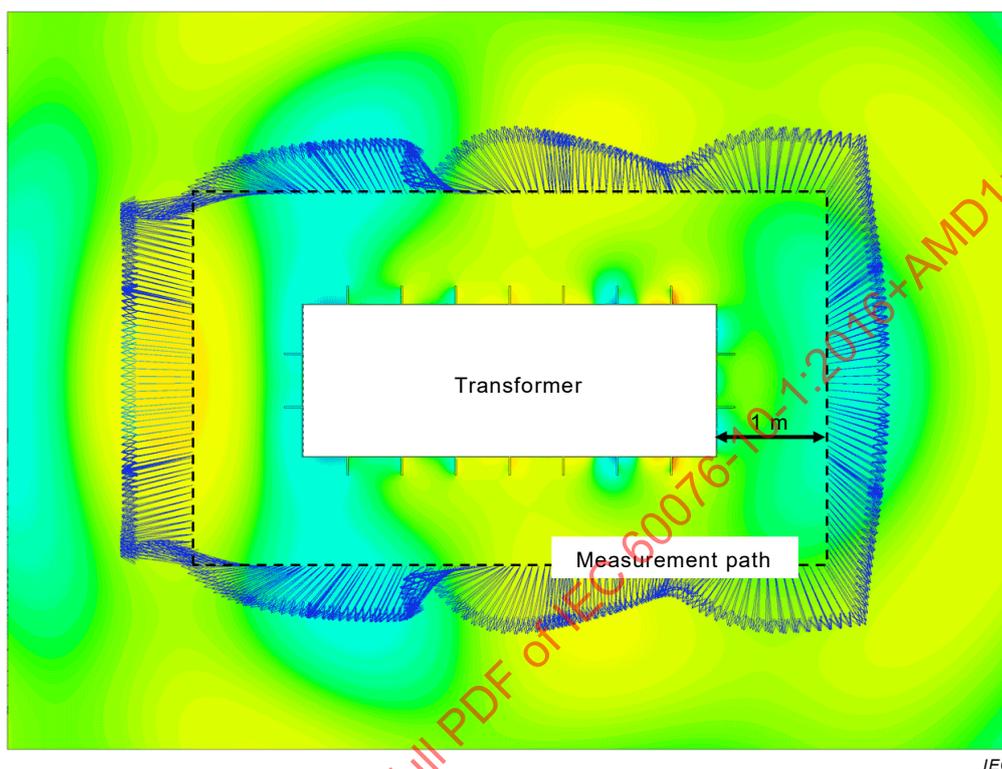


Figure 8 – Simulation of a sound pressure field (coloured) of a 31,5 MVA transformer at 100 Hz with corresponding sound intensity vectors along the measurement path

## 5 Measurement principles

### 5.1 General

The sound power of a transformer is required to allow its operational noise impact to be predicted when it is in its intended position. Sound power cannot be directly measured, it is determined from direct measurement of sound pressure or sound intensity around the transformer.

Sound power estimation is based on the enveloping principle as per ISO 3746; in a modified fashion however because of the inaccessibility of the tank cover due to safety restrictions. The assumption is made that the average sound measured around the sides of the transformer tank can be extrapolated to the tank cover.

This extrapolation is managed by the application of the measurement surface area formula given by Equation (8) in IEC 60076-10:2016. In this formula the measuring height is increased upwards by the measurement distance so as to provide some sensitivity to sound radiated from the tank cover and approximately maintaining the enveloping principle.

### 5.2 A-weighting

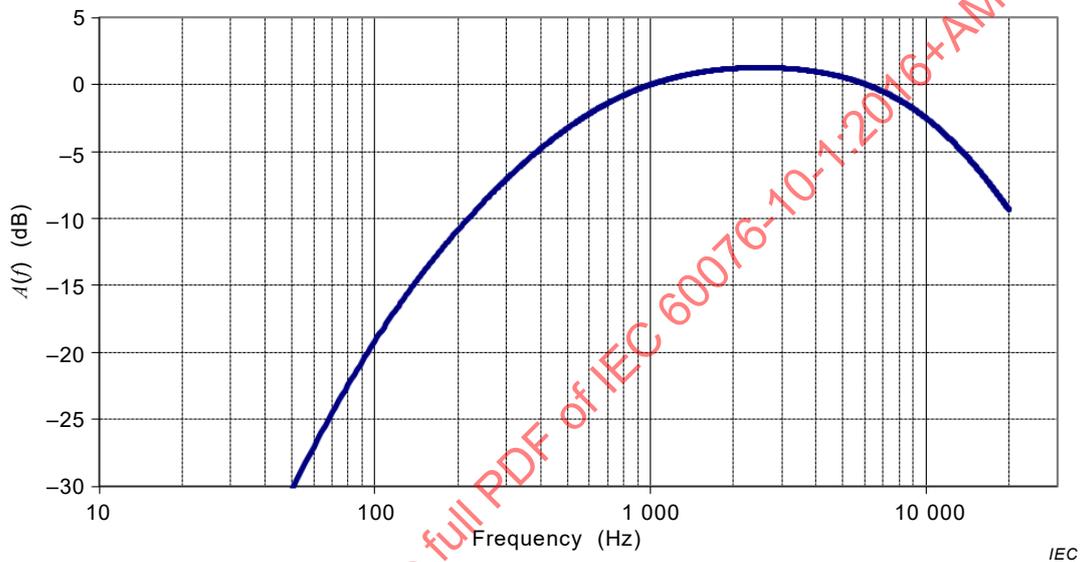
Human hearing is frequency dependent. The sensitivity is highest at about 2 kHz to 3 kHz reducing at lower and higher frequencies. The A-weighted sound level has been shown to

correlate well with the human subjective response to sound. It has been shown to be consistent in comparisons with other weighting scales. This fact has led to it becoming the preferred scale for national and international standards and it is universally used in the field of transformer sound measurement.

The A-weighting function  $A(f)$  as per IEC 61672-1 is given as

$$A(f) = 2 + 20 \times \lg \left[ \frac{12\,200^2 \times f^4}{(f^2 + 20,6^2) \times \sqrt{(f^2 + 107,7^2) \times (f^2 + 737,9^2) \times (f^2 + 12\,200^2)}} \right] \quad (5)$$

and is graphically depicted in Figure 9.



**Figure 9 – A-weighting graph derived from function  $A(f)$**

The above is a continuous function valid for individual frequencies (not frequency bands) in the range of audible sound. Weighting is applied (when selected) to the input signal of an analyser before any band filtering is applied.

If measurements are made without weighting selected, care shall be taken when applying post weighting based on band measurements because band weighting is correct only for the band centre frequency. If a tone lies off the centre frequency of the band an error is introduced. Errors of up to 5 dB can be expected in extreme cases when the tone lies close to the band edge.

Table 1 provides A-weighting values for the characteristic transformer fundamental and harmonic tones.

**Table 1 – A-weighting values for the first fifteen transformer tones**

50 Hz excitation		60 Hz excitation	
Frequency Hz	A-weighting value dB	Frequency Hz	A-weighting value dB
100	-19,1	120	-16,7
200	-10,8	240	-9,1
300	-7,1	360	-5,6
400	-4,8	480	-3,5
500	-3,2	600	-2,2
600	-2,2	720	-1,3
700	-1,4	840	-0,6
800	-0,8	960	-0,1
900	-0,3	1 080	0,2
1 000	0	1 200	0,5
1 100	0,3	1 320	0,7
1 200	0,5	1 440	0,8
1 300	0,7	1 560	1,0
1 400	0,8	1 680	1,1
1 500	0,9	1 800	1,1

### 5.3 Sound measurement methods

#### 5.3.1 General

The purpose of a sound measurement, whether pressure or intensity, is to enable the estimation of the sound power emitted by the test object.

Sound power is the sound intensity integrated over the measuring surface enclosing the test object. The measurement of the sound intensity therefore leads directly to the sound power estimation. Sound intensity is the product of sound pressure and particle velocity and its measurement requires sophisticated measuring techniques.

Another method to estimate sound power is to measure sound pressure with more simple techniques which assumes the sound pressure and particle velocity being in phase and proportional. Measuring sound pressure provides limited information and this method requires corrections where the assumption is not fulfilled.

When sound pressure and particle velocity are in phase (free field condition) a unique relationship exists between sound pressure,  $p$ , and sound intensity,  $I$ , Equation (6):

$$|I| = \frac{p^2}{\rho c}, \quad (6)$$

where  $\rho c$  is the acoustic impedance of the medium through which the sound is propagating. Under standard conditions of pressure and temperature in air,  $\rho c = 412 \text{ kg}/(\text{m}^2\text{s})$ .

Using Equation (6) in the normal sound intensity level equation, the relationship between normal sound intensity level,  $L_I$ , and sound pressure level,  $L_p$ , is shown in Equation (7) as

$$L_I = 10 \times \lg \frac{|\bar{I}|}{I_0} = 10 \times \lg \frac{p^2}{\rho c I_0} = 10 \times \lg \frac{p^2}{p_0^2} + 10 \times \lg \frac{p_0^2}{\rho c I_0} = L_p + 10 \times \lg \frac{p_0^2}{\rho c I_0} \quad (7)$$

For the given reference values of  $I_0$  and  $p_0$  ( $10^{-12} \text{ Wm}^{-2}$  and  $20 \times 10^{-6} \text{ Pa}$  respectively), the term  $10 \times \lg \frac{p_0^2}{\rho c I_0}$  is small when compared with  $L_p$  for most measurements in air at ambient conditions (0,13 dB at 22 °C and  $1,013 \times 10^{-5} \text{ Pa}$ ).

Sound pressure level measurements and sound intensity level measurements performed outside the near-field, i.e. in an ideal free field environment will therefore have the same numerical value.

### 5.3.2 Sound pressure method

Sound pressure is a scalar quantity without directivity information; it is measured with a single measurement microphone. Because the measurement device can locally disturb the sound field significantly it is good practice to point the measurement microphone towards the test object.

Practical test environments usually differ significantly from the ideal free field condition. Transformer sound pressure measurements are generally adversely affected as described below. Test measurements will therefore require a correction based on an understanding of the acoustical properties of the test environment as described in 11.2 of IEC 60076-10:2016.

Pressure waves leaving the radiating surfaces of the test object will be reflected from the floor, walls and other objects in the test room. Reflected sound pressure waves interfere constructively with direct sound pressure waves emitted by the test object.

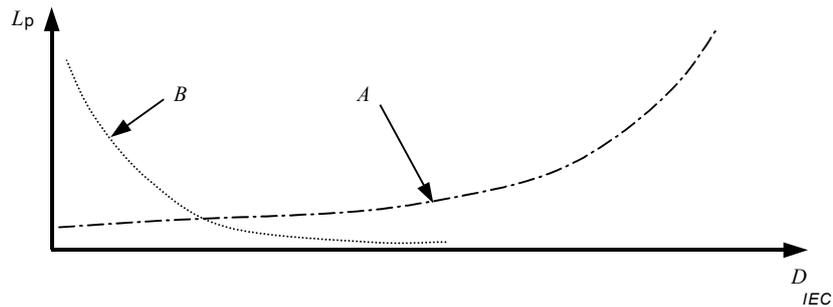
In some cases standing waves can occur. Sound pressure measurements made in the region of standing waves will give an over-estimation of sound power. Standing waves should be avoided or minimised by appropriate placement of the test object in the test room as it is not possible to correct the measurement for this effect (see 6.2 of this standard and 11.1.1 of IEC 60076-10:2016).

Practical test environments are often affected by noise from external sources such as manufacturing processes, the test generator and other energised test transformers. This will increase the measured sound pressure level around the test object.

Sound pressure measurements cannot distinguish between active and reactive sound fields. Near-field effects tend to increase the measured sound pressure level.

As is evident from Figure 10, the effects of some of the above disturbances on the sound pressure can be minimised but they cannot be eliminated.

Standard measurement distances as specified in Clause 8 of IEC 60076-10:2016 are practical compromises based on experience.



**Key**

- A reflection or external sound source pressure disturbance
- B near-field sound source pressure disturbance
- $L_p$  sound pressure level
- D distance between test object and microphone

**Figure 10 – Distribution of disturbances to sound pressure in the test environment**

**5.3.3 Sound intensity method**

Sound intensity is a vector quantity which indicates the direction of sound propagation and therefore allows the sound power entering and the sound power leaving through the measurement surface around the test object to be distinguished. This characteristic allows measurements in non-ideal test environments without corrections. The magnitude of the sound intensity is the time-averaged product of the pressure and particle velocity.

As already stated, a single microphone can measure pressure; however, measuring particle velocity is more complex. Particle velocity is related to the pressure gradient, i.e. the rate at which the instantaneous pressure changes with distance.

The principle of particle velocity measurement is based on Newton's second law applied to air. Newton's second law relates the acceleration given to a mass to the force acting on it. If the force and the mass are known, the acceleration can be found and then integrated with respect to time to find the velocity.

In a sound wave, the pressure gradient accelerates the air of density  $\rho$ .

With the knowledge of the pressure gradient and the density of air, the particle acceleration can be calculated using Equation (8):

$$a = -\frac{1}{\rho} \times \frac{\delta p}{\delta r} \tag{8}$$

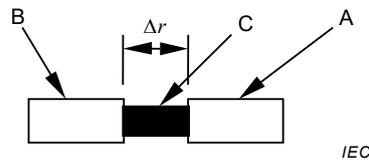
where  $a$  is the particle acceleration due to a pressure change  $\delta p$  in air with density  $\rho$  across a distance  $\delta r$ .

Integrating the above, Equation (9) gives the particle velocity  $u$  as follows:

$$u = -\int \left( \frac{1}{\rho} \times \frac{\delta p}{\delta r} \right) dt \tag{9}$$

It is possible to measure the pressure gradient with two closely spaced microphones, A and B, separated by a spacer of length  $\Delta r$ . With a finite difference approximation of Equation (9) the

pressure gradient can be obtained by taking the difference in their measured pressures  $p_A$  and  $p_B$ , and dividing it by the distance  $\Delta r$  between them.



**Key**

A and B microphones

C spacer of length  $\Delta r$

**Figure 11 – Microphone arrangement**

The pressure gradient signal is then integrated to give the time-averaged particle velocity  $u$  as shown in Equation (10):

$$u = -\frac{1}{\rho} \int \left( \frac{p_A - p_B}{\Delta r} \right) dt \quad (10)$$

Sound intensity is subsequently calculated as the product of the sound pressure in the midst of the microphone pair and the time-averaged particle velocity:

$$I = -\frac{p_A + p_B}{2\rho} \int \left( \frac{p_A - p_B}{\Delta r} \right) dt \quad (11)$$

This is the basic principle of signal processing in sound intensity measuring equipment.

The principle of the sound intensity method theoretically accounts for the disturbances discussed above; in practical test environments however there are limitations for its application.

Where the difference  $(p_A - p_B)$  in pressure between the two microphones is small compared to the absolute pressure magnitude  $(p_A + p_B)/2$  the determination of the pressure gradient tends to become inaccurate.

An indication of this effect can be derived from the difference between the uncorrected sound pressure level containing the disturbances and the sound intensity level of the sound power propagating from the test object alone. Experiments have shown that sound intensity measurement accuracy strongly correlates to this difference  $\Delta L$ , called the P-I index:

$$\Delta L = \overline{L_{pA0}} - \overline{L_{IA}} \quad (12)$$

It has to be recognised that all types of disturbance contribute to the P-I index and the larger a disturbance, the larger is the P-I index.

