IEC 60076-10-1

Edition 2.1 2020-11
CONSOLIDATED VERSION

INTERNATIONAL STANDARD

colour inside

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

IEC 60076-10-1:2016-03+AMD1:2020-11 CSV(en)

Documents
Document Sharing Hub

Full document details: IEC 60076-10-1-2020

THIS PUBLICATION IS COPYRIGHT PROTECTED
Copyright © 2020 IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester. If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

About the IEC
The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications
The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigendum or an amendment might have been published.

IEC publications search - webstore.iec.ch/advsearchform
The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee,…). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished
Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and once a month by email.

IEC Customer Service Centre - webstore.iec.ch/csc
If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: sales@iec.ch.

Electropedia - www.electropedia.org
The world's leading online dictionary on electrotechnology, containing more than 22 000 terminological entries in English and French, with equivalent terms in 16 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

IEC Glossary - std.iec.ch/glossary
67 000 electrotechnical terminology entries in English and French extracted from the Terms and definitions clause of IEC publications issued between 2002 and 2015. Some entries have been collected from earlier publications of IEC TC 37, 77, 86 and CISPR.

Documents
Document Sharing Hub

Full document details: IEC 60076-10-1-2020

IEC 60076-10-1

Edition 2.1 2020-11
CONSOLIDATED VERSION

INTERNATIONAL STANDARD

colour inside

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

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.180

ISBN 978-2-8322-9027-9

Warning! Make sure that you obtained this publication from an authorized distributor.

® Registered trademark of the International Electrotechnical Commission

Documents
Document Sharing Hub

Full document details: IEC 60076-10-1-2020

Documents
Document Sharing Hub

Full document details: IEC 60076-10-1-2020

IEC 60076-10-1

Edition 2.1 2020-11
CONSOLIDATED VERSION

REDLINE VERSION

colour inside

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

IEC 60076-10-1:2016-03+AMD1:2020-11 CSV(en)

Documents
Document Sharing Hub

Full document details: IEC 60076-10-1-2020

CONTENTS

FOREWORD 5
1 Scope 7
2 Normative references 7
3 Basic physics of sound 7
3.1 Phenomenon 7
3.2 Sound pressure, p 7
3.3 Particle velocity, u 8
3.4 Sound intensity, $\bar{I}$ 8
3.5 Sound power, W 8
3.6 Sound fields 9
3.6.1 General 9
3.6.2 The free field 9
3.6.3 The diffuse field 9
3.6.4 The near-field 9
3.6.5 The far-field 10
3.6.6 Standing waves 10
4 Sources and characteristics of transformer and reactor sound 11
4.1 General 11
4.2 Sound sources 11
4.2.1 Core 11
4.2.2 Windings 14
4.2.3 Stray flux control elements 14
4.2.4 Sound sources in reactors 15
4.2.5 Effect of current harmonics in transformer and reactor windings 15
4.2.6 Fan noise 18
4.2.7 Pump noise 18
4.2.8 Relative importance of sound sources 18
4.3 Vibration transmission 18
4.4 Sound radiation 19
4.5 Sound field characteristics 19
5 Measurement principles 20
5.1 General 20
5.2 A-weighting 20
5.3 Sound measurement methods 22
5.3.1 General 22
5.3.2 Sound pressure method 23
5.3.3 Sound intensity method 24
5.3.4 Selection of appropriate sound measurement method 27
5.4 Information on frequency bands 27
5.5 Information on measurement surface 29
5.6 Information on measurement distance 29
5.7 Information on measuring procedures (walk-around and point-by-point) 30
6 Practical aspects of making sound measurements 31
6.1 General 31
6.2 Orientation of the test object to avoid the effect of standing waves 31
6.3 Device handling for good acoustical practice 32

