Determination of Transformer Sound Power Level in respect to Tests Methods and Measurement Conditions

Michal Swiatkowski
ABB Power Transformers, Poland

Adam Jaros
ABB Power Transformers, Poland

Michal Kozupa
ABB Corporate Research, Krakow, Poland

Christoph Ploetner
ABB Power Transformers, Germany

Summary

While the sound power level of a transformer is a unique device characteristic, its determination is influenced by many factors. The final test result of a transformer sound measurement is affected by the selected test method but also by the measurement conditions given in the specific test environment and the conditions that are pre-set in the applicable sound measurement standard.

Latest version of IEC 60076-10 "Power Transformers – Determination of sound levels", published in year 2016, provides clear instructions for transformer sound level measurements. Such requirements can be technically and practically seen as a best approach in average and are therefore justified as standard requirements, they however cannot be considered acoustically as the only possible and absolute true way for a transformer sound measurement! In practice, deviations from the standard test requirements become often necessary for mainly practical constraints and cannot be avoided. Even though, such deviations are technically and acoustically justified – it is important to know how much an actually measured sound level can deviate from the sound level hypothetically measured entirely according standard test requirements. The paper will discuss a number of affecting parameters.

PACS no. 43.15.+s, 43.20.Ye

1. Methodology and uncertainty of sound level measurements on transformers

1.1. General

The determination of sound power levels of power transformers is described in international transformer standards [1,2]. Technically most advanced is edition 2.0 of IEC 60076-10 "Power Transformers – Determination of sound levels", published in year 2016. The underlying principles are adopted from international acoustic standards [3,4,5]. Such principles however – due to several practical constraints – cannot be fully applied to transformer sound level measurements, but need modifications / simplifications. The requirements for sound level measurements laid out in IEC 60076-10 can technically and practically be seen as a best approach in average and are justified as standard requirements, they however cannot be considered acoustically as the only possible and absolute true way for the determination of transformers sound power level! Consequently, the question of uncertainty in the determined sound power level is arising: What is the difference between the true sound power level of the transformer under test and the sound power level determined by the test as per standard requirements? Of course, this question cannot be answered absolutely because the true value is never known. It is however of interest to gain information about the range of uncertainty 'around' the pre-set test procedure and measurement conditions by standards, i.e. the relative uncertainty. By performing sound level measurements in a specific laboratory under slightly different conditions – but all within plausible acoustic boundaries – this range of relative uncertainty can be approached and is subject of this paper. About 100 sound level measurements were performed in no-load and load condition on six different power transformers with rated power between 90 MVA and 450 MVA. The impact of five selected factors affecting sound level measurements is presented and discussed. It is noted, that the five factors are exemplarily chosen and other test modifications affect sound level measurements too. Consequently, the paper is intended as contribution to a wider subject. As reference information, IEC 60076-10 states a 3 dB standard deviation of reproducibility for sound power level determinations made in different laboratories.

1.2. The enveloping principle and its limitations for transformer sound level measurements

The sound power / sound power level of machines and devices such as transformers cannot be directly measured. One way to determine the sound power level, widely used in transformer standards, is the application of the so-called enveloping principle. As per this principle, the sound power is determined from direct sound pressure or sound intensity measurements around the test object sitting on a reflecting plane, and the object's enveloping surface at which the measurements are supposed to be taken. The principle assumes the entire sound power emitted by the test object being radiated through the enveloping surface, see Fig. 1.
The determination of the sound power level L_W as per this principle is achieved by the summation of the spatially and timely averaged sound pressure level L_p or sound intensity level L_I plus the so-called surface measure and is described with the following well-known formulas

$$L_w = L_p + 10 \cdot \log {}^{S}/_{S_0}\,,$$
$$L_w = L_I + 10 \cdot \log {}^{S}/_{S_0}\,, \qquad (1)$$
$$S_0 = 1\,m^2\,.$$

It is obvious, the better the sound pressure/sound intensity averaging procedure all over the enveloping surface is, the more accurate will be the determined sound power. This however has practically limitations. Looking to Fig. 1 immediately triggers the fact, that the application of the enveloping principle in the power transformer business requires simplifications: Most significant is the restricted accessibility of the enveloping surface. For safety reasons it is usually not possible to perform any sound measurement on the region above tank height. This situation is reflected in the standard requirements with well-defined measurement locations below the height of the tank cover only. Such a simplification presumes the average sound level in the upper region (above the tank cover) being close to that measured in the lower region. This of course imposes uncertainty when determining the sound power level as per equations (1).

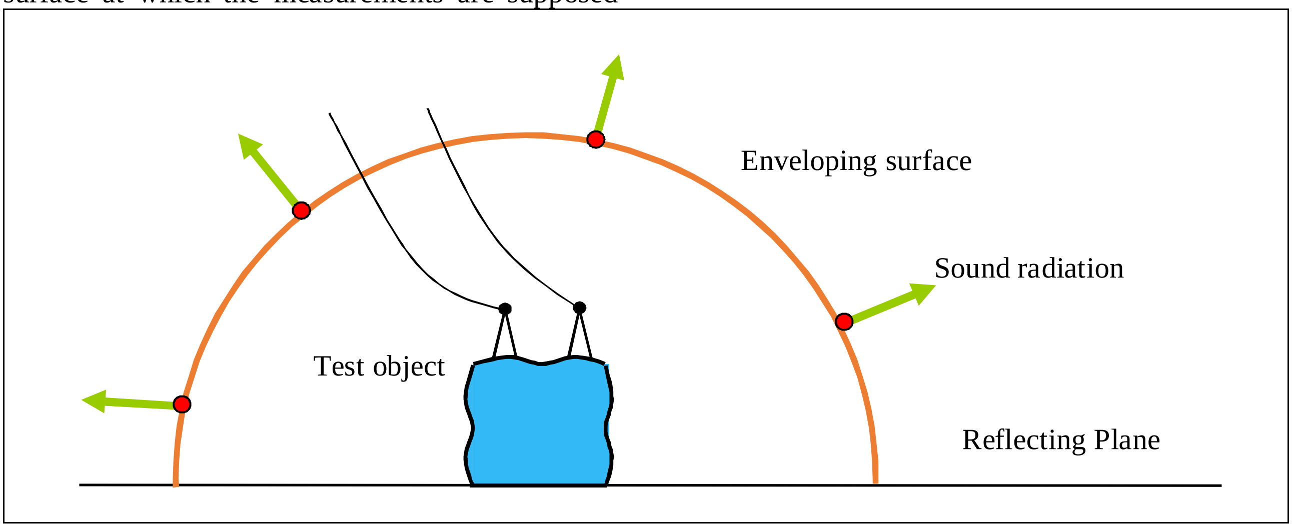

Figure 1. Visualization of the enveloping principle.

Another factor imposing uncertainty to the sound power level is set by the limited space in test laboratories, reflected in standard measurement distances close to the test object (0.3…2 m). Of interest to the transformer user is however the sound power radiated into the 'far field' and would be best determined with measurements at large distances from the test object.
Near field effects but also dimensional and shape effects of the test object, affective in relative vicinity of the sound source, would be minimized. The uncertainty due to the close measurement distance can be limited to a good extent by performing sound intensity measurements instead of sound pressure measurements. The sound intensity method