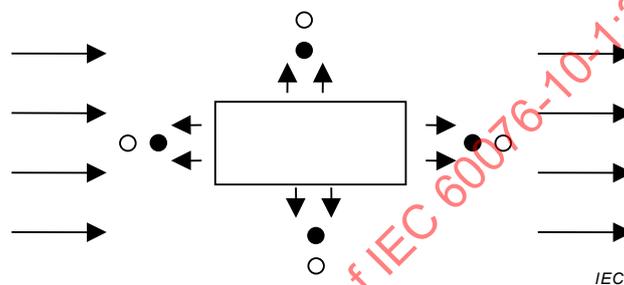
The larger the P-I index, the higher is also the tendency to underestimate the sound intensity level. For this reason, the maximum permissible P-I index has to be limited to assure the measurement quality (see 11.3.5 of IEC 60076-10:2016). It is also noted, that in such situations the sound pressure is overestimated.

Sound waves leaving the radiating surfaces of the test object will be reflected from the floor, walls and other objects in the test room. Due to the sensitivity of the sound intensity probe to the sound propagation direction, sound intensity measurements are usually not adversely affected by such reflections.

NOTE In the situation of a highly or fully diffuse sound field (for instance inside an acoustic enclosure) the sound intensity is close to zero and the P-I index is high, indicating that the measurement is rejected.

Standing waves should be avoided or minimised by careful placement of the test object in the test room, see 6.2 of this standard and 11.1.1 of IEC 60076-10:2016. At locations where standing waves occur, the measuring device will measure intensity close to zero because sound pressure and particle velocity are out of phase. In consequence the intensity level will be reduced and this is indicated by a high P-I index.

Practical test environments are often affected by noise from external sources such as manufacturing processes, the test generator and other energised test transformers. Figure 12 indicates such an environment with steady-state background noise propagation from left to right across the test object.



Microphone pair positions are indicated by the white microphone A and the black microphone B.

**Figure 12 – Illustration of background sound passing through test area and sound radiated from the test object**

With the test object not energised there will be negative intensity measured on the left side, positive intensity on the right side and no intensity measured on the long sides. The spatially averaged intensity will therefore be zero. When the test object is energised there will be an additional amount of positive intensity on all four sides emitted. As mentioned above the net effect on the intensity due to the background noise is zero and therefore has no effect on the test objects intensity. It is noted that this does not apply for the sound pressure.

The ideal situation above does not hold true if the background noise is high relative to the test object noise. In such situations the intensity on the left (short) side is small or even negative and on the right (short) side the intensity is increased. This is not a problem as long as the absolute pressure magnitude  $(p_A + p_B)/2$  does not swamp the pressure difference  $(p_A - p_B)$ . On the top and bottom (long) sides of the test object this effect is more severe because both microphones are exposed to the same absolute pressure increase due to the background noise. The P-I index accounts for this and it is essential to derive the P-I index only from the spatially averaged measurements along the entire (closed) measurement path around the test object.

In summary, the sound intensity method accounts for steady-state background noise but only up to a certain extent. With increasing levels of steady-state background noise, the measured sound intensity level of the test object decreases which is obviously unacceptable. At the same time the P-I index value increases. Working within the limits for the P-I index as stated in 11.3.5 of IEC 60076-10:2016 maintains the acceptability of the measurement.

Sound intensity measurements distinguish between active and reactive sound fields; therefore, near-field effects will not adversely affect the measured sound intensity level.

As stated in 11.3.1 of IEC 60076-10:2016, it is inherent to the sound intensity method that the measurement surface and therefore the measurement path shall completely encircle the test object. Whilst spot indication of sound intensity and P-I index can be informative to identify locations with problematic sound emission, measurements performed to estimate sound power and the corresponding P-I index shall be derived from measurements along the entire measurement path.

#### 5.3.4 Selection of appropriate sound measurement method

Both sound pressure method and sound intensity method can be used for the estimation of sound power and they are expected to give comparable values.

The sound intensity method inherently accounts for the physics of sound and this is reflected in the fact that there is no requirement for corrections. Measured results are acceptable provided the limits for the P-I index (11.3.5 of IEC 60076-10:2016) are maintained. The value of 4 dB as the base limit is introduced after careful consideration and evaluation of the effects imposed by each individual type of disturbance and is backed-up by practical experience. Such experience also revealed that sound power estimations based on sound intensity measurements within this limit represent the true value of the sound power more accurately than sound power estimations based on corrected sound pressure measurements.

Beyond the base limit of 4 dB for the P-I index, sound intensity tends to underestimate and sound pressure tends to overestimate sound power. In this situation the reported sound intensity level is assumed to be 4 dB below the measured sound pressure level, see 11.3.5 of IEC 60076-10:2016. This approximation avoids the risk of sound power underestimation.

The upper limit for the P-I index of 8 dB given in 11.3.5 of IEC 60076-10:2016 is intended to maintain a minimum quality of the test environment.

Where the above conditions cannot be met, i.e. the P-I index exceeds 8 dB and where the sound pressure level is believed to overestimate the sound power, alternative measurement methods such as band selected narrow-band and time-synchronous measurement can be considered.

#### 5.4 Information on frequency bands

The default bandwidth in this standard is 1/3-octave. This bandwidth is commonly used in industry and is routinely available on sound level meters. It normally provides sufficient details for the evaluation of the test object, specifically with respect to transformer tones.

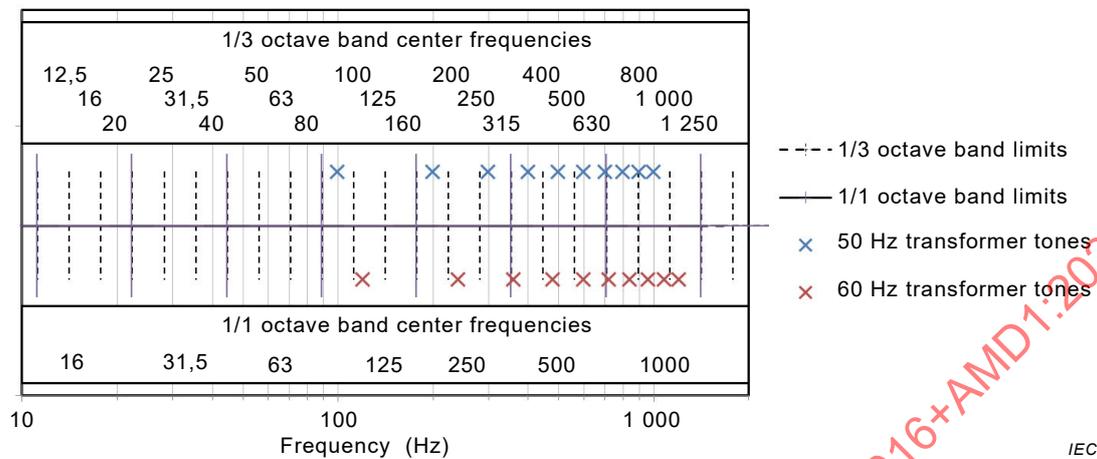
NOTE Octave band levels and the total sound level can be derived from 1/3-octave band levels.

In order to measure individual transformer fundamental and harmonic tones, it is necessary to select appropriately narrow measurement bands. When a tone falls in between two adjacent bands, then the energy of this tone will be distributed across these two adjacent bands.

For 50 Hz systems, the tones up to 600 Hz coincide well with the useful width of the 1/3-octave bands; this is not the case for 60 Hz systems. The 3<sup>rd</sup> harmonic of the 60 Hz system for instance is located on the lower band limit of the 400 Hz band; hence a fraction of the tone energy is represented in the 315 Hz band. To determine the magnitude of a tone split across two adjacent bands, these two band levels have to be summated else a wider bandwidth shall be adopted.

Figure 13 demonstrates the tones of interest and the corresponding 1/3- and 1/1-octave bands.

Dominant tones of interest for the majority of transformers and reactors usually do not go beyond the 6<sup>th</sup> harmonic.



**Figure 13 – 1/1- and 1/3-octave bands with transformer tones for 50 Hz and 60 Hz systems**

Noise of forced air cooling devices and pumps is of broad band character sometimes with tonal components present and 1/3-octave band measurements are generally suitable.

Measurement systems with greater frequency resolution exist, for example the 1/12-octave band system where each 1/3-octave band is subdivided into four smaller bands, generally referred to as a narrow-band measurement. Narrow-band measurements are more selective for tonal sound components compared to 1/3-octave band measurements and allow the suppression of unwanted signals present in the background noise. For the sound power evaluation, only the bands representing characteristic tones of the test object are considered. This method is equally applicable for sound pressure and sound intensity measurements and can be used to determine sound power levels.

A consequence of using narrow-bands is the risk of tonal energy being represented across two adjacent bands. Therefore, when evaluating narrow-band measurements the contribution from adjacent bands shall be considered.

A further consequence of using narrow-bands is the increased sampling time required, particularly for the lower frequencies. To avoid erroneous measurements the sampling time is to be as per measurement device instruction.

Two techniques are commonly used to perform narrow-band measurements.

The digital filter technique works as a bank of parallel real time filters. With this technique 1/*n*-octave band measurements represent the frequency spectrum on a logarithmic scale using constant percentage bandwidth (*cpb*), where for instance the 1/3-octave bandwidth is 23 % and the 1/12-octave bandwidth is 6 % of the band centre frequency.

The Fast Fourier Transform (FFT) technique represents the frequency spectrum on a linear frequency scale using constant bandwidth. It is recommended that the measurement bandwidth is selected to 10 Hz or lower and that the “flat-top” time window of the instrument is used. With this time window the measured amplitude of a tone is insensitive to wherever it falls within the band however a pure tone will also show high levels in adjacent bands. This so-called “leakage” is an artefact which does not affect the accuracy of the band in which a tone falls. If only the individual bands containing characteristic tones are added the presence of this artefact is clearly not relevant. It shall be considered however when consecutive frequency bands are added such as in the case of measurements with cooling equipment in service. The sum of consecutive frequency bands includes the “leakage” and exceeds the true

level by a filter window specific amount. Total sound levels returned from modern devices account for this.

## 5.5 Information on measurement surface

The estimation of the sound power is based on the enveloping method as per ISO 3746. The condition for the application is that no sound power is transmitted through the reflecting plane on which the sound source is placed and all sound power is transmitted through a surface completely enveloping the source. As sound measurements are performed along this surface, this surface is called measurement surface. The sound power of the source is theoretically derived by surface integration of the normal sound intensity over the entire measurement surface. For practical purposes the surface is subdivided into partial surfaces for which individual measurements are performed. In case the partial surfaces are of equal area it is possible to derive an average normal intensity value of all the individual measurements and multiply this value with the entire surface area to obtain the sound power. This explains why it is required to calculate the height of the measurement surface starting from the reflecting plane and any support structures between reflecting plane and test object have to be included in the measurement surface. See also ISO 3746.

For transformers it is usually not possible to access the cover for sound measurements. Therefore, when defining the measurement surface, this situation has to be taken into account and is traditionally done with an extension of the measurement height. Two approaches were used in the past.

First approach:  $S = 1,25 h l_m$

Second approach:  $S = (h + x) l_m$

The first approach is applicable for short measurement distances, practically 0,3 m, only. It includes the cover surface area in an approximate way by the factor 1,25. If the measuring distance increases, the cover area is largely underestimated and this does not comply with the enveloping principle. The second approach accounts for this and is therefore in line with the enveloping principle. It also coincides with the far field hemisphere approach (see 10.2 of IEC 60076-10:2016) at the defined boundary measurement distance of 30 m sufficiently well.

As for a measurement distance of 0,3 m both formulas deviate less than 1 dB for the surface measure and the second formula maintains the enveloping principle also at all other relevant measurement distances, only this formula is selected for use in IEC 60076-10:2016.

## 5.6 Information on measurement distance

The standard measurement distance defined as 0,3 m for distribution type transformers, 1 m for all other transformers and 2 m for measurements with forced air cooling devices in service and for dry-type air-core reactors (see Clause 8 of IEC 60076-10:2016) have been identified as optimal for the following reasons.

### 1) Signal-to-noise ratio

The nearer the microphone is to the test object the better the signal-to-background noise ratio and this in itself is desirable; however this conflicts with other requirements as detailed below.

Achieving a satisfactory signal-to-noise ratio is often the main driver when testing distribution type transformers or low-noise units and the adoption of 0,3 m measuring distance for these applications recognises this requirement.

### 2) Minimisation of near-field effects

As explained in 3.6.4 the near-field decays exponentially with the measuring distance and its effect on the sound pressure method becomes acceptably small for measuring distances of 1 m or larger even for the lowest frequencies of interest.

The above, coupled with the acceptable signal-to-noise ratio at 1 m distance for the majority of transformers other than distribution type transformers, has driven the decision to specify the standard measurement distance to be 1 m for the sound pressure method.

### 3) Minimisation of P-I index

Two effects influence the P-I index. Close to the test object the presence of high reactive sound field components increases the P-I index as do measurements close to the test environment boundaries. These facts coupled with the acceptable signal-to-noise ratio at 1 m distance for the majority of transformers have driven the decision to specify the standard measurement distance to be 1 m for the sound intensity method.

### 4) Minimisation of the effects of turbulence in the microphone

Measurement microphones are extremely sensitive to turbulence. The sound field itself is also disturbed by the presence of turbulences. Both effects have driven the adoption of the 2 m measurement distance for forced air cooling devices when in service. More information on turbulence impacts on sound fields is given in Annex C of ISO 9614-1:1993 and Annex C of ISO 9614-2:1996.

Microphone wind shields reduce the impact of turbulence on the microphone and shall be used.

### 5) Safety aspects

Safety aspects due to exposed high voltage parts shall override the preferred measurement distances mentioned above.

Air-core reactors in particular highlight the above circumstance; 2 m measuring distance is universally adopted.

### 6) Test bay limitation

Specified measurement distances shall be implemented wherever possible; however test bay limitations may have to be accepted leading to the adoption of the next smallest measurement distance.

NOTE In extreme situations, i.e. when reliable sound measurements as per IEC 60076-10:2016 are not achievable in the test lab, a replacement test at site can be considered.

## 5.7 Information on measuring procedures (walk-around and point-by-point)

The standard recognizes the equivalence of the two procedures, i.e. walk-around and point-by-point. Both procedures also provide levels of repeatability within normal tolerances.

It is noted that the walk-around procedure is usually faster; a useful feature for when multiple tests representing different operating conditions are required. Further, the effort for processing the results is minimised.

In Clause 9 of IEC 60076-10:2016 the maximum walking speed for the walk-around procedure is specified at 1 m/s. Operators may favour slower speeds of about 0,5 m/s. This speed may be more easily maintained at a constant level, boom control may be easier and foot step noise may be minimised.

The use of the walk-around procedure may not be advisable if the step noise approaches or exceeds the measured signal. For more details see 6.3.

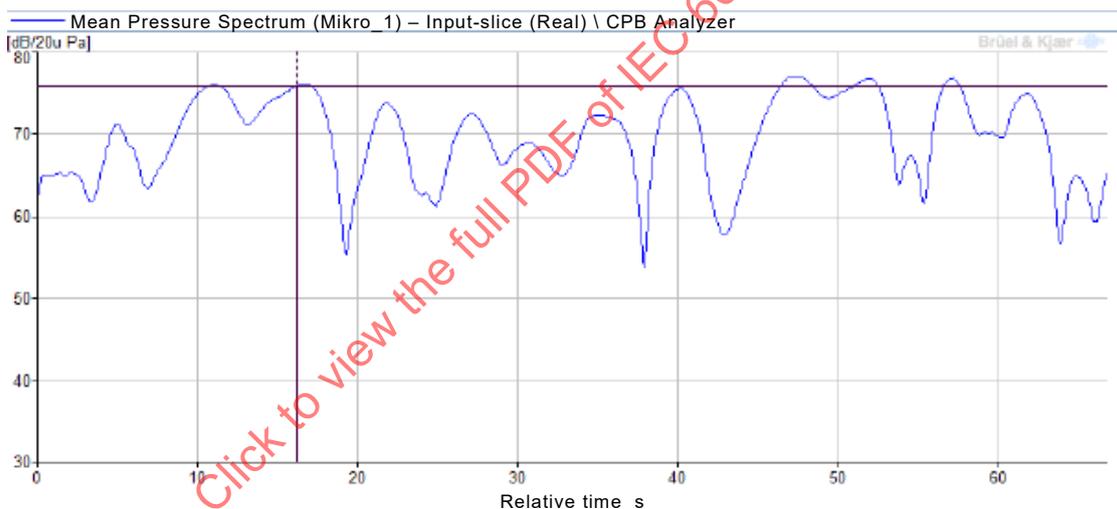
As explained in 4.5 the sound level varies along the measurement path. The sound pressure variation for large units is usually in the range of 5 dB, however a few extreme variations up to 16 dB within one meter can occur, especially for sound level measurements due to load

current (see Figure 14). For small units (distribution type transformers) the variation will be less pronounced.