AVA Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020

6.4 Choice of microphone spacer for the sound intensity method 33
6.5 Measurements with tank mounted sound panels providing incomplete coverage 33
6.6 Testing of reactors 34
7 Difference between factory tests and field sound level measurements 34
7.1 General 34
7.2 Operating voltage 34
7.3 Load current 34
7.4 Load power factor and power flow direction 35
7.5 Operating temperature 35
7.6 Harmonics in the load current and in voltage 35
7.7 DC magnetization 36
7.8 Effect of remanent flux 36
7.9 Sound level build-up due to reflections 36
7.10 Converter transformers with saturable reactors (transductors) 37
Annex A (informative) Sound level built up due to harmonic currents in windings 38
A.1 Theoretical derivation of winding forces due to harmonic currents 38
A.2 Force components for a typical current spectrum caused by a B6 bridge 39
A.3 Estimation of sound level increase due to harmonic currents by calculation 42
Bibliography 44

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 10
Figure 2 – Example curves showing relative change in lamination length for one type 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 11
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 12
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 12
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 13
Figure 6 – Sound level increase due to d.c. current in windings 13
Figure 7 – Typical sound spectrum due to load current 14
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 20
Figure 9 – A-weighting graph derived from function $A(f)$ 21
Figure 10 – Distribution of disturbances to sound pressure in the test environment 24
Figure 11 – Microphone arrangement 25
Figure 12 – Illustration of background sound passing through test area and sound radiated from the test object 26
Figure 13 – 1/1- and 1/3-octave bands with transformer tones for 50 Hz and 60 Hz systems 28
Figure 14 – Logging measurement demonstrating spatial variation along the measurement path 31
Figure 15 – Test environment 32
Figure A.1 – Current wave shape for a star and a delta connected winding for the current spectrum given in Table A.2 40
AVA Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020

Table 1 – A-weighting values for the first fifteen transformer tones 22
Table A.1 – Force components of windings due to harmonic currents 39
Table A.2 – Current spectrum of a B6 converter bridge 39
Table A.3 – Calculation of force components and test currents 41
Table A.4 – Summary of harmonic forces and test currents 42

Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020

INTERNATIONAL ELECTROTECHNICAL COMMISSION

POWER TRANSFORMERS –

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

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

This consolidated version of the official IEC Standard and its amendment has been prepared for user convenience.

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.

Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020

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

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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

Documents
Document Sharing Hub

Full document details: IEC 60076-10-1-2020

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.

Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020

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.

AVA Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020

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.

AVA Documents
Document Sharing Hub

Full document details: IEC 60076-10-1-2020

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.

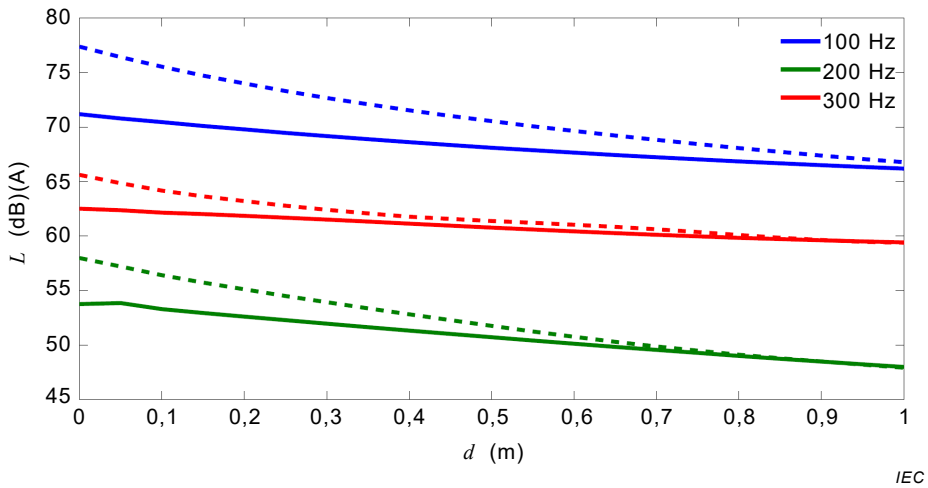


Figure 1 – Simulation of the spatially averaged sound intensity level (solid lines) and sound pressure level (dashed lines) versus measurement distance d in the near-field

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_ν depends upon the distance d between the reflecting walls as follows:

$$f_\nu = \nu \frac{c}{2d} \tag{2}$$

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.

AVA Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020

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}.

