IEC 60076-10-1

Edition 2.0 2016-03

INTERNATIONAL STANDARD

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inside

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

Transformateurs de puissance –
Partie 10-1: Détermination des niveaux de bruit – Guide d'application

IEC 60076-10-1:2016-03(en-fr)

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FOREWORD

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

This second edition cancels and replaces the first edition published in 2005. This 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.

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

FDIS	Report on voting
14/847/FDIS	14/850/RVD

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

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

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

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- replaced by a revised edition, or
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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 µPa. 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 µPa 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:

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

It is measured in watts per square metre, W/m^2.

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 ¼ 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.

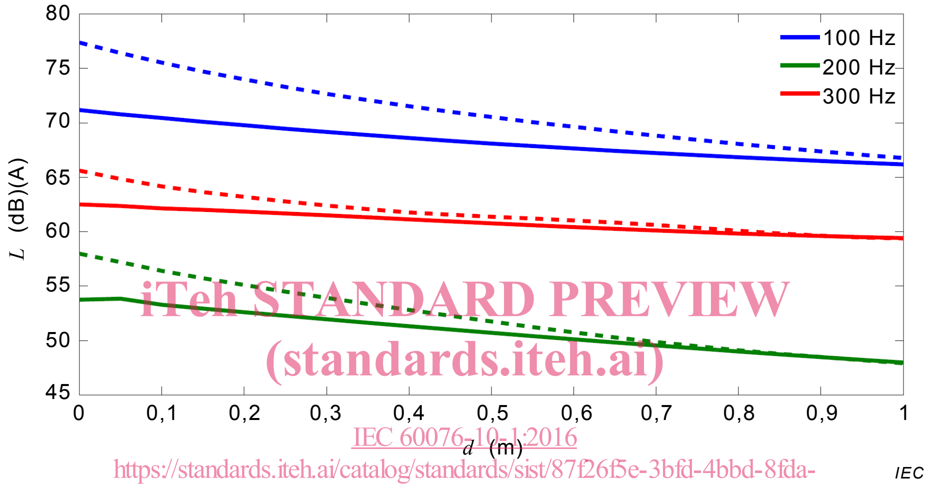


Figure 1 – Simulation of the spatially averaged sound intensity level (solid lines) and sound pressure level (dashed lines) versus measurement distance *d* in the near-field

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:

$$f_{\nu} = \nu \frac{c}{2d} \qquad (2)$$

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

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 µm to 10 µm per metre length (µm/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_{max}.

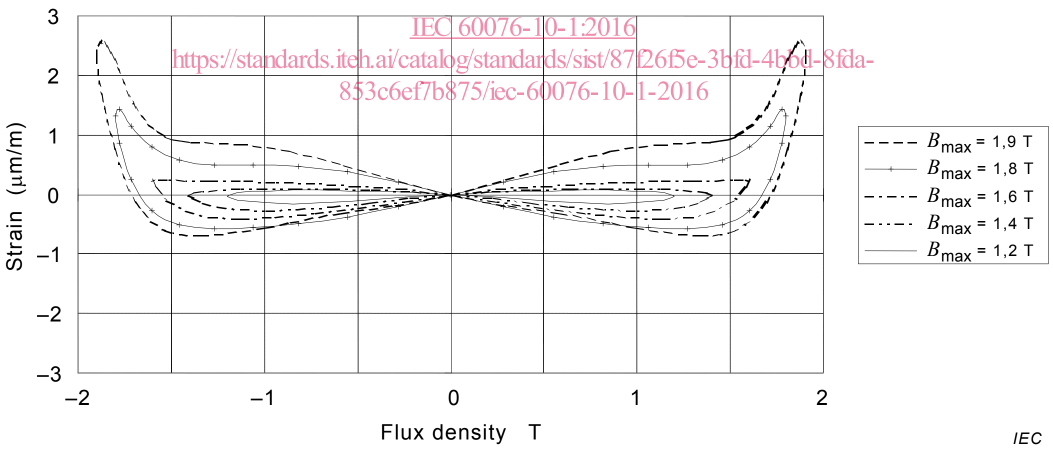


Figure 2 – Example curves showing relative change in lamination length f e of electrical core steel during complete cycles of applied 50 Hz a.c. induction up to peak flux densities B_{max} in the range of 1,2 T to 1,9 T

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_{max} = 1,8 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.

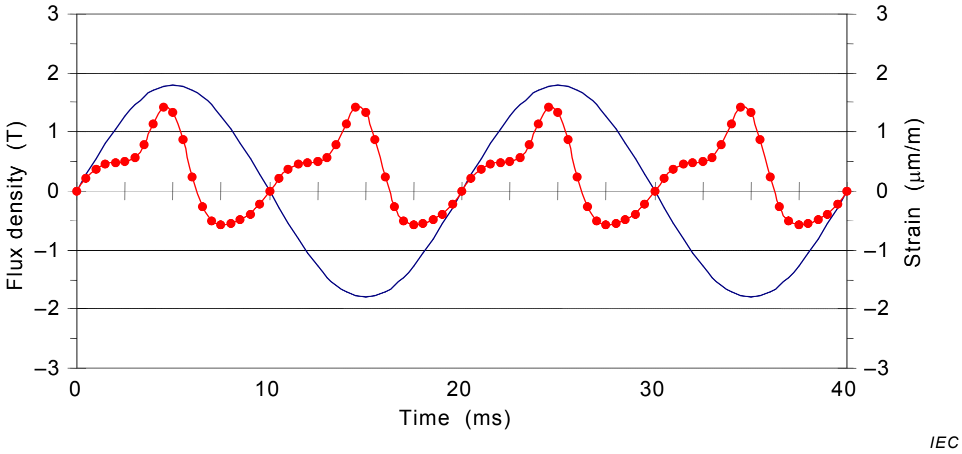


Figure 3 – Induction (smooth line) and relative change in lamination length (dotted line) as a function of time due to applied 50 Hz a.c. induction at 1,8 T – no d.c. bias

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.