The walk-around procedure provides a spatially averaged measurement which deals with the variations noted above. The point-by-point procedure also addresses these variations by limiting the maximum microphone spacing to 1 m and by specifying the minimum number of microphone positions for small units.

Figure 14 below depicts an actual walk-around procedure sound pressure measurement showing the variation with time / distance when moving the microphone along the measuring path. The test object and test set up parameters are noted as follows:

Test object:	3-phase / 40 MVA / ONAN
Performed test:	Sound level at rated current
Measurement height:	1/3 and 2/3 of tank height
Measurement distance:	0,3 m
Length of measuring path:	25,7 m
Measuring time:	70 s
Walking speed:	$2 \times 25,7 \text{ m} / 70 \text{ s} = 0,73 \text{ m/s}$
Resolution:	100 ms logging measurement



IEC

**Figure 14 – Logging measurement demonstrating spatial variation along the measurement path**

NOTE For intensity measurements, the logging signal would be more complex because the direction of the intensity usually changes to negative values at certain locations.

## 6 Practical aspects of making sound measurements

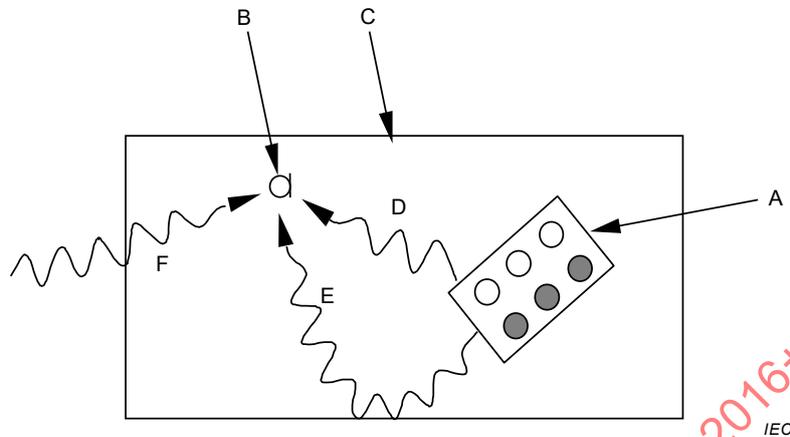
### 6.1 General

This clause provides practical advice on making quality and repeatable sound pressure and sound intensity measurements.

### 6.2 Orientation of the test object to avoid the effect of standing waves

When a test object is placed with its walls in parallel to reflecting walls of the test environment this may result in an extensive amount of standing waves, see 3.6.6. Sound pressure

measurements made in the region of standing waves will result in an over-estimate of the sound power. Sound intensity measurements made in the region of standing waves will result in an under-estimate of the sound power. It is therefore recommended to orientate the test object as illustrated in Figure 15.



**Key**

- |                                       |                        |
|---------------------------------------|------------------------|
| A test object                         | D direct sound wave    |
| B microphone position                 | E reflected sound wave |
| C reflecting surface of the test room | F background noise     |

**Figure 15 – Test environment**

### 6.3 Device handling for good acoustical practice

It is often necessary to mount the microphone on a boom. The operator is obliged to assure the same measuring performance with and without extension boom in use.

In case the handheld device is used without a boom, the operator has to avoid reflections from his body. This is normally achieved if the device is not held between test object and operator's body.

For the intensity method, the microphone spacer shall have a tight contact to the microphones.

A normal life time of a foam windshield (windscreen) in a clean environment is in the range of 5 years but atmospheric pollution can reduce this span dramatically to even just months. To avoid impacts on the sound level measurement aged windshields have to be replaced. Signs of ageing are the loss of elasticity and brittleness. Also dirty and sticky windshields shall be replaced.

Slapping microphone cables can adversely affect the sound level measurements. A fluctuating sound level built up of certain components in the frequency range of 500 Hz to 1 250 Hz is a typical indication for a slapping cable. Measurements performed either with or without long measuring booms can be affected. Fixing the microphone cable to the boom or run it ideally inside the boom may mitigate the effect.

When measuring sound pressure levels below about 40 dB(A) the foot step noise of operators could have an impact on the result derived with the walk-around procedure. Therefore this source of noise should be as low as possible. If this cannot be sufficiently mitigated, consideration should be given to using the point-by-point procedure. Alternatively the measurement path can be subdivided into smaller paths where it is possible to move the microphone with a constant speed without making a step. The single measurements have then to be merged for the final result. This usually applies to small transformers.

The calibration procedure shall be understood and applied with care.

- The calibrator itself requires regular laboratory calibration according to required QA procedures.
- The calibrator shall be coupled to the microphone correctly.
- The microphone / intensity probe calibration shall follow the manufacturer's requirements.
- The calibration shall be made with extension cables included where used.

#### 6.4 Choice of microphone spacer for the sound intensity method

When using the sound intensity method, it is necessary to select a spacer (see Figure 11) appropriate to the frequency range being measured. Assumptions made in the theory of sound intensity measurements impose an upper frequency limit for accurate measurements – the smaller the spacer, the higher the frequency that can be measured. Phase mismatch in the analysing system introduces a low frequency limit – the larger the spacer, the lower the frequency that can be measured accurately.

Operators should refer to the measurement equipment manufacturer's instructions in order to determine the appropriate spacer length for each measurement. As a guide, a spacer of length 50 mm is typically used for low frequency (approximately 63 Hz to 1 250 Hz) sound from transformers and reactors, while a 12 mm spacer is required for higher frequency (approximately 250 Hz to 5 000 Hz) sound from cooling equipment. Nevertheless, common practice is to use just one spacer length for all transformer sound measurements in a specific test lab and this is acceptable if the intensity calibration procedure demonstrates sufficient accuracy over the frequency range of interest.

#### 6.5 Measurements with tank mounted sound panels providing incomplete coverage

Where transformers are provided with tank mounted panels with parts of the tank not covered (usually the top of the tank) it can no longer be assumed that the sound energy radiates equally in all directions. Consequently the approximation  $S=(h+1)l_m$  for the standard measuring distance of 1 m exemplarily will not be valid and would result in an under-estimate of the sound energy radiated into the far-field.

One method to estimate the radiated sound power by using the sound intensity method for a unit with fully covered side walls (voids between panel and tank are closed) but open tank cover is to perform two measurements according the procedure described in IEC 60076-10 one with and one without panels mounted. The measurement performed without panels represents the not covered area whereas the measurement performed with mounted panels is a representative for the covered area. The relevant physical area calculated at the appropriate measuring distance is then taken to determine the partial sound power; the total sound power level is finally derived by logarithmic addition of the partial sound power levels.

Where tank walls are covered only partially, the intensity method as applied in this standard is not applicable because the intensity level measured at the microphone positions will not be representative to the complete transformer surface. The sound power level in such a situation is estimated best with a single measurement based on the sound pressure method as described in the standard at a measuring distance not smaller than 1 m. This procedure can also be applied to units with fully covered side walls but with open tank cover.

The first situation (tank walls fully covered with panels) takes advantage of the directional sensitivity of the sound intensity probe whereas in the second situation (tank walls partly covered with panels) this directional sensitivity would lead to errors.

Other methods, such as intensity mapping are not specifically excluded but would need to be agreed with the purchaser.

## 6.6 Testing of reactors

Reactor testing requires the full reactor power to be supplied. Specifically the voltage often causes high sound levels emitted by the supply transformer which may interfere with the measurement of the reactor sound level. The application of the intensity method can mitigate this and avoids the individual determination of the sound power level of the loaded supply transformer by two separate measurements.

It may not be possible to energize large reactors at rated voltage due to limitations in lab power. In these situations it may be necessary that the sound level measurement is performed at site. This shall be stated in the tender and shall be agreed upon between manufacturer and purchaser. Alternatively, where three-phase units have a path for the return flux (five limb reactors), the sound level may be measured for the three separate single phases under full load and the resulting values summated logarithmically. This provides only an approximation of the total sound level because it assumes that the three sound sources are uncorrelated, which will not be the case when the unit is in operation. The use of this approximation shall be agreed at the tender stage.

## 7 Difference between factory tests and field sound level measurements

### 7.1 General

To assure repeatability, factory measurements are made under controlled conditions specified in sound measurement standards. Sound level measurements made in service are likely to differ from those made in the factory because the test object's operating conditions will deviate from those used in the factory. Such operating conditions are transformer orientation and placement, method of mounting, reflecting objects like firewalls, bund walls and buildings, a variation in operating frequency, voltage and current harmonics, network voltage un-symmetries, proximity of other units, substation and overhead line corona. Meteorological conditions cannot be controlled but should be noted.

Some effects of the above and other factors are described in 7.2 to 7.9 in more detail and should therefore be considered when the purchaser specifies sound level requirements for a transformer and when interpreting sound level measurements made in service.

When switched in service, the transformer sound level is temporarily increased due to d.c. magnetization. This effect may take minutes, hours or even days for large units with low nominal induction to decay (see also 7.7).

### 7.2 Operating voltage

Network voltage can vary by as much as  $\pm 10\%$  under realistic operating conditions and consequently core induction and core sound power level will vary. Depending on transformer design, a sound power level deviation from factory test results up to 5 dB or even 10 dB can be expected.

### 7.3 Load current

In-service load current varies between no-load condition and overload situations. Between these extremes the sound power level due to load current will vary in accordance with Equation (7) of IEC 60076-10:2016.

This formula however does not consider saturation effects caused by leakage flux in magnetic shielding (e.g. tank shunts) due to load current. This may occur during overload situations.

For power transformer designs having a low no-load sound power level loading can significantly impact the total sound power level. In addition load currents also change the internal voltage drop across the transformer impedance (see 7.4). This impacts the core induction level and causes a variation in the transformer core sound power level.

When sound level measurements are made in service, current, voltage and tapping position at each winding shall be noted if available in order to understand excitation levels in different parts of the core and the winding loading.

Some transformers are supplied with an internal current-limiting reactor connected in the tertiary winding circuit. When this tertiary is loaded, the reactor contributes to the sound power level, the contribution varying strongly with the loading level. In these circumstances, the measured sound power level due to load current may deviate from the reported level during final acceptance test. Separate sound power measurements with an open circuit tertiary may be required.

#### **7.4 Load power factor and power flow direction**

In the factory, no-load and load sound power levels are measured separately. These two levels are then added to predict the total sound power level of the test object. This assumes however the vibrations of core and winding are uncorrelated.

Under in-service conditions, depending upon the power factor of the load and the direction of power flow, flux in portions of the core may be modified by superposition of winding stray flux. The phase angle between voltage and load current causes the sound power measured in service to differ from the factory predicted sound power by a small amount, generally in the order of  $\pm 1$  dB. Reversing the power flow may enhance this effect, sometimes, significantly. Shunt connected reactive loading may also have a significant effect, either increasing or decreasing the sound power level. A typical example would be that of SVC transformers.

#### **7.5 Operating temperature**

For the majority of transformers, the sound level will be effectively constant with varying operating temperature; however, for certain units, the sound level may vary. In these cases the variation from a cold start to equilibrium at normal operating conditions can reach up to 3 dB.

#### **7.6 Harmonics in the load current and in voltage**

During factory acceptance testing, the standard requires voltage and current to be sinusoidal and the radiated sound power is the result of this condition.

The sound power level at in-service condition may increase due to the presence of harmonics.

Since our networks are operated with a constant voltage and limits for the harmonic distortion have to be maintained, the sinusoidal voltage wave shape will be preserved to a high degree, resulting in only minor influence on transformer no-load sound levels. This also applies for converter connected transformers.

However, when harmonic currents are injected in windings of transformers and reactors by power electronic devices this results in an increased load sound power level. This effect on the overall sound power level can be significant because these higher frequencies are attenuated less by A-weighting than the 100 Hz or 120 Hz fundamental.

For details see 4.2.5 and Annex A.

Grid coupling transformers, generator step-up transformers and step-down transformers will usually not be subject to harmonic current distortion.

As the rating of the power electronic converter approaches the rating of the transformer, harmonic current distortion becomes progressively more significant. This applies to the following application: HVDC transformers, rectifier transformers, transformers for SVC and VSC application, railway feeders based on converters, traction transformers and transformers for drive applications.

## 7.7 DC magnetization

Even moderate d.c. magnetization of a transformer core, as described in 4.2.1 may result in a significant increase in the transformer sound level. Transformer cores usually have very low no-load currents and when subjected to d.c. bias currents, they may develop sound levels as much as 30 dB higher than the factory test value (see also Figure 6).

Traditionally, circuits such as d.c. feeders to transportation systems have been a source of d.c. fields in transformers. However, with the increased presence of high power electronic equipment inherent to power transmission systems and industry, the number of possible sources for d.c. magnetization continues to increase. As an example, HVDC systems operating in ground return mode may introduce d.c. currents into transformer neutrals which then spread out into the surrounding a.c. network.

Another source causing d.c. or quasi d.c. currents can be galvanic facilities including cathodic protection systems.

Moderate d.c. currents can be generated by switching un-symmetries in transformer connected VSC converters.

If a.c. and d.c. lines are routed in parallel (supported by the same tower) this results in small stray d.c. currents flowing in the a.c. line.

In transformers connected to long transmission lines, geomagnetic storms may cause so called geomagnetically induced currents (GIC), which can also result in severe d.c. magnetization. Single-phase, three-phase five limb and all shell-type transformers are particularly sensitive.

Blocking d.c. currents will mitigate the issue for a specific transformer, however this may shift the problem to another place in the network.

## 7.8 Effect of remanent flux

Remanent flux has a similar effect on the no-load sound level to that produced by d.c. bias currents. During factory testing, great care is taken to ensure that the remanent flux originating from impulse testing (mainly switching impulse) or resistance measurements is dissipated prior to performing the sound level tests.

On site, energising and de-energising the transformer or switching actions in the network can introduce remanent flux and hence increase the transformer sound level. These remanent flux effects will decay naturally with time; this can take minutes, hours or even days for large units with low nominal induction.

## 7.9 Sound level build-up due to reflections

Factory sound level measurements account for the presence of reflections by either using the sound intensity method or corrected sound pressure method.

On-site installations are frequently characterized by the presence of reflecting objects like firewalls, bund walls and buildings. In these circumstances where free field conditions do not exist, measurements will be adversely affected by the presence of reflections. This will result in higher sound pressure levels at locations in front of the reflecting plane (particularly between the transformer and the large reflecting plane). Valid sound level measurements may not be possible.

In case of a complete enclosure or an indoor installation, the build-up of sound pressure level can be estimated by application of the environmental correction  $K$  according to 11.2.5 of IEC 60076-10:2016. In these circumstances  $K$  may acceptably exceed the limit of 7 dB.