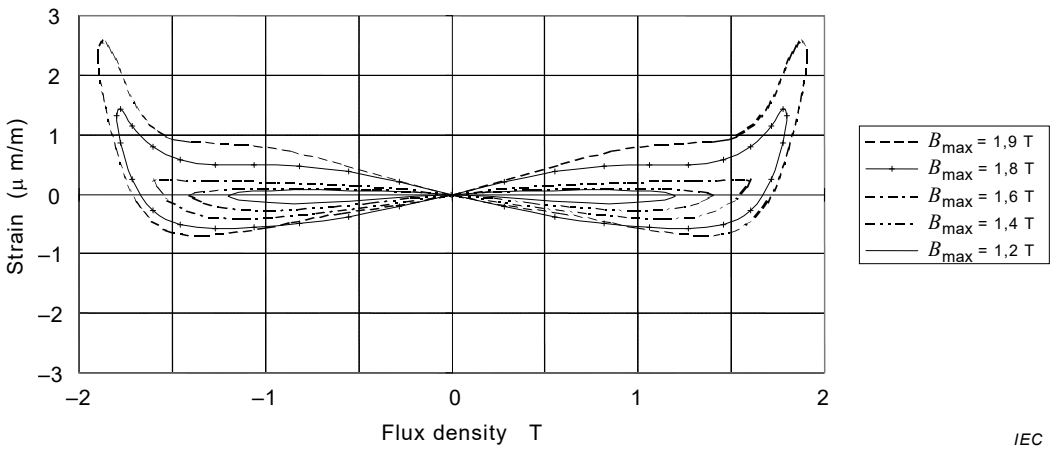


Figure 2 – Example curves showing relative change in lamination length f[illegible] of electrical core steel during complete cycles of applied 50 Hz a.c. induction up to peak flux densities B_{max} in the range of 1,2 T to 1,9 T

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.

Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020

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.

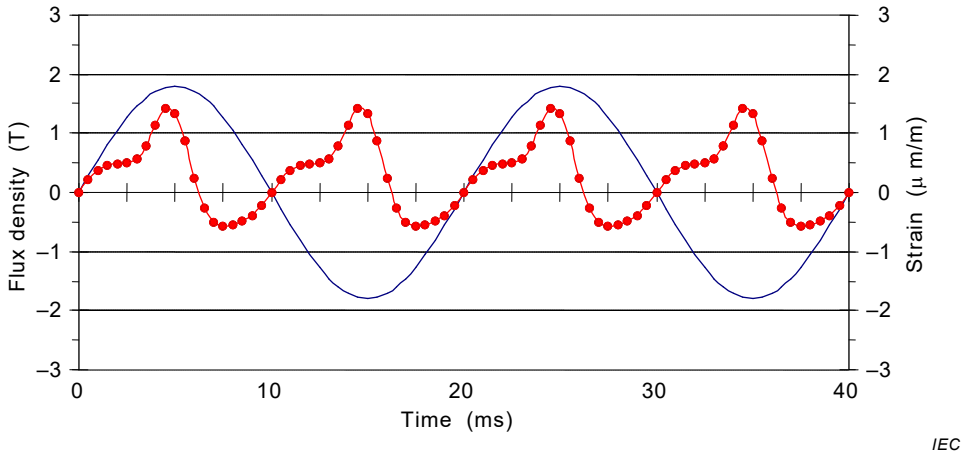


Figure 3 – Induction (smooth line) and relative change in lamination length (dotted line) as a function of time due to applied 50 Hz a.c. induction at 1,8 T – no d.c. bias

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.