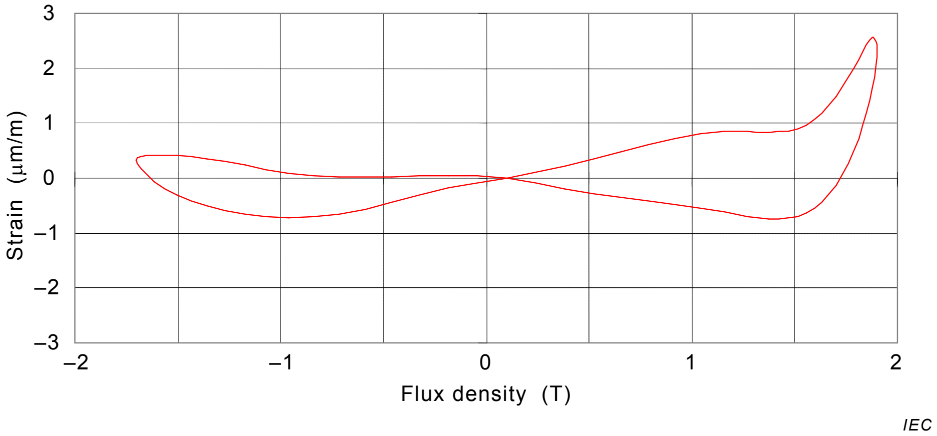


Figure 4 – Example curve showing relative change in lamination length during one complete cycle of applied 50 Hz a.c. induction at 1,8 T with a small d.c. bias of 0,1 T

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.

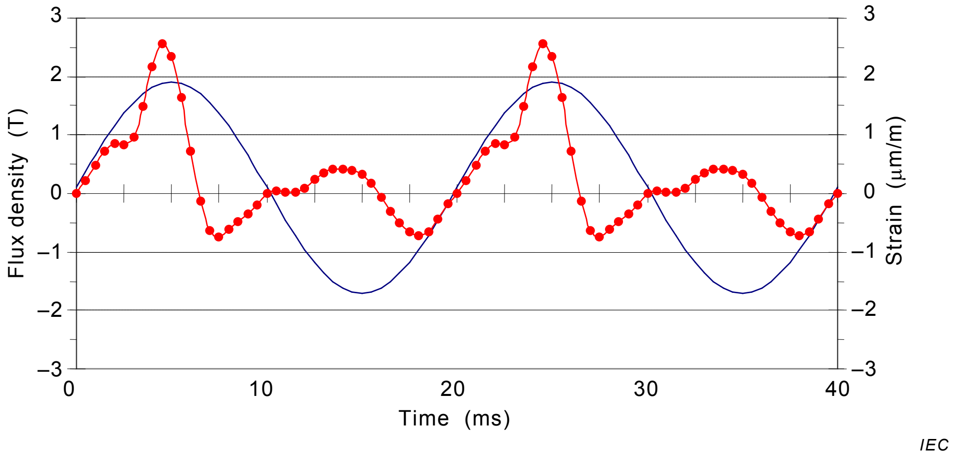
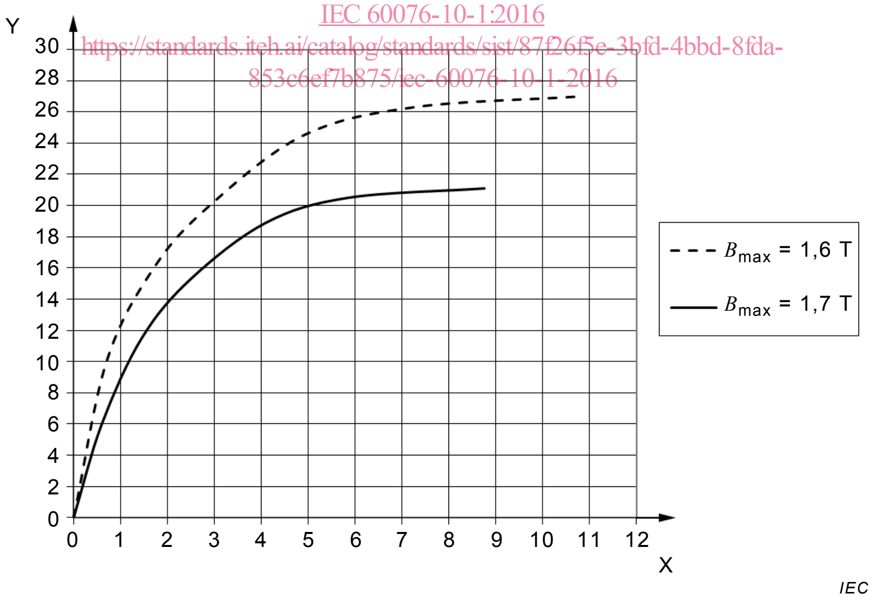


Figure 5 – Induction (smooth line) and relative change in lamination length (dotted line) as a function of time due to applied 50 Hz a.c. induction at 1,8 T with a small d.c. bias of 0,1 T

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.