## 7.10 Converter transformers with saturable reactors (transducers)

~~It is normally not possible to perform factory sound level measurements on converter transformers with built-in saturable reactors with the reactors functioning as in service, i.e. with nominal d.c. current. During factory test a.c. currents are applied and those do not cause saturable reactors to produce any significant sound.~~

~~Because saturable reactors are essentially continuously wound cores made from electrical steel without any gaps, the vibration of such reactors is comparatively small, even if operating close to or in saturation. This behaviour together with their relatively small sound radiation surface results in a sound power level of the built-in saturable reactors which is negligible compared to the sound power level produced by the converter transformer, specifically in service with the presence of current harmonics.~~

~~NOTE Sound levels from converter transformers are also discussed in IEC TS 61973:2012 and in CIGRÉ Technical Brochure No. 202:2002, "HVDC stations audible noise".~~

It is normally not possible to perform factory sound level measurements on converter transformers with built-in saturable reactors with the reactors functioning as in service, i.e. with nominal d.c. current. During factory test, a.c. currents are applied, and the saturable reactors thereby experience strong saturation in both directions. This saturation generates a specific audible noise that normally significantly exceeds the generated sound level of the transformer itself.

The main operating component of a saturable reactor is the magnetic core, which is the source of the noise. When the reactor cores enter saturation during transformer testing with a.c. load current, the accompanied magnetic flux in the saturable reactor cores is heavily distorted and causes vibration components of higher harmonic frequencies that dominate the measured converter transformer sound level. Converter transformer sound levels measured under such conditions are consequently found to be significantly higher than those of regular transformers of same power rating.

The service sound level of converter transformers with built-in saturable reactors due to load current is normally dominated by the presence of current harmonics produced by the converters (see Annex A). However, higher frequency sound components are also produced by the saturable reactors in regular service condition. There are no reliable methods to calculate the sound level of saturable reactors.

NOTE Sound levels from converter transformers are also discussed in IEC TS 61973:2012, IEC 61378-3:2015, CIGRÉ Technical Brochure 202: "HVDC stations audible noise" and CIGRÉ Paper "Sound contribution of saturable reactors in rectifier transformers during FAT".

## Annex A (informative)

### Sound level built up due to harmonic currents in windings

#### A.1 Theoretical derivation of winding forces due to harmonic currents

A current  $i(t)$  composed of a fundamental component (index 1) and a harmonic component of  $n^{\text{th}}$  order is given as

$$\begin{aligned} i(t) &= \hat{i}_1 \sin(\omega t) + \hat{i}_n \sin(n(\omega t) + \varphi_n) \\ i(t) &= \sqrt{2} i_1 \sin(\omega t) + \sqrt{2} i_n \sin(n(\omega t) + \varphi_n) \end{aligned} \quad (\text{A.1})$$

where

- $\omega = 2 \pi f$  is the fundamental angular frequency;
- $f$  is the fundamental frequency (e.g. 50 Hz);
- $t$  is the time;
- $\varphi_n$  is the phase angle of the  $n^{\text{th}}$  harmonic in relation to the fundamental.

The force  $F$  in windings which causes the vibration and finally the acoustic emission is proportional to the square of the current:

$$\begin{aligned} F \sim i(t)^2 &= 2 [i_1 \sin(\omega t) + i_n \sin(n(\omega t) + \varphi_n)]^2 \\ &= 2 [i_1^2 \sin^2(\omega t) + i_n^2 \sin^2(n(\omega t) + \varphi_n) + 2 i_1 i_n \sin(\omega t) \sin(n(\omega t) + \varphi_n)] \end{aligned} \quad (\text{A.2})$$

By using the identities

$$\begin{aligned} \sin^2(x) &= \frac{1}{2} [1 - \cos(2x)] \\ \sin(x) \times \sin(y) &= \frac{1}{2} [\cos(x - y) - \cos(x + y)] \end{aligned}$$

Equation (A.2) can be rewritten as

$$\begin{aligned} F \sim i(t)^2 &= (i_1^2 + i_n^2) - \\ &- [i_1^2 \cos(2\omega t) + i_n^2 \cos(2n(\omega t) + 2\varphi_n)] + \\ &+ 2 i_1 i_n [\cos((n-1) \times (\omega t) + \varphi_n) - \cos((n+1) \times (\omega t) + \varphi_n)] \end{aligned} \quad (\text{A.3})$$

The first term in Equation (A.3) is time independent and as such describing a static force which does not cause any winding vibration and sound power.

Table A.1 outlines the force components from Equation (A.3) which cause winding vibrations and subsequently sound power.

**Table A.1 – Force components of windings due to harmonic currents**

Sound frequency	Magnitude (r.m.s.)	Phase angle	Vibration component caused by
$2f$	$i_1^2$	$180^\circ$	fundamental current
$(n-1)f$	$2i_1i_n$	$\varphi_n$	interaction between fundamental and harmonic current (lower inter-harmonic)
$(n+1)f$	$2i_1i_n$	$180^\circ + \varphi_n$	interaction between fundamental and harmonic current (upper inter-harmonic)
$2nf$	$i_n^2$	$180^\circ + 2\varphi_n$	harmonic current of $n^{\text{th}}$ order

The last component with a sound frequency of double the  $n^{\text{th}}$  harmonic frequency is of minor significance for the sound level increase. This is due to the practically small magnitude of the harmonic current compared to the fundamental.

When the current spectrum contains, beside the fundamental, more than one harmonic, e.g. the 5<sup>th</sup>, 7<sup>th</sup>, 11<sup>th</sup> and 13<sup>th</sup> harmonic, it is practically usually sufficient to consider only force components which involve the fundamental current.

## A.2 Force components for a typical current spectrum caused by a B6 bridge

The current spectrum of the widely used B6 converter bridge, as for instance in HVDC schemes, is well known in magnitude and phase. Whereas the magnitude is identical for star and delta connected windings this is not the case for the phase angle. The figures of both cases are disclosed in Table A.2 together with a third case, in which the phase relation is assumed to be unknown.

**Table A.2 – Current spectrum of a B6 converter bridge**

harmonic current order	harmonic current frequency	Delta connected winding		Star connected winding		Unknown phase relation	
		Current amplitude p.u.	Current phase degree el.	Current amplitude p.u.	Current phase degree el.	Current amplitude p.u.	Current phase degree el.
1 <sup>st</sup>	50 Hz	1,000	$0^\circ$	1,000	$0^\circ$	1,000	unknown
5 <sup>th</sup>	250 Hz	0,200	$0^\circ$	0,200	$180^\circ$	0,200	unknown
7 <sup>th</sup>	350 Hz	0,143	$0^\circ$	0,143	$0^\circ$	0,143	unknown
11 <sup>th</sup>	550 Hz	0,091	$0^\circ$	0,091	$180^\circ$	0,091	unknown
13 <sup>th</sup>	650 Hz	0,077	$0^\circ$	0,077	$0^\circ$	0,077	unknown
17 <sup>th</sup>	850 Hz	0,059	$0^\circ$	0,059	$180^\circ$	0,059	unknown
19 <sup>th</sup>	950 Hz	0,053	$0^\circ$	0,053	$0^\circ$	0,053	unknown



**Figure A.1 – Current wave shape for a star and a delta connected winding for the current spectrum given in Table A.2**

The application of the theory revealed in Clause A.1 on the current spectrum in Table A.2 allows the estimation of the winding forces per sound frequency. From those quantities a set of equivalent test currents can be derived. The test currents produce the same winding forces as the provided current spectrum and need to be injected in case of subsequent sound level measurements per frequency, as outlined in 4.2.5.2.

In Table A.3 the calculation of forces and test currents is provided in detail for all components which involve the fundamental current, as those are the significant contributors for the sound level increase in this case. It may be required by a purchaser to prove this significance by extending the calculations on harmonics and pairs of harmonics. As the current spectrum is given in p.u. so are the forces and test currents.

**Table A.3 – Calculation of force components and test currents**

Frequency of sound harmonic	Harmonic order of current	Magnitude of force harmonics	Phase / force / test current / test frequency		
			Force as per SRSS method: $F_n = [(2I_n I_1)^2 + (2I_m I_1)^2]^{1/2}$ Test current: $i_{Tn} = F_n^{1/2}$		
Hz		p.u.	Delta connected winding	Star connected winding	Unknown phase relation
100	1 <sup>st</sup>	1,000	$F_1 = 1,000 / i_{1T} = 1,000 / 50 \text{ Hz}$		
200	5 <sup>th</sup> – 1 <sup>st</sup>	$2 \times 0,200 \times 1,000 = 0,400$	$F_2 = 0,400 / i_{2T} = 0,632 / 100 \text{ Hz}$		
300	5 <sup>th</sup> + 1 <sup>st</sup>	$2 \times 0,200 \times 1,000 = 0,400$	$\varphi_5 = 0^\circ$	$\varphi_5 = 180^\circ$	SRSS $F_3 = 0,492 /$ $i_{3T} = 0,701 /$ 150 Hz
	7 <sup>th</sup> – 1 <sup>st</sup>	$2 \times 0,143 \times 1,000 = 0,286$	$\varphi_7 = 0^\circ$ difference $F_3 = 0,114 /$ $i_{3T} = 0,338 / 150$ Hz	$\varphi_7 = 0^\circ$ sum $F_3 = 0,686 /$ $i_{3T} = 0,828 /$ 150 Hz	
400	7 <sup>th</sup> + 1 <sup>st</sup>	$2 \times 0,143 \times 1,000 = 0,286$	$F_4 = 0,286 / i_{4T} = 0,535 / 200 \text{ Hz}$		
500	11 <sup>th</sup> – 1 <sup>st</sup>	$2 \times 0,091 \times 1,000 = 0,182$	$F_5 = 0,182 / i_{5T} = 0,427 / 250 \text{ Hz}$		
600	11 <sup>th</sup> + 1 <sup>st</sup>	$2 \times 0,091 \times 1,000 = 0,182$	$\varphi_{11} = 0^\circ$	$\varphi_{11} = 180^\circ$	SRSS $F_6 = 0,238 /$ $i_{6T} = 0,488 /$ 300 Hz
	13 <sup>th</sup> – 1 <sup>st</sup>	$2 \times 0,077 \times 1,000 = 0,154$	$\varphi_{13} = 0^\circ$ difference $F_6 = 0,028 /$ $i_{6T} = 0,167 /$ 300 Hz	$\varphi_{13} = 0^\circ$ sum $F_6 = 0,336 /$ $i_{6T} = 0,580 /$ 300 Hz	
700	13 <sup>th</sup> + 1 <sup>st</sup>	$2 \times 0,077 \times 1,000 = 0,154$	$F_7 = 0,154 / i_{7T} = 0,392 / 350 \text{ Hz}$		
800	17 <sup>th</sup> – 1 <sup>st</sup>	$2 \times 0,059 \times 1,000 = 0,118$	$F_8 = 0,118 / i_{8T} = 0,344 / 400 \text{ Hz}$		
900	17 <sup>th</sup> + 1 <sup>st</sup>	$2 \times 0,059 \times 1,000 = 0,118$	$\varphi_{17} = 0^\circ$	$\varphi_{17} = 180^\circ$	SRSS $F_9 = 0,159 /$ $i_{9T} = 0,398 /$ 450 Hz
	19 <sup>th</sup> – 1 <sup>st</sup>	$2 \times 0,053 \times 1,000 = 0,106$	$\varphi_{19} = 0^\circ$ difference $F_9 = 0,012 /$ $i_{9T} = 0,110 /$ 450 Hz	$\varphi_{19} = 0^\circ$ sum $F_9 = 0,224 /$ $i_{9T} = 0,473 /$ 450 Hz	
1 000	19 <sup>th</sup> + 1 <sup>st</sup>	$2 \times 0,053 \times 1,000 = 0,106$	$F_{10} = 0,106 / i_{10T} = 0,326 / 500 \text{ Hz}$		

The results given in Table A.3 are summarized in Table A.4.

**Table A.4 – Summary of harmonic forces and test currents**

Frequency of sound harmonic	Frequency of test current	Delta connected winding		Star connected winding		Unknown phase relation	
		Forces	Test currents	Forces	Test currents	Forces	Test currents
Hz	Hz	p.u.	p.u.	p.u.	p.u.	p.u.	p.u.
100	50	1,000	1,000	1,000	1,000	1,000	1,000
200	100	0,400	0,632	0,400	0,630	0,400	0,630
300	150	0,114	0,338	0,686	0,828	0,492	0,701
400	200	0,286	0,535	0,286	0,535	0,286	0,535
500	250	0,182	0,427	0,182	0,427	0,182	0,427
600	300	0,028	0,167	0,336	0,580	0,238	0,488
700	350	0,154	0,392	0,154	0,392	0,154	0,392
800	400	0,118	0,344	0,118	0,344	0,118	0,344
900	450	0,012	0,110	0,224	0,473	0,159	0,398
1 000	500	0,106	0,326	0,106	0,326	0,106	0,326

Table A.4 reveals at a glance the impact of the harmonic current's phase angle to the winding force and sound harmonics. The sound level increase due to the current spectrum of a B6 bridge is larger in a star connected winding than in a delta connected winding. As the phase relation of the harmonic currents is often not provided in practice, the application of the SRRS method (see 4.2.5.3) may be the only way to approach the situation. As can be seen, this method results in force values which are in between those for the star and delta connected windings but closer to the higher values of the star connected winding. The application of the SRRS method is therefore considered to be a reasonable approach in situations where the phase relation cannot be provided.

Table A.4 furthermore indicates the need to consider sound frequency components up to 1 000 Hz or even higher when calculating or testing the sound level increase of a transformer / reactor due to harmonic currents. It is common practice to measure the sound level of filter reactors by harmonic current injection up to 1 000 Hz.

### A.3 Estimation of sound level increase due to harmonic currents by calculation

In cases where it is not possible to excite a transformer / reactor at higher frequencies, estimation by calculation may be the only possibility to predict the sound level built up due to harmonic currents. This situation usually applies to large power transformers but may also be used for other units, depending on the test equipment available in the test facility.

The sound power radiated by a vibrating surface is given by Equation (4) of this standard as

$$W = \rho_0 c S \sigma \omega^2 x^2$$

With the sound power of a transformer / reactor known at a current of fundamental frequency it is possible to calculate relatively to that the sound power at any other harmonic current and frequency as long as the winding displacement  $x$  and the radiation efficiency  $\sigma$  as a function of the sound frequency are known. The sequence of the calculation procedure is outlined in 4.2.5.3 with steps a) to c) detailed in A.1 and A.2. Steps d) to i) are briefly explained in the following.

- Application of a logarithmic approach for the dynamic response of winding displacement to forces (steps d) and e) of 4.2.5.3)

The winding displacement  $x$  is proportional to the acting forces  $F$  but is also dependent of the sound frequency. The relation between force and displacement is given by the dynamic response or transfer function  $R(f)$ . It can be written

$$x(f) \sim R(f) \times F \quad \text{and also} \quad x^2(f) \sim R^2(f) \times F^2 \quad (\text{A.4})$$

which in a logarithmic approach relative to the fundamental sound frequency  $f_0$  (for instance 100 Hz) contributes to the sound level change as

$$\Delta x(f) = 20 \times \lg [R(f) / R(f_0)] + 20 \times \lg [F(f) / F(f_0)] \quad (\text{A.5})$$

Whereas the derivation of the harmonic force components is demonstrated in A.2 the dynamic response function  $R(f)$  requires a design specific approach.