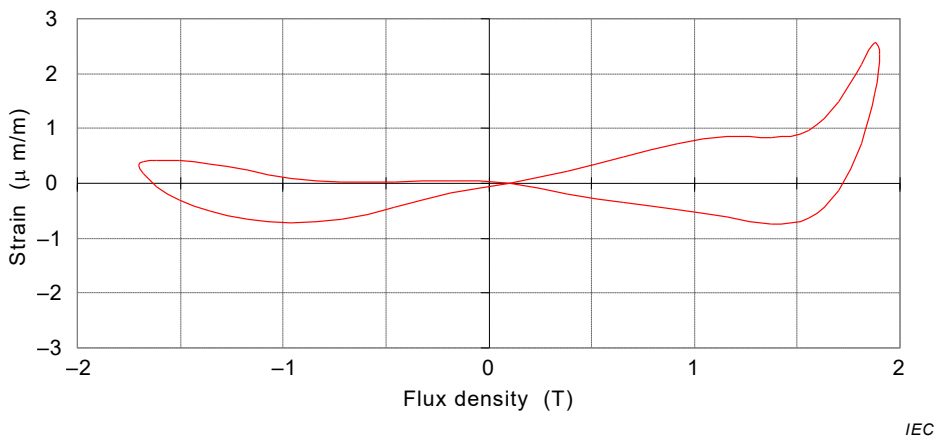


Figure 4 – Example curve showing relative change in lamination length during one complete cycle of applied 50 Hz a.c. induction at 1,8 T with a small d.c. bias of 0,1 T

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.

Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020

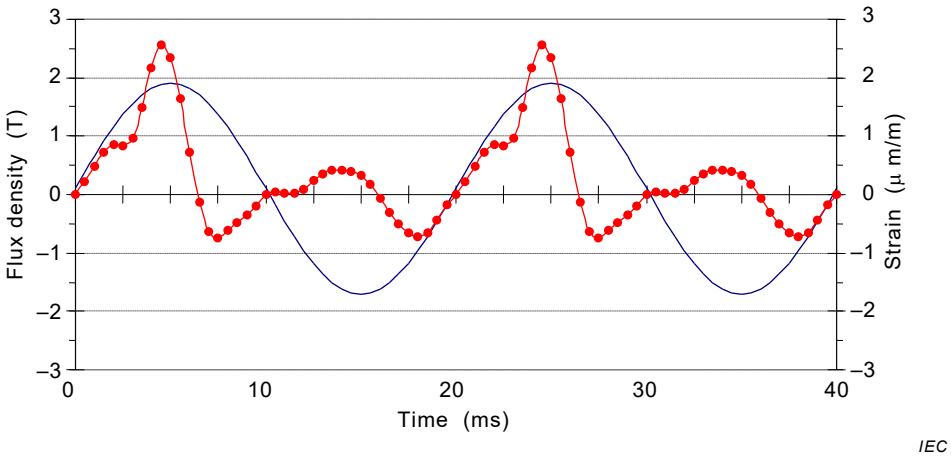
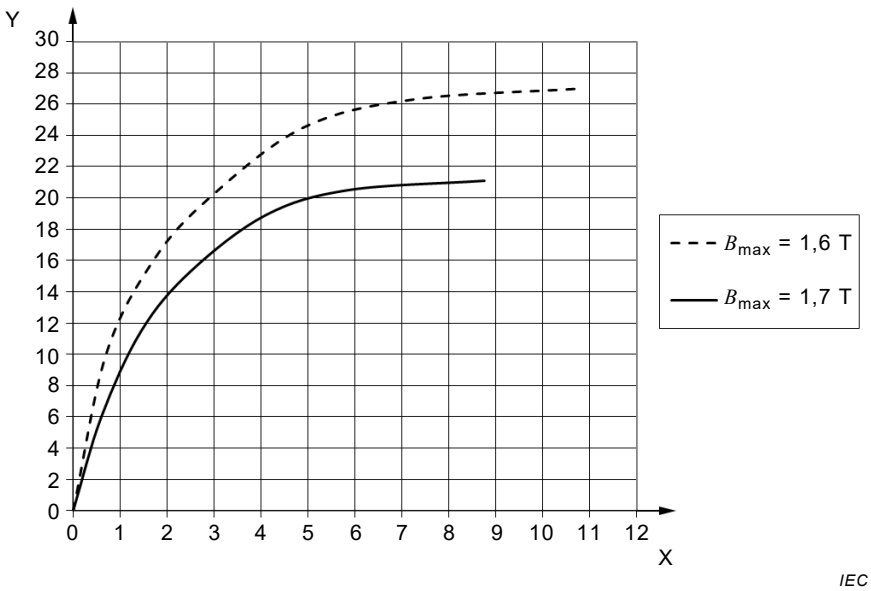


Figure 5 – Induction (smooth line) and relative change in lamination length (dotted line) as a function of time due to applied 50 Hz a.c. induction at 1,8 T with a small d.c. bias of 0,1 T

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.

Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020

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.

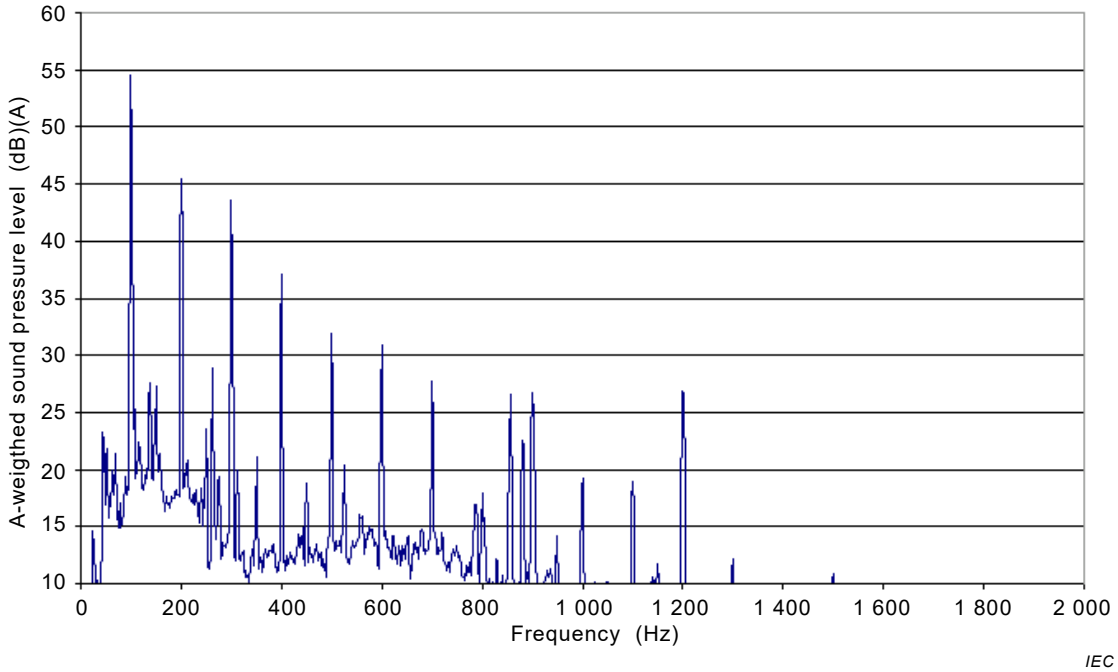


Figure 7 – Typical sound spectrum due to load current

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’;

AVA Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020

- 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.

Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020

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 … 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 5th and 7th order):

Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020

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):

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

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:

a) Calculate the relative amplitude of forces for harmonics I_n by applying $(I_n/I_1)^2$ resulting in components with frequencies of $(2\ f_n)$

b) 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 $(f_m - f_n)$

c) 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)

d) Application of a logarithmic approach per frequency for the dynamic response of winding displacement to the forces (consideration of winding transfer function)

e) Conversion of force components per frequency into a logarithmic figure relative to the fundamental force

f) Conversion of circular frequency into a logarithmic figure relative to the fundamental frequency

g) Application of a logarithmic approach per frequency for the radiation efficiency relative to the fundamental radiation efficiency

h) Application of A-weighting per frequency relative to the A-weighting of the fundamental

i) Summation of all components d) to h) expressed in dB(A) to derive the total sound power level increase.

AVA Documents
Document Sharing Hub

Full document details: IEC 60076-10-1-2020

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 SF6 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.

Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020

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)

$$W = \rho_0 \, c \, S \, \sigma \, \omega^2 x^2 \tag{4}$$

where

W	is the radiated sound power in W;
ρ_0	is the air density in kg/m^3;
c	is the speed of sound in air in m/s;
S	is the area of the sound radiating surface in m^2;
σ	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^{-1} 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

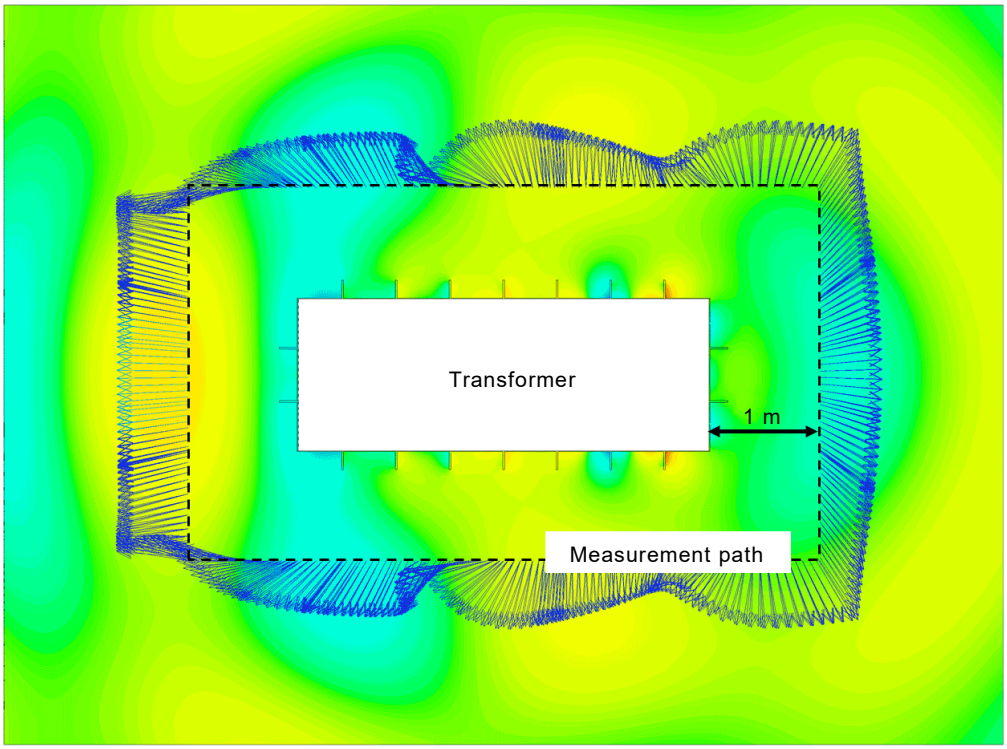
Transformer sound radiation is mainly caused by bending waves of the tank walls. With reference to Figure 8 it can be seen that the resulting sound radiation around the tank is non-uniform. The distinct patterns result from constructive and destructive interference of sound waves originating from different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

Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020

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.



IEC

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

AVA Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020

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

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

and is graphically depicted in Figure 9.