- Conversion of the circular frequency into a logarithmic figure (step f) of 4.2.5.3)

The conversion of the square circular frequency  $\omega^2$  as per Equation (4) of this standard into a figure relative to the fundamental sound frequency  $f_0$  results in a sound level change of

$$\Delta \omega = 20 \times \lg [f / f_0]. \quad (\text{A.6})$$

- Application of a logarithmic approach for the radiation efficiency (step g) of 4.2.5.3)

The radiation efficiency of a winding or a tank is frequency dependent (see 4.4) and this shall be considered for the sound level change at sound frequency  $f$  relative to fundamental sound frequency  $f_0$ . The contribution is given as

$$\Delta \sigma(f) = 10 \times \lg [\sigma(f) / \sigma(f_0)]. \quad (\text{A.7})$$

- Application of A-weighting (step h) of 4.2.5.3)

As sound levels have to be provided in A-weighted form (see 5.2), this is to be considered for the relative sound level change and contributes as

$$\Delta A(f) = A(f) - A(f_0). \quad (\text{A.8})$$

- Summation of components (steps d) to h) of 4.2.5.3)

The total sound level increase  $\Delta L(f)$  due to an equivalent harmonic current with the associated sound frequency  $f$  relative to a current associated with the fundamental sound frequency  $f_0$  expressed in dB(A) is calculated by summation of the outcome of Equations (A.5) till (A.8)

$$\Delta L(f) = \Delta x(f) + \Delta \omega + \Delta \sigma(f) + \Delta A(f) \quad (\text{A.9})$$

The application of the full procedure with the force values as given in Table A.4 and with specific functions for the dynamic winding response and radiation efficiency of a certain design of large power transformers results in a sound level increase between 9 dB(A) for the harmonic spectrum of a delta connected winding and 15 dB(A) for the harmonic spectrum of a star connected winding.

NOTE Field measurements on converter transformers have shown increased levels of up to 20 dB(A) or more.

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## FINAL VERSION



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

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## INTERNATIONAL ELECTROTECHNICAL COMMISSION

### POWER TRANSFORMERS –

#### Part 10-1: Determination of sound levels – Application guide

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**IEC 60076-10-1 edition 2.1 contains the second edition (2016-03) [documents 14/847/FDIS and 14/850/RVD] and its amendment 1 (2020-11) [documents 14/1037/CDV and 14/1047/RVC].**

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

International Standard IEC 60076-10-1 has been prepared by technical committee 14: Power transformers.

This second edition constitutes a technical revision.

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

- a) extended information on sound fields provided;
- b) effect of current harmonics in windings enfolded;
- c) updated information on measuring methods sound pressure and sound intensity given;
- d) supporting information on measuring procedures walk-around and point-by-point given;
- e) clarification of A-weighting provided;
- f) new information on frequency bands given;
- g) background information on measurement distance provided;
- h) new annex on sound-built up due to harmonic currents in windings introduced.

This standard is to be read in conjunction with IEC 60076-10.

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

A list of all parts in the IEC 60076 series, published under the general title *Power transformers*, can be found on the IEC website.

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

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## POWER TRANSFORMERS –

### Part 10-1: Determination of sound levels – Application guide

#### 1 Scope

This part of IEC 60076 provides supporting information to help both manufacturers and purchasers to apply the measurement techniques described in IEC 60076-10. Besides the introduction of some basic acoustics, the sources and characteristics of transformer and reactor sound are described. Practical guidance on making measurements is given, and factors influencing the accuracy of the methods are discussed. This application guide also indicates why values measured in the factory may differ from those measured in service.

This application guide is applicable to transformers and reactors together with their associated cooling auxiliaries.

#### 2 Normative references

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

IEC 60076-10:2016, *Power transformers – Part 10: Determination of sound levels*

#### 3 Basic physics of sound

##### 3.1 Phenomenon

Sound is a wave of pressure variation (in air, water or other elastic media) that the human ear can detect. Pressure variations travel through the medium (for the purposes of this document, air) from the sound source to the listener's ears.

The number of cyclic pressure variations per second is called the 'frequency' of the sound measured in hertz, Hz. A specific frequency of sound is perceived as a distinctive tone or pitch. Transformer 'hum' is low in frequency, typically with fundamental frequencies of 100 Hz or 120 Hz, while a whistle is of higher frequency, typically above 3 kHz. The normal frequency range of hearing for a healthy young person extends from approximately 20 Hz to 20 kHz.

##### 3.2 Sound pressure, $p$

The root-mean-square (r.m.s.) of instantaneous sound pressures over a given time interval at a specific location is called the sound pressure. It is measured in pascal, Pa.

Sound pressure is a scalar quantity, meaning that it is characterised by magnitude only.

The lowest sound pressure that a healthy human ear can detect is strongly dependent on frequency; at 1 kHz it has a magnitude of 20  $\mu$ Pa. The threshold of pain corresponds to a sound pressure of more than a million times higher, 20 Pa. Because of this large range, to avoid the use of large numbers, the decibel scale (dB) is used in acoustics. The reference level for sound pressure for the logarithmic scale is 20  $\mu$ Pa corresponding to 0 dB and the 20 Pa threshold of pain corresponds to 120 dB.

An additional and very useful aspect of the decibel scale is that it gives a better approximation to the human perception of loudness than the linear pascal scale as the ear responds to sound logarithmically.

In the field of acoustics it is generally accepted that

- 1 dB change in level is imperceptible;
- 3 dB change in level is perceptible;
- 10 dB change in level is perceived to be twice as loud.

Human hearing is frequency dependent. The sensitivity peaks at about 1 kHz and reduces at lower and higher frequencies. An internationally standardized filter termed 'A-weighting' ensures that sound measurements reflect the human perception of sound over the whole frequency range of hearing (see 5.2).

### 3.3 Particle velocity, $u$

The root-mean-square (r.m.s.) of instantaneous particle velocity over a given time interval at a specific location is called particle velocity. It is measured in metres per second, m/s.

This quantity describes the oscillation velocity of the particles of the medium in which the sound waves are propagating. It is characterised by magnitude and direction and is therefore a vector quantity.

### 3.4 Sound intensity, $\bar{I}$

The time-averaged product of the instantaneous sound pressure and instantaneous particle velocity at a specific location is called sound intensity:

$$\bar{I} = \frac{1}{T} \int_T (p(t) \times \bar{u}(t)) dt \quad (1)$$

It is measured in watts per square metre, W/m<sup>2</sup>.

Sound intensity describes the sound power flow per unit area and is a vector quantity with magnitude and direction. The normal sound intensity is the sound power flow per unit area measured in a direction normal, i.e. at 90° to the specified unit area.

The direction of the sound power flow is determined by the phase angle of the particle velocity at the specific location.

### 3.5 Sound power, $W$

Sound power is the rate of acoustic energy radiated from a sound source. It is stated in watts.

A sound source radiates power into the surrounding air resulting in a sound field. Sound power characterises the emission of the sound source. Sound pressure and particle velocity characterise the sound at a specific location. The sound pressure which is heard or measured with a microphone is dependent on the distance from the source and the properties of the acoustic environment. Therefore, the sound power of a source cannot be quantified by simply measuring sound pressure or intensity alone. The determination of sound power requires an integration of sound pressure or sound intensity over the entire enveloping surface. Sound power is more or less independent of the environment and is therefore a unique descriptor of the sound source.

### 3.6 Sound fields

#### 3.6.1 General

A sound field is a region through which sound waves propagate. It is classified according to the manner in which the sound waves propagate.

When sound pressure and particle velocity are in phase, the corresponding sound field is said to be active. When sound pressure and particle velocity are 90° out of phase, the corresponding sound field is said to be reactive. With an active field the sound energy propagates entirely outwards from the source, as it does (approximately) in far-fields (see 3.6.5). In case of a reactive field the sound energy is travelling outwards but it will be returned at a later instant; the energy is stored as if in a spring. Examples for reactive fields are the diffuse field of a reverberant room (see 3.6.3) and standing waves (see 3.6.6). Averaged over a cycle, the net energy transfer in a reactive field is zero and hence the measured sound intensity is zero, although sound pressure and particle velocity are present.

A practical sound field is composed of both active and reactive components.

#### 3.6.2 The free field

A sound field in a homogeneous isotropic medium whose boundaries exert a negligible effect on sound waves is called a free field. It is an idealised free space where there are no disturbances and through which active sound power propagates.

These conditions hold in the open air when sufficiently far away from the ground and any walls, or in a fully anechoic chamber where all the sound striking the walls, ceiling and floor is absorbed.

Sound propagation from a theoretical point source within a free field environment is characterised by a 6 dB drop in sound pressure level and intensity level each time the distance from the source is doubled. This is also approximately correct when the distance from an area source is large enough for it to appear as a theoretical point source.

When measuring power transformer sound levels free field conditions will be approached with the exception of reflections from the floor.

IEC 60076-10 requires all sound measurements to be made over a reflecting surface. Therefore, measurements in fully anechoic chambers are not allowed.

#### 3.6.3 The diffuse field

In a diffuse field, multiple reflections result in a sound field with equal probability of direction and magnitude, hence the same sound pressure level exists at all locations and the sound intensity tends to zero. This field is approximated in a reverberant room. According to the law of conservation of energy, an equilibrium condition will occur when the sound power absorbed by or transmitted through the room boundaries equals the sound power emitted by the source. This phenomenon may result in very high sound pressure levels in environments having low sound absorption or transmission characteristics.

A practical example of a diffuse field may be the interior of a transformer sound enclosure.

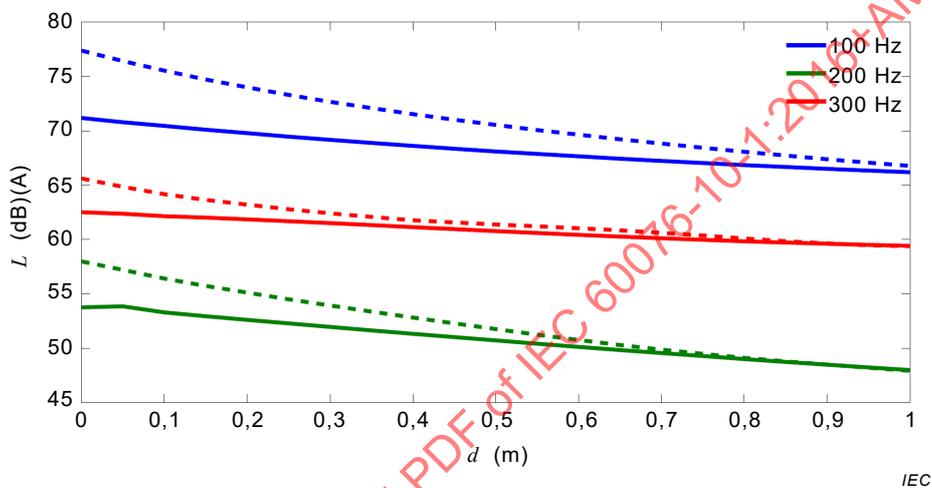
#### 3.6.4 The near-field

The acoustic near-field is considered to be the region adjacent to the vibrating surface of the sound source, usually defined as being within a distance of  $\frac{1}{4}$  of the wavelength of the particular frequency of interest. This region is characterized by the existence of both active and reactive sound components. The reactive sound component decays exponentially with distance from the vibrating surface of the sound source.

Reactive sound components are created if the bending wavelength of the vibrating structure is shorter than the wavelength of the radiated sound. Sound radiation at this condition is characterised by acoustic short-circuits between adjacent regions with over-pressure and under-pressure. In such acoustic short-circuits the air acts as a mass-spring system storing and releasing energy in every cycle. As a result, a part of the sound power is always being circulated and not all of it is radiated into the far-field (see 3.6.5).

The extent of the near-field reduces with increasing frequency.

Sound pressure measurements applied in the near-field will result in a systematic overestimation (Figure 1) because of the inherent phase difference between the sound pressure and particle velocity in the near-field (see 3.6.1). As a result, spatially averaged sound pressure levels are typically 2 dB to 5 dB higher whilst spot measurements may be up to 15 dB higher than the corresponding measured sound intensity level.



**Figure 1 – Simulation of the spatially averaged sound intensity level (solid lines) and sound pressure level (dashed lines) versus measurement distance  $d$  in the near-field**

### 3.6.5 The far-field

The sound field beyond a certain distance from the source where inherent disturbances due to the size and shape of the source as well as other interfering disturbances become insignificant is called the far-field. In this field the source can be treated as a theoretical point source and approximate free field conditions exist.

### 3.6.6 Standing waves

Standing waves are the result of interference between two sound waves of the same frequency travelling in opposite directions. Standing waves are formed as a result of reflections between a sound source and structural discontinuities such as the boundaries of the sound field, emphasised if the reflecting surfaces are parallel and when the relationship between sound frequency and distance meets certain conditions. The existence of standing waves of frequency  $f_v$  depends upon the distance  $d$  between the reflecting walls as follows:

$$f_v = v \frac{c}{2d} \quad (2)$$

where  $c$  is the speed of sound in air in m/s (at 20 °C,  $c = 343$  m/s),  $v = 1, 2, 3, \dots$

A standing wave does not transmit energy to the far-field; it is an example of a reactive field.

Within the region of a standing wave

- large variations in measured sound pressure will occur over small distances with the tendency to overestimate sound pressure;
- sound intensity measurements tend to be inaccurate and underestimate the actual sound intensity.

## 4 Sources and characteristics of transformer and reactor sound

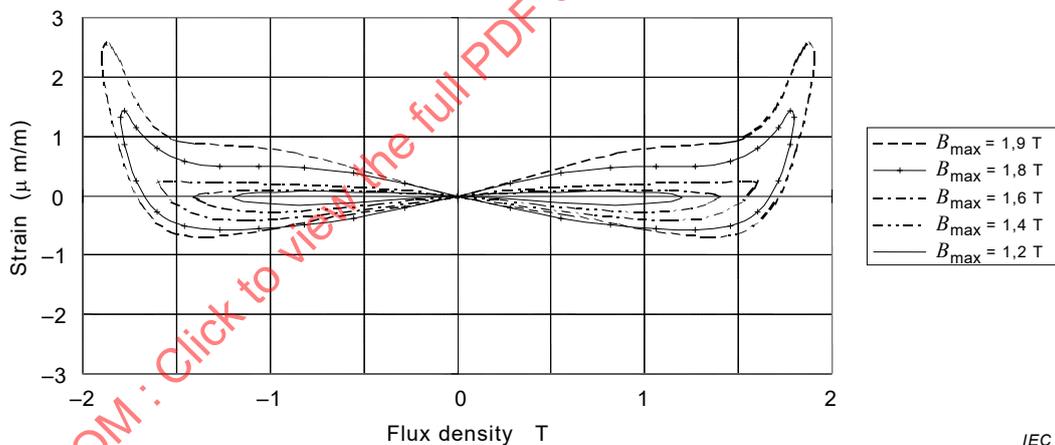
### 4.1 General

Transformer and reactor sound has several inherent physical origins. The significance of those origins of sound generation depends on the design of the equipment and its operating conditions. The design will impact the sound producing vibrations and their propagation from the origin to the transformer tank or enclosure surface and finally the sound radiation into the air.

### 4.2 Sound sources

#### 4.2.1 Core

Magnetostriction is the change in dimension observed in ferromagnetic materials when they are subjected to a change in magnetic flux density (induction). In electrical core steel this dimensional change is in the range of 0,1  $\mu\text{m}$  to 10  $\mu\text{m}$  per metre length ( $\mu\text{m}/\text{m}$ ) at typical induction levels. Figure 2 shows magnetostriction versus flux density for one type of core lamination measured at five different flux densities. Each loop describes one 50 Hz cycle with flux density  $B_{\text{max}}$ .