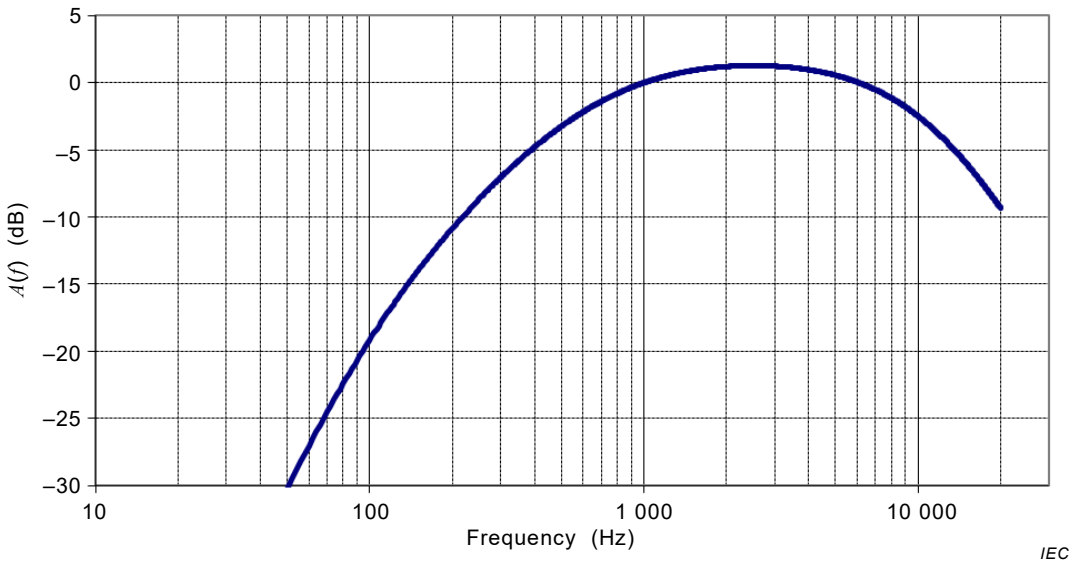


Figure 9 – A-weighting graph derived from function $A(f)$

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.

Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020

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

50 Hz excitation

Frequency Hz	A-weighting value dB
100	-19,1
200	-10,8
300	-7,1
400	-4,8
500	-3,2
600	-2,2
700	-1,4
800	-0,8
900	-0,3
1 000	0
1 100	0,3
1 200	0,5
1 300	0,7
1 400	0,8
1 500	0,9

60 Hz excitation

Frequency Hz	A-weighting value dB
120	-16,7
240	-9,1
360	-5,6
480	-3,5
600	-2,2
720	-1,3
840	-0,6
960	-0,1
1 080	0,2
1 200	0,5
1 320	0,7
1 440	0,8
1 560	1,0
1 680	1,1
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):

$$|I| = \frac{p^2}{\rho c}, \tag{6}$$

where ρc is the acoustic impedance of the medium through which the sound is propagating. Under standard conditions of pressure and temperature in air, ρc = 412 kg/(m^{2}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

AVA Documents
Document Sharing Hub

$$L_{\mathrm{I}} = 10 \times \lg \frac{\left|\vec{I}\right|}{I_0} = 10 \times \lg \frac{p^2}{\rho c\, I_0} = 10 \times \lg \frac{p^2}{p_0^2} + 10 \times \lg \frac{p_0^2}{\rho c\, I_0} = L_{\mathrm{p}} + 10 \times \lg \frac{p_0^2}{\rho c\, I_0} \quad (7)$$

For the given reference values of I_0 and p_0 (10^{-12} Wm^{-2} and 20 × 10^{-6} 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 1,013×10^{-5} 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).

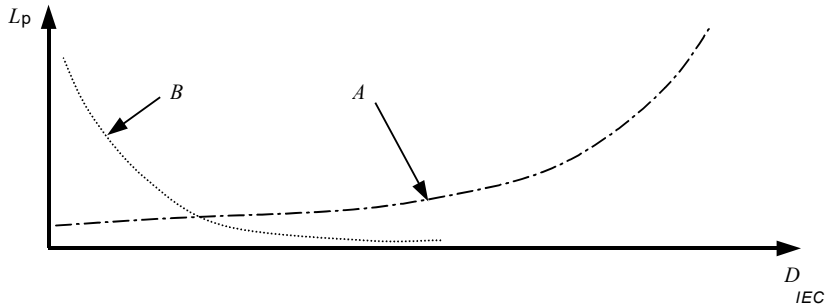
Practical test environments are often affected by noise from external sources such as manufacturing processes, the test generator and other energised test transformers. This will increase the measured sound pressure level around the test object.

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.

Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020



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 ρ.

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 δp in air with density ρ across a distance δr.

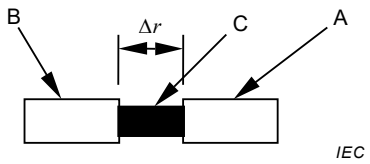
Integrating the above, Equation (9) gives the particle velocity u as follows:

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

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

AVA Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020

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



Key

A and B microphones

C spacer of length Δr

Figure 11 – Microphone arrangement

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

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

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:

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

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 ΔL, called the P-I index:

$$\Delta L = \overline{L_{pA0}} - \overline{L_{IA}} \tag{12}$$

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.

Documents
Document Sharing Hub
Full document details: IEC 60076-10-1-2020