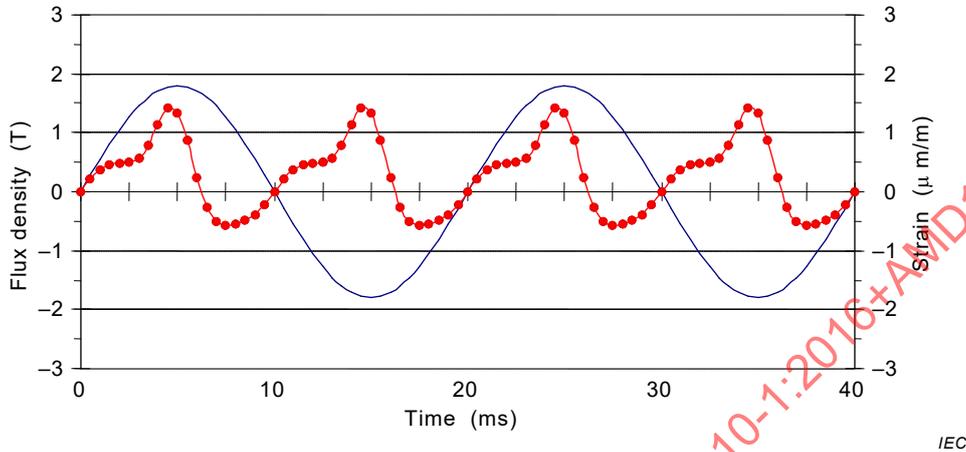


**Figure 2 – Example curves showing relative change in lamination length of electrical core steel during complete cycles of applied 50 Hz a.c. induction up to peak flux densities  $B_{\text{max}}$  in the range of 1,2 T to 1,9 T**

NOTE 1 Mechanical stresses in core laminations will have a strong influence on magnetostriction.

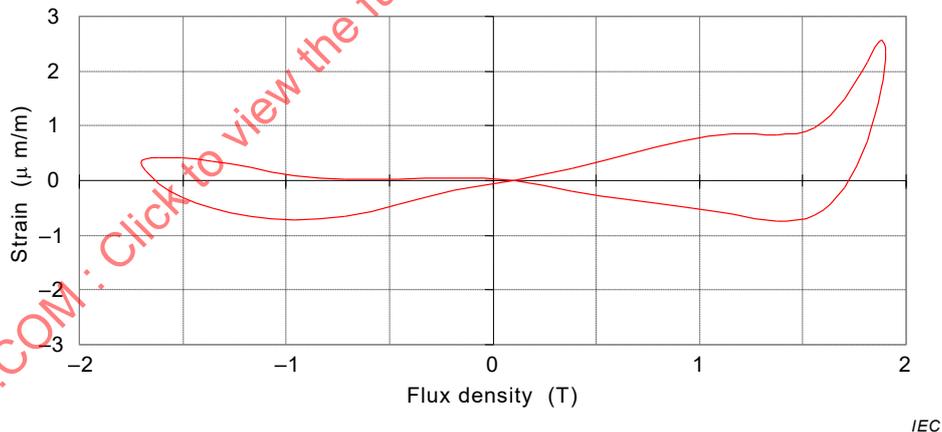
The strain does not depend on the sign of the flux density, only on its magnitude and orientation relative to certain crystallographic axes of the material. Therefore, when excited by a sinusoidal flux, the fundamental frequency of the dimensional change will be twice the exciting frequency. The effect is highly non-linear, especially at induction levels near saturation. This non-linearity will result in a significant harmonic content of the strain and this causes the vibration spectrum of the core. Figure 3 shows the magnetostriction for a sinusoidal induction with  $B_{\text{max}} = 1,8 \text{ T}$  and a frequency of 50 Hz. It has a periodicity of double the exciting frequency with peaks at 5 ms and 15 ms which are indistinguishable.

The sound emitted by transformer cores depends on the velocity of the vibrations, i.e. the rate of change of the magnetostriction (dotted line in Figure 3). This results in an amplification of the harmonics (distortion) in relation to the fundamental which is at double the exciting frequency. Several even multiples of the exciting frequency will be seen in the spectrum; in such cases the fundamental component at double the exciting frequency is seldom the dominant frequency component of the A-weighted sound.



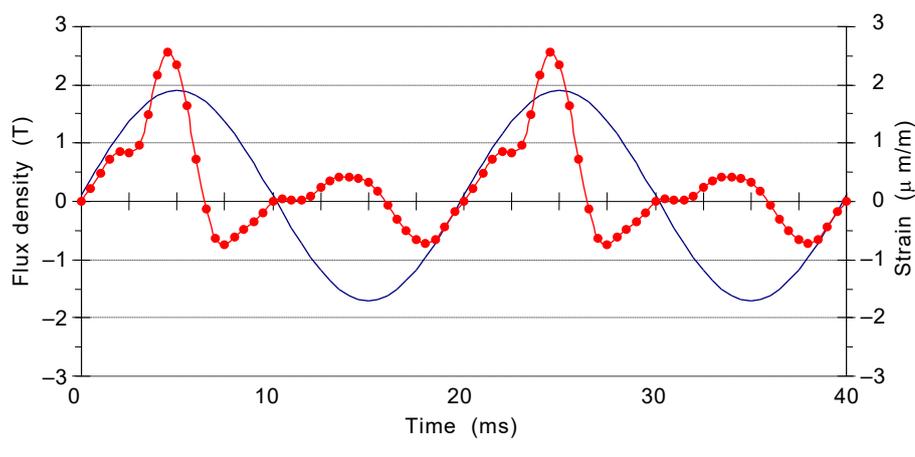
**Figure 3 – Induction (smooth line) and relative change in lamination length (dotted line) as a function of time due to applied 50 Hz a.c. induction at 1,8 T – no d.c. bias**

If the flux has a d.c. bias, for example due to remanence in the core from preceding testing of the windings' resistance, or due to a d.c. component in the current, the strong non-linearity of magnetostriction causes a significant increase in vibration amplitudes. With a d.c. bias on the induction, the peaks in magnetostriction at the positive and negative peak flux density differ significantly; obvious in the magnetostriction loop in Figure 4.



**Figure 4 – Example curve showing relative change in lamination length during one complete cycle of applied 50 Hz a.c. induction at 1,8 T with a small d.c. bias of 0,1 T**

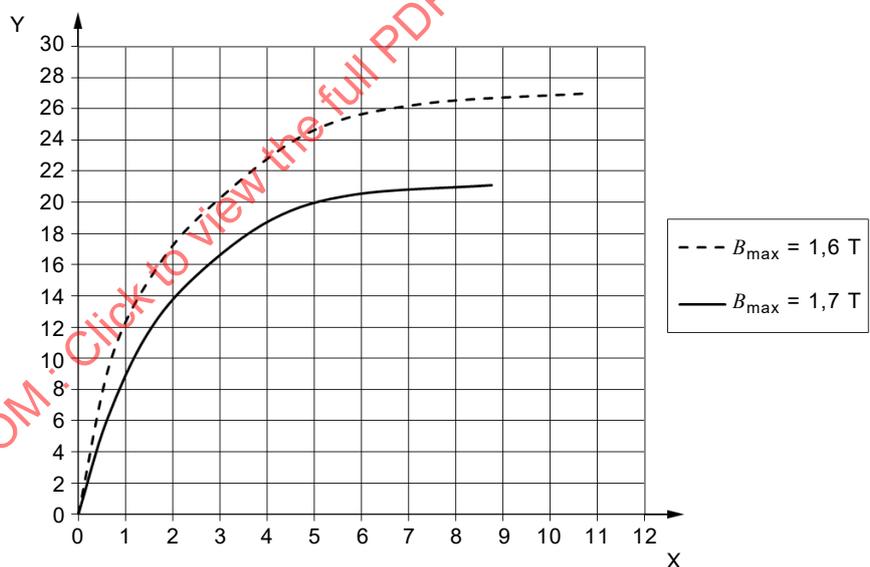
The vibration pattern is now repeated every cycle, that is every 20 ms in a 50 Hz system, indicating a magnetostriction at exciting frequency (see Figure 5). The presence of odd harmonics in the sound spectrum is a clear indication of d.c. bias in the induction.



**Figure 5 – Induction (smooth line) and relative change in lamination length (dotted line) as a function of time due to applied 50 Hz a.c. induction at 1,8 T with a small d.c. bias of 0,1 T**

A d.c. bias in magnetization can significantly affect the sound level of a transformer. Therefore, a transformer undergoing sound tests shall be energised until the temporary effects of inrush currents and remanence have decayed and the sound levels have stabilised.

The ratio between the d.c. bias current and the r.m.s. no-load current is a useful parameter for predicting the increase in sound power due to the d.c. bias current. The relationship between d.c. bias current over no-load current and sound level increase has been measured on a number of large power transformers; Figure 6 shows one set of this data.



**Key**

- X axis d.c. bias current as per unit of a.c. no-load current (r.m.s.)
- Y axis increase in total sound level in dB(A)

**Figure 6 – Sound level increase due to d.c. current in windings**

NOTE 2 Figure 6 shows the results for a certain design of large power transformers with a core having a path for flux return and the core made from high permeable electrical steel. For other constructions, for example with different core form or different electrical steel type, the curve can deviate in detail but will contain the same upward trend.

### 4.2.2 Windings

Load currents in transformer and reactor windings generate a magnetic field that oscillates at the excitation frequency. The resultant electromagnetic forces on the windings act both axially and radially. The magnitude of these forces depends on the magnitude of the load current and on the magnetic field, which itself is a function of the load current. Thus, the magnetic forces on the windings are proportional to the square of the load current while their frequency is twice the excitation frequency. The resulting vibration amplitudes depend on the elastic properties of the conductor, those of the electrical insulation and the proximity of the mechanical eigenfrequencies (natural frequencies of the windings) to the vibration frequency. In a well clamped and tightly wound winding, the elastic properties of the insulating material are almost linear in the range of displacements occurring under normal operating currents. Metals have very linear elastic moduli. Therefore harmonic vibration is normally minimal and the fundamental frequency (double the exciting frequency) dominates the vibration spectrum of windings (see Figure 7).

Winding deflections and their vibrational velocities are proportional to the excitation force which is proportional to the square of the load current. The sound power radiated from a vibrating body is proportional to the square of the vibration velocity (see 4.4). Consequently, the sound power generated by windings varies with the fourth power of the load current.

Harmonics in the load current appear in the sound spectrum at twice their electrical frequency and at the sum and difference of all their frequencies. They can contribute significantly to the transformer or reactor sound level. For more details see 4.2.5.

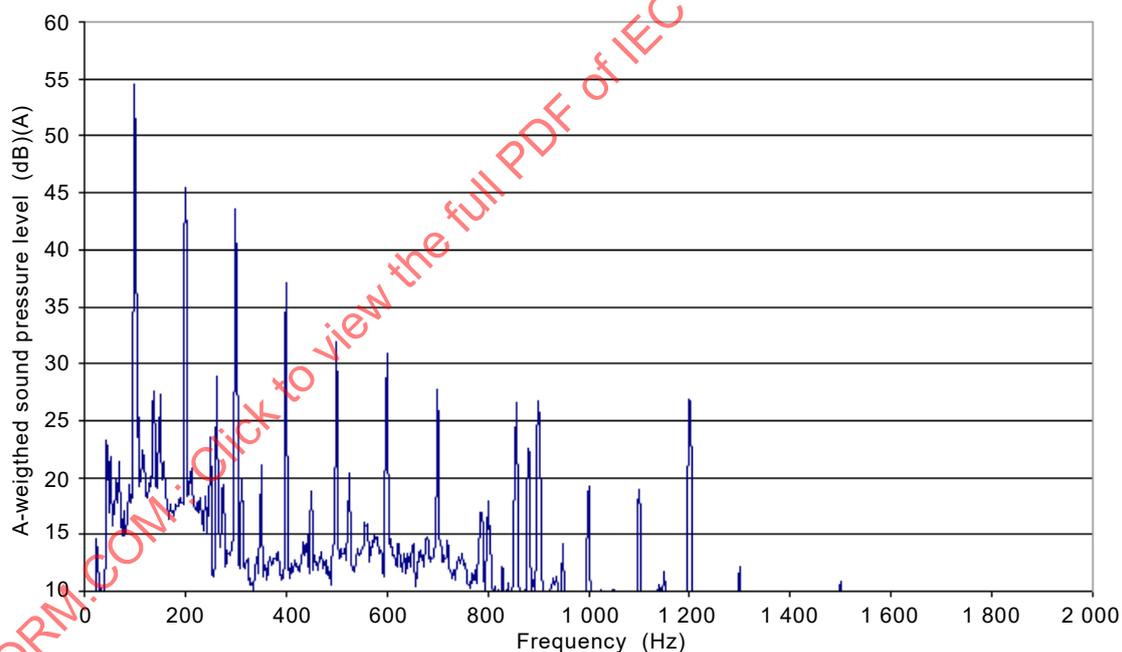


Figure 7 – Typical sound spectrum due to load current

### 4.2.3 Stray flux control elements

Magnetic stray flux in loaded transformers is linked to windings and connection leads. This stray flux shall be controlled to avoid the overheating of inactive metal parts such as the tank by reducing eddy current losses. There are in principle three possibilities to control magnetic stray flux:

- by application of laminated electrical steel the stray flux is guided in a controlled way. Elements providing this guidance are commonly called ‘shunts’ or ‘tank shunts’;

- by application of copper or aluminium shields the stray flux is repelled by eddy current loops in the shield;
- by sizing the tank such that stray flux control is not necessary.

Elements used for stray flux control as well as the tank itself are also sources of vibration due to electromagnetic forces and magnetostriction and they impact the overall sound power level.

The method of attachment of stray flux control elements may influence the sound power level.

#### 4.2.4 Sound sources in reactors

There are several types of single-phase and three-phase reactors, generally utilising two different technologies in their design.

- In air-core reactors, the sound power produced by the winding due to the load current is dominant. The interaction of the current flowing through the winding and its magnetic field lead to vibrational winding forces. While the oscillating forces can be clearly determined, the vibrational response of the winding structure is complex. The vibrational amplitude, the size of the sound radiating surface and its radiation efficiency determine the sound power. The sound power is governed by the magnitude of the winding vibration in the radial direction (because 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 power is usually low.
- In magnetically-shielded reactors (with or without gapped cores), the magnetic force between the yokes tends to close the gap as the flux increases; the cyclic displacement thus produced is the dominant sound source. This force mechanically excites the entire magnetic circuit of the reactor, resulting in a sound spectrum dominated by double the excitation frequency and its first few harmonics. Magnetostriction, winding vibrations and stray flux control elements are also contributing factors to sound power radiation.

NOTE See IEC 60076-6 for definitions of different types of reactor.

#### 4.2.5 Effect of current harmonics in transformer and reactor windings

##### 4.2.5.1 General

As indicated in 7.6 of this standard, power electronic devices can be a source of current harmonics. This effect on the overall sound power level can be significant.

The spectrum of harmonic currents in magnitude and phase shall be specified by the purchaser or the manufacturer of the power electronic device in order to predict a realistic in service sound power level. Where phase angles are not available a statistical approach may be applied.

More detailed information of the theory and engineering practice of additional sound produced by harmonic currents in windings is given in Annex A of this standard.

Radiated sound power from a transformer/reactor depends on the current at all frequencies but usually it is only the fundamental and the most significant harmonic currents out of the current spectrum that contribute significantly.

The determination of the additional sound power due to harmonic currents can be performed with two different approaches:

- by exciting and measuring individual frequencies (usually applicable only for special reactors, such as filter reactors);
- by calculation of the individual frequency contributions.

#### 4.2.5.2 Measuring sound levels of individual frequency components

A set of harmonic exciting currents has to be determined for this test, representing the significant sound harmonics.

Since currents at power frequency and at other frequencies usually cannot be applied simultaneously for testing, the transformer/reactor may be successively tested with power frequency current and currents at other harmonic frequencies. In this case the transformer/reactor shall be tested at currents and frequencies which reflect the current harmonics but also the interaction of currents having different frequencies.

For a transformer/reactor current spectrum with currents  $I_1, I_2, I_3, I_4, I_5 \dots$  the sound significant currents are for example determined to be  $I_1, I_2, I_3$ . These currents result in the following sound components:

Amplitude of currents	Frequency of currents	Sound frequencies
$I_1$	$f_1$	$2 f_1$
$I_2$	$f_2$	$2 f_2$
$I_3$	$f_3$	$2 f_3$

$f_1, f_2, f_3$  are the frequencies of the transformer/reactor r.m.s. currents  $I_1, I_2, I_3$ . Usually  $f_1$  is the power frequency and  $f_2, f_3$  are the frequencies of the significant currents of the current spectrum (significant harmonics).

Pairs of transformer/reactor currents in the table above, for instance  $I_1$  and  $I_2$ , result in two additional frequency components due to interactive effects.

Amplitude of a pair	Frequencies of a pair	Sound frequencies
$(2 I_1 I_2)^{1/2}$	$(f_2 + f_1)/2$	$f_2 + f_1$
$(2 I_1 I_2)^{1/2}$	$(f_2 - f_1)/2$	$f_2 - f_1$

All harmonics and pairs with the same frequency have to be summed and the derived value forms the test current at this frequency. For a correct summation it is necessary to consider the phase correlation, see Annex A for detailed information. Where this is unavailable a statistical approach may be taken by calculating the square root of the sum of squares (SRSS) of the individual current components. If for example  $f_1$  is the power frequency and  $f_2$  and  $f_3$  are the frequencies of the significant harmonics then the following components would usually be taken into account for the derivation of the test currents.

Contributing amplitude	Contributing frequency	Sound frequency
$I_1$	$f_1$	$2 f_1$
$(2 I_1 I_2)^{1/2}$	$(f_2 + f_1)/2$	$f_2 + f_1$
$(2 I_1 I_2)^{1/2}$	$(f_2 - f_1)/2$	$f_2 - f_1$
$(2 I_1 I_3)^{1/2}$	$(f_3 + f_1)/2$	$f_3 + f_1$
$(2 I_1 I_3)^{1/2}$	$(f_3 - f_1)/2$	$f_3 - f_1$

Note that the harmonics themselves and the sum and difference frequency pairs of harmonics usually do not significantly contribute to the radiated sound power. Significant components always involve the excitation frequency current and such pairs require consideration.

When applying the SRSS approach to the above considered current components  $I_1, I_2, I_3$  the following test currents would then be derived for a typical current spectrum comprising the current at excitation frequency  $f_1$  and the significant harmonics at frequencies  $f_2$  and  $f_3$  ( $f_2$  and  $f_3$  are commonly the harmonics of 5<sup>th</sup> and 7<sup>th</sup> order):

Amplitude of test current	Frequency of test current	Sound frequency
$I_{1T} = (I_1 I_1)^{1/2}$	$f_1$	$2 f_1$
$I_{2T} = (2 I_1 I_2)^{1/2}$	$(f_2 - f_1)/2$	$f_2 - f_1$
$I_{3T} = \{[(2 I_1 I_2)^2 + (2 I_1 I_3)^2]^{1/2}\}^{1/2}$	$(f_2 + f_1)/2 \equiv (f_3 - f_1)/2$	$f_2 + f_1$
$I_{4T} = (2 I_1 I_3)^{1/2}$	$(f_3 + f_1)/2$	$f_3 + f_1$

Where the full test current at a harmonic frequency  $f_i$  cannot be applied due to test lab limitations the test can be performed at reduced currents and the sound power at full test current shall then be derived by calculation based on Equation (7) of IEC 60076-10:2016 to

$$L_{iT} = L_{ired} + 40 \times \lg \frac{I_{iT}}{I_{ired}}$$

where

$L_{iT}$  sound level at harmonic frequency  $f_i$  at full test current  $I_{iT}$

$L_{ired}$  sound level at harmonic frequency  $f_i$  at reduced test current  $I_{ired}$

The total sound power level shall then be calculated using the following Equation (3):

$$L_{tot} = 10 \times \lg \left( \sum_i 10^{L_i/10} \right) \quad (3)$$

where

$L_{tot}$  is the total sound power level and

$L_i$  is the sound power level of the individually tested harmonic component  $i$ .

NOTE For power converter transformers, such as industrial and HVDC transformers, application of harmonic test currents is usually impracticable due to unavailability of test equipment.

#### 4.2.5.3 Calculation of the predicted sound level increase due to harmonics

This method of calculation is relative to the known sound level for excitation at fundamental frequency. Calculation steps are as follows:

- Calculate the relative amplitude of forces for harmonics  $I_n$  by applying  $(I_n/I_1)^2$  resulting in components with frequencies of  $(2 f_n)$
- Calculate the relative amplitude of forces for harmonic pairs  $I_n, I_m$  by applying  $(2 I_n I_m)/I_1^2$  resulting in two components per pair with frequencies  $(f_m + f_n)$  and  $(f_m - f_n)$
- Summation of all relative force components per frequency using the given phase relation. If this is not available a statistical approach may be considered (SRSS = square root of the sum of the squares)
- Application of a logarithmic approach per frequency for the dynamic response of winding displacement to the forces (consideration of winding transfer function)
- Conversion of force components per frequency into a logarithmic figure relative to the fundamental force
- Conversion of circular frequency into a logarithmic figure relative to the fundamental frequency
- Application of a logarithmic approach per frequency for the radiation efficiency relative to the fundamental radiation efficiency
- Application of A-weighting per frequency relative to the A-weighting of the fundamental
- Summation of all components d) to h) expressed in dB(A) to derive the total sound power level increase.

Annex A provides more details of this method.

#### 4.2.6 Fan noise

The origin of fan noise is the turbulent flow of air, resulting in pressure fluctuations with a wide range of frequencies, i.e. it is a broadband noise mainly in the range of 300 Hz to 2 kHz. The sound power level of fans is predominantly ruled by the tip speed of the blades, this being a function of blade diameter and rotational speed. By adjusting the angle of attack of the blades the noise and airflow can be influenced.

NOTE A reduction in airflow can invalidate the temperature rise test.

#### 4.2.7 Pump noise

Pump noise and oil flow in general do not contribute significantly to sound power except at very high flow rates or on extremely low-noise transformers. In case of an unexpected pump noise the direction of rotation may be incorrect.

#### 4.2.8 Relative importance of sound sources

Historically, sound level measurements on transformers have been made in the no-load condition with only the magnetising current flowing in the windings. This was acceptable because the magnetostrictive deformation of the core was the primary source of the transformer sound. However, present day transformer designs utilizing high quality electrical steel and having low induction levels often result in a low no-load sound power level to the extent that the sound due to load currents, mainly caused by the windings, becomes significant.

A rough indication, based on empirical data, as to whether a measurement under load conditions may be relevant is given by Equations (5) and (6) of IEC 60076-10:2016 together with an indication of the significance of the result. A general rule of acoustics is that when a sound signal is 10 dB below another signal its contribution to the total (of the two) is insignificant.

The sound power of cooling devices assumes greater significance with low-noise transformer designs or for transformers intended to be used within an enclosure, to the extent that in certain circumstances cooling may be specified without fans (ONAN, ODAN).

### 4.3 Vibration transmission

The magnetic circuit, windings, tank and acoustic enclosure (where provided) are all mechanical structures with their own mechanical resonance frequencies. If the frequency of one of the exciting forces coincides with a structural resonance, a significant amplification of this frequency may occur. Resonances should be eliminated at the design stage, or sufficient damping provided to control the vibration amplitude.

In liquid-filled transformers, vibrations from both the core and windings are transmitted to the tank through the structural supports of the core and coil assemblies and through the incompressible liquid.

If the insulating fluid is a gas, as in the case of dry-type transformers with enclosure or SF<sub>6</sub> transformers, the excitation of vibrations is dominated by the structural supports of the active part.

Vibration isolators beneath core supports inside the tank reduce the transmission of vibrations to the tank and hence decrease the radiated sound power.

Vibration isolators beneath the tank or enclosure are intended to reduce the vibration transmitted to the foundation. Whilst such isolators are intended to minimize vibration propagation they do not significantly influence the sound power of the transformer itself.

NOTE It is noted that the scope of IEC 60076-10 is sound power radiation only and vibration transmission is not included.

In some applications, the transmission of structural vibration may be significant enough to cause problems to the support structure, for instance if a transformer is installed in a building or an offshore platform.

Similarly, transformers mounted on bedrock can cause problems in other buildings mounted on the same bedrock at remote locations.

#### 4.4 Sound radiation

The r.m.s. sound power radiated into the far-field depends on the square of the vibration velocity, the area of the radiating surface and the radiation efficiency of that surface as given in Equation (4)

$$W = \rho_0 c S \sigma \omega^2 x^2 \quad (4)$$

where

- $W$  is the radiated sound power in W;
- $\rho_0$  is the air density in kg/m<sup>3</sup>;
- $c$  is the speed of sound in air in m/s;
- $S$  is the area of the sound radiating surface in m<sup>2</sup>;
- $\sigma$  is the radiation efficiency in per unit, a function of frequency and geometrical and structural properties of the radiating surface;
- $\omega = 2\pi f$  is the acoustic angular velocity in s<sup>-1</sup> for each frequency under consideration;
- $x$  is the r.m.s. vibrational amplitude in m;
- $\rho_0 c$  is the acoustic impedance of air;
- $\omega x$  is the r.m.s. vibration velocity in m/s.

Vibrating objects with dimensions small relative to the wavelength of the radiating frequency have low radiation efficiency; where the dimension of the vibrating object is approaching or larger than the wavelength the radiation efficiency approaches unity. Where acoustic resonances are present the radiation efficiency can exceed unity. Such resonances may occur for example in an open void between tank base and floor or also within the air volume enclosed by the winding of an air core reactor.

NOTE Large, flexible plates with complex vibration patterns radiate less sound than stiff plates with simpler vibration patterns when the vibration amplitudes are equal.

#### 4.5 Sound field characteristics

Transformer sound radiation is mainly caused by bending waves of the tank walls. With reference to Figure 8 it can be seen that the resulting sound radiation around the tank is non-uniform. The distinct patterns result from constructive and destructive interference of sound waves originating from different parts of tank surfaces vibrating with different amplitude and phase.

Non-uniform sound field patterns apply to all tanked transformers but also to dry-type transformers and reactors, whether enclosed or not.

In Figure 8 it is also noted that the distinct pattern of sound intensity is present at all distances which emphasises the fundamental importance of obtaining spatially averaged sound level measurements.

The radiation patterns of higher order sound harmonics show an increased number of interference structures due to the shorter acoustic wavelength.

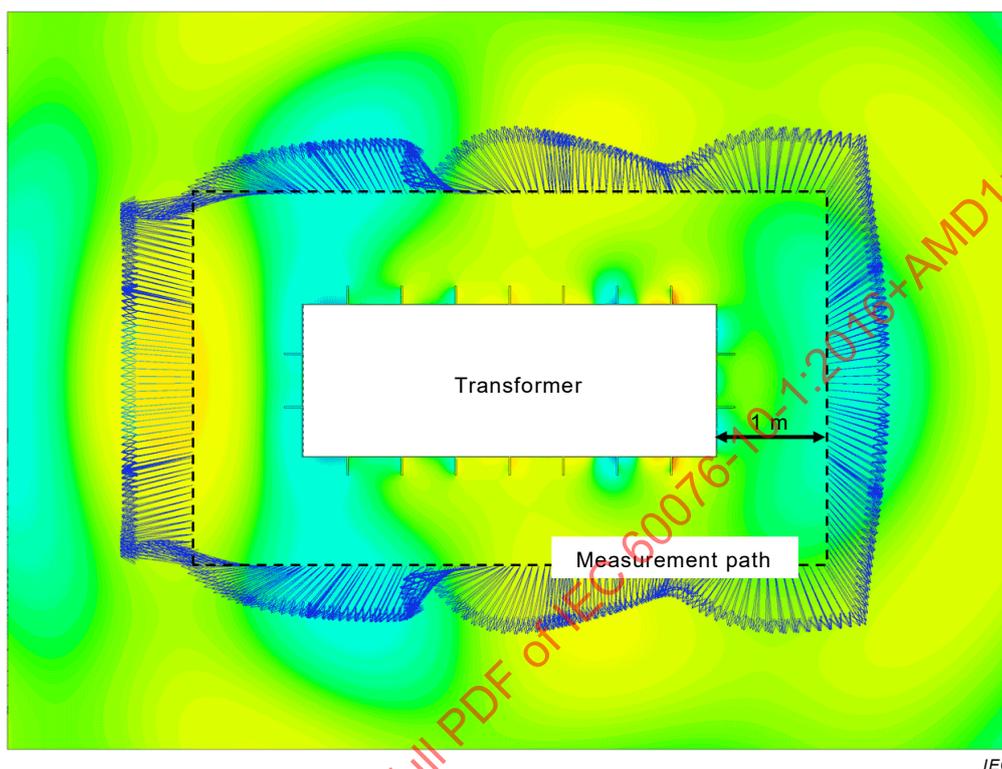


Figure 8 – Simulation of a sound pressure field (coloured) of a 31,5 MVA transformer at 100 Hz with corresponding sound intensity vectors along the measurement path

## 5 Measurement principles

### 5.1 General

The sound power of a transformer is required to allow its operational noise impact to be predicted when it is in its intended position. Sound power cannot be directly measured, it is determined from direct measurement of sound pressure or sound intensity around the transformer.

Sound power estimation is based on the enveloping principle as per ISO 3746; in a modified fashion however because of the inaccessibility of the tank cover due to safety restrictions. The assumption is made that the average sound measured around the sides of the transformer tank can be extrapolated to the tank cover.

This extrapolation is managed by the application of the measurement surface area formula given by Equation (8) in IEC 60076-10:2016. In this formula the measuring height is increased upwards by the measurement distance so as to provide some sensitivity to sound radiated from the tank cover and approximately maintaining the enveloping principle.

### 5.2 A-weighting

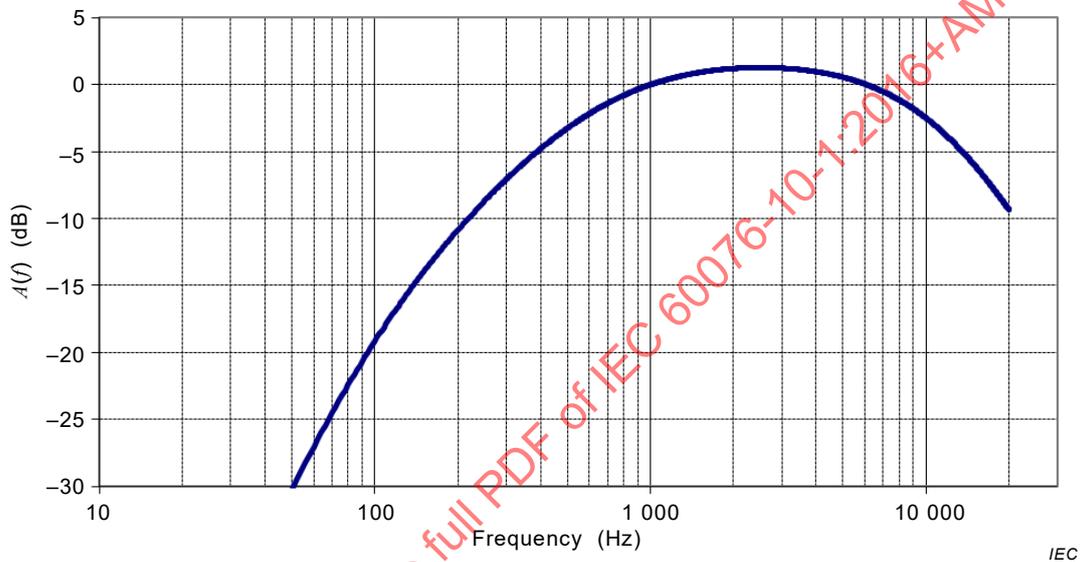
Human hearing is frequency dependent. The sensitivity is highest at about 2 kHz to 3 kHz reducing at lower and higher frequencies. The A-weighted sound level has been shown to

correlate well with the human subjective response to sound. It has been shown to be consistent in comparisons with other weighting scales. This fact has led to it becoming the preferred scale for national and international standards and it is universally used in the field of transformer sound measurement.

The A-weighting function  $A(f)$  as per IEC 61672-1 is given as

$$A(f) = 2 + 20 \times \lg \left[ \frac{12\,200^2 \times f^4}{(f^2 + 20,6^2) \times \sqrt{(f^2 + 107,7^2) \times (f^2 + 737,9^2) \times (f^2 + 12\,200^2)}} \right] \quad (5)$$

and is graphically depicted in Figure 9.



**Figure 9 – A-weighting graph derived from function  $A(f)$**

The above is a continuous function valid for individual frequencies (not frequency bands) in the range of audible sound. Weighting is applied (when selected) to the input signal of an analyser before any band filtering is applied.

If measurements are made without weighting selected, care shall be taken when applying post weighting based on band measurements because band weighting is correct only for the band centre frequency. If a tone lies off the centre frequency of the band an error is introduced. Errors of up to 5 dB can be expected in extreme cases when the tone lies close to the band edge.

Table 1 provides A-weighting values for the characteristic transformer fundamental and harmonic tones.

**Table 1 – A-weighting values for the first fifteen transformer tones**

50 Hz excitation		60 Hz excitation	
Frequency Hz	A-weighting value dB	Frequency Hz	A-weighting value dB
100	-19,1	120	-16,7
200	-10,8	240	-9,1
300	-7,1	360	-5,6
400	-4,8	480	-3,5
500	-3,2	600	-2,2
600	-2,2	720	-1,3
700	-1,4	840	-0,6
800	-0,8	960	-0,1
900	-0,3	1 080	0,2
1 000	0	1 200	0,5
1 100	0,3	1 320	0,7
1 200	0,5	1 440	0,8
1 300	0,7	1 560	1,0
1 400	0,8	1 680	1,1
1 500	0,9	1 800	1,1

### 5.3 Sound measurement methods

#### 5.3.1 General

The purpose of a sound measurement, whether pressure or intensity, is to enable the estimation of the sound power emitted by the test object.

Sound power is the sound intensity integrated over the measuring surface enclosing the test object. The measurement of the sound intensity therefore leads directly to the sound power estimation. Sound intensity is the product of sound pressure and particle velocity and its measurement requires sophisticated measuring techniques.

Another method to estimate sound power is to measure sound pressure with more simple techniques which assumes the sound pressure and particle velocity being in phase and proportional. Measuring sound pressure provides limited information and this method requires corrections where the assumption is not fulfilled.

When sound pressure and particle velocity are in phase (free field condition) a unique relationship exists between sound pressure,  $p$ , and sound intensity,  $I$ , Equation (6):

$$|I| = \frac{p^2}{\rho c}, \quad (6)$$

where  $\rho c$  is the acoustic impedance of the medium through which the sound is propagating. Under standard conditions of pressure and temperature in air,  $\rho c = 412 \text{ kg}/(\text{m}^2\text{s})$ .

Using Equation (6) in the normal sound intensity level equation, the relationship between normal sound intensity level,  $L_I$ , and sound pressure level,  $L_p$ , is shown in Equation (7) as

$$L_I = 10 \times \lg \frac{|\bar{I}|}{I_0} = 10 \times \lg \frac{p^2}{\rho c I_0} = 10 \times \lg \frac{p^2}{p_0^2} + 10 \times \lg \frac{p_0^2}{\rho c I_0} = L_p + 10 \times \lg \frac{p_0^2}{\rho c I_0} \quad (7)$$

For the given reference values of  $I_0$  and  $p_0$  ( $10^{-12} \text{ Wm}^{-2}$  and  $20 \times 10^{-6} \text{ Pa}$  respectively), the term  $10 \times \lg \frac{p_0^2}{\rho c I_0}$  is small when compared with  $L_p$  for most measurements in air at ambient conditions (0,13 dB at 22 °C and  $1,013 \times 10^{-5} \text{ Pa}$ ).

Sound pressure level measurements and sound intensity level measurements performed outside the near-field, i.e. in an ideal free field environment will therefore have the same numerical value.

### 5.3.2 Sound pressure method

Sound pressure is a scalar quantity without directivity information; it is measured with a single measurement microphone. Because the measurement device can locally disturb the sound field significantly it is good practice to point the measurement microphone towards the test object.

Practical test environments usually differ significantly from the ideal free field condition. Transformer sound pressure measurements are generally adversely affected as described below. Test measurements will therefore require a correction based on an understanding of the acoustical properties of the test environment as described in 11.2 of IEC 60076-10:2016.

Pressure waves leaving the radiating surfaces of the test object will be reflected from the floor, walls and other objects in the test room. Reflected sound pressure waves interfere constructively with direct sound pressure waves emitted by the test object.

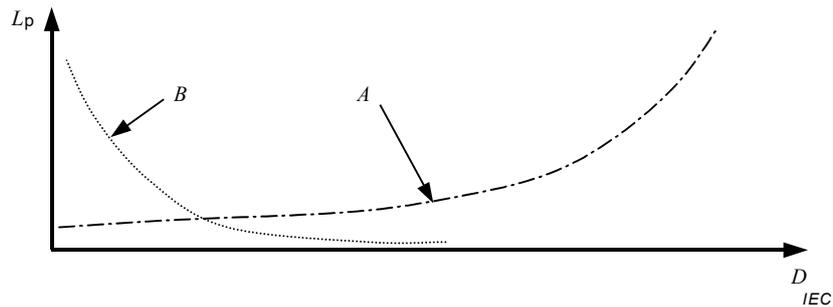
In some cases standing waves can occur. Sound pressure measurements made in the region of standing waves will give an over-estimation of sound power. Standing waves should be avoided or minimised by appropriate placement of the test object in the test room as it is not possible to correct the measurement for this effect (see 6.2 of this standard and 11.1.1 of IEC 60076-10:2016).

Practical test environments are often affected by noise from external sources such as manufacturing processes, the test generator and other energised test transformers. This will increase the measured sound pressure level around the test object.

Sound pressure measurements cannot distinguish between active and reactive sound fields. Near-field effects tend to increase the measured sound pressure level.

As is evident from Figure 10, the effects of some of the above disturbances on the sound pressure can be minimised but they cannot be eliminated.

Standard measurement distances as specified in Clause 8 of IEC 60076-10:2016 are practical compromises based on experience.



**Key**

- A reflection or external sound source pressure disturbance
- B near-field sound source pressure disturbance
- $L_p$  sound pressure level
- D distance between test object and microphone

**Figure 10 – Distribution of disturbances to sound pressure in the test environment**

**5.3.3 Sound intensity method**

Sound intensity is a vector quantity which indicates the direction of sound propagation and therefore allows the sound power entering and the sound power leaving through the measurement surface around the test object to be distinguished. This characteristic allows measurements in non-ideal test environments without corrections. The magnitude of the sound intensity is the time-averaged product of the pressure and particle velocity.

As already stated, a single microphone can measure pressure; however, measuring particle velocity is more complex. Particle velocity is related to the pressure gradient, i.e. the rate at which the instantaneous pressure changes with distance.

The principle of particle velocity measurement is based on Newton's second law applied to air. Newton's second law relates the acceleration given to a mass to the force acting on it. If the force and the mass are known, the acceleration can be found and then integrated with respect to time to find the velocity.

In a sound wave, the pressure gradient accelerates the air of density  $\rho$ .

With the knowledge of the pressure gradient and the density of air, the particle acceleration can be calculated using Equation (8):

$$a = -\frac{1}{\rho} \times \frac{\delta p}{\delta r} \tag{8}$$

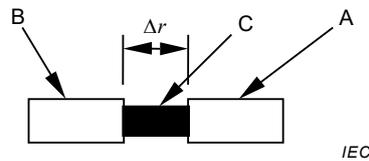
where  $a$  is the particle acceleration due to a pressure change  $\delta p$  in air with density  $\rho$  across a distance  $\delta r$ .

Integrating the above, Equation (9) gives the particle velocity  $u$  as follows:

$$u = -\int \left( \frac{1}{\rho} \times \frac{\delta p}{\delta r} \right) dt \tag{9}$$

It is possible to measure the pressure gradient with two closely spaced microphones, A and B, separated by a spacer of length  $\Delta r$ . With a finite difference approximation of Equation (9) the

pressure gradient can be obtained by taking the difference in their measured pressures  $p_A$  and  $p_B$ , and dividing it by the distance  $\Delta r$  between them.



#### Key

A and B microphones

C spacer of length  $\Delta r$

**Figure 11 – Microphone arrangement**

The pressure gradient signal is then integrated to give the time-averaged particle velocity  $u$  as shown in Equation (10):

$$u = -\frac{1}{\rho} \int \left( \frac{p_A - p_B}{\Delta r} \right) dt \quad (10)$$

Sound intensity is subsequently calculated as the product of the sound pressure in the midst of the microphone pair and the time-averaged particle velocity:

$$I = -\frac{p_A + p_B}{2\rho} \int \left( \frac{p_A - p_B}{\Delta r} \right) dt \quad (11)$$

This is the basic principle of signal processing in sound intensity measuring equipment.

The principle of the sound intensity method theoretically accounts for the disturbances discussed above; in practical test environments however there are limitations for its application.

Where the difference ( $p_A - p_B$ ) in pressure between the two microphones is small compared to the absolute pressure magnitude  $(p_A + p_B)/2$  the determination of the pressure gradient tends to become inaccurate.

An indication of this effect can be derived from the difference between the uncorrected sound pressure level containing the disturbances and the sound intensity level of the sound power propagating from the test object alone. Experiments have shown that sound intensity measurement accuracy strongly correlates to this difference  $\Delta L$ , called the P-I index:

$$\Delta L = \overline{L_{pA0}} - \overline{L_{IA}} \quad (12)$$

It has to be recognised that all types of disturbance contribute to the P-I index and the larger a disturbance, the larger is the P-I index.

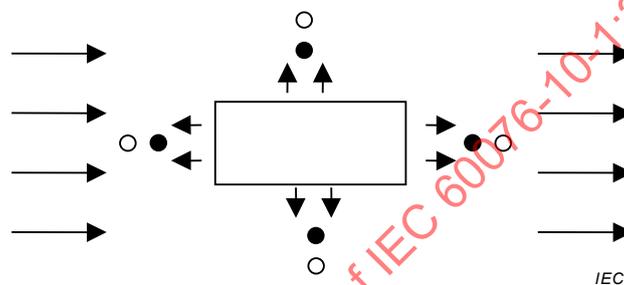
The larger the P-I index, the higher is also the tendency to underestimate the sound intensity level. For this reason, the maximum permissible P-I index has to be limited to assure the measurement quality (see 11.3.5 of IEC 60076-10:2016). It is also noted, that in such situations the sound pressure is overestimated.

Sound waves leaving the radiating surfaces of the test object will be reflected from the floor, walls and other objects in the test room. Due to the sensitivity of the sound intensity probe to the sound propagation direction, sound intensity measurements are usually not adversely affected by such reflections.

NOTE In the situation of a highly or fully diffuse sound field (for instance inside an acoustic enclosure) the sound intensity is close to zero and the P-I index is high, indicating that the measurement is rejected.

Standing waves should be avoided or minimised by careful placement of the test object in the test room, see 6.2 of this standard and 11.1.1 of IEC 60076-10:2016. At locations where standing waves occur, the measuring device will measure intensity close to zero because sound pressure and particle velocity are out of phase. In consequence the intensity level will be reduced and this is indicated by a high P-I index.

Practical test environments are often affected by noise from external sources such as manufacturing processes, the test generator and other energised test transformers. Figure 12 indicates such an environment with steady-state background noise propagation from left to right across the test object.



Microphone pair positions are indicated by the white microphone A and the black microphone B.

**Figure 12 – Illustration of background sound passing through test area and sound radiated from the test object**

With the test object not energised there will be negative intensity measured on the left side, positive intensity on the right side and no intensity measured on the long sides. The spatially averaged intensity will therefore be zero. When the test object is energised there will be an additional amount of positive intensity on all four sides emitted. As mentioned above the net effect on the intensity due to the background noise is zero and therefore has no effect on the test objects intensity. It is noted that this does not apply for the sound pressure.

The ideal situation above does not hold true if the background noise is high relative to the test object noise. In such situations the intensity on the left (short) side is small or even negative and on the right (short) side the intensity is increased. This is not a problem as long as the absolute pressure magnitude  $(p_A + p_B)/2$  does not swamp the pressure difference  $(p_A - p_B)$ . On the top and bottom (long) sides of the test object this effect is more severe because both microphones are exposed to the same absolute pressure increase due to the background noise. The P-I index accounts for this and it is essential to derive the P-I index only from the spatially averaged measurements along the entire (closed) measurement path around the test object.

In summary, the sound intensity method accounts for steady-state background noise but only up to a certain extent. With increasing levels of steady-state background noise, the measured sound intensity level of the test object decreases which is obviously unacceptable. At the same time the P-I index value increases. Working within the limits for the P-I index as stated in 11.3.5 of IEC 60076-10:2016 maintains the acceptability of the measurement.

Sound intensity measurements distinguish between active and reactive sound fields; therefore, near-field effects will not adversely affect the measured sound intensity level.

As stated in 11.3.1 of IEC 60076-10:2016, it is inherent to the sound intensity method that the measurement surface and therefore the measurement path shall completely encircle the test object. Whilst spot indication of sound intensity and P-I index can be informative to identify locations with problematic sound emission, measurements performed to estimate sound power and the corresponding P-I index shall be derived from measurements along the entire measurement path.

#### 5.3.4 Selection of appropriate sound measurement method

Both sound pressure method and sound intensity method can be used for the estimation of sound power and they are expected to give comparable values.

The sound intensity method inherently accounts for the physics of sound and this is reflected in the fact that there is no requirement for corrections. Measured results are acceptable provided the limits for the P-I index (11.3.5 of IEC 60076-10:2016) are maintained. The value of 4 dB as the base limit is introduced after careful consideration and evaluation of the effects imposed by each individual type of disturbance and is backed-up by practical experience. Such experience also revealed that sound power estimations based on sound intensity measurements within this limit represent the true value of the sound power more accurately than sound power estimations based on corrected sound pressure measurements.

Beyond the base limit of 4 dB for the P-I index, sound intensity tends to underestimate and sound pressure tends to overestimate sound power. In this situation the reported sound intensity level is assumed to be 4 dB below the measured sound pressure level, see 11.3.5 of IEC 60076-10:2016. This approximation avoids the risk of sound power underestimation.

The upper limit for the P-I index of 8 dB given in 11.3.5 of IEC 60076-10:2016 is intended to maintain a minimum quality of the test environment.

Where the above conditions cannot be met, i.e. the P-I index exceeds 8 dB and where the sound pressure level is believed to overestimate the sound power, alternative measurement methods such as band selected narrow-band and time-synchronous measurement can be considered.

#### 5.4 Information on frequency bands

The default bandwidth in this standard is 1/3-octave. This bandwidth is commonly used in industry and is routinely available on sound level meters. It normally provides sufficient details for the evaluation of the test object, specifically with respect to transformer tones.

NOTE Octave band levels and the total sound level can be derived from 1/3-octave band levels.

In order to measure individual transformer fundamental and harmonic tones, it is necessary to select appropriately narrow measurement bands. When a tone falls in between two adjacent bands, then the energy of this tone will be distributed across these two adjacent bands.

For 50 Hz systems, the tones up to 600 Hz coincide well with the useful width of the 1/3-octave bands; this is not the case for 60 Hz systems. The 3<sup>rd</sup> harmonic of the 60 Hz system for instance is located on the lower band limit of the 400 Hz band; hence a fraction of the tone energy is represented in the 315 Hz band. To determine the magnitude of a tone split across two adjacent bands, these two band levels have to be summated else a wider bandwidth shall be adopted.

Figure 13 demonstrates the tones of interest and the corresponding 1/3- and 1/1-octave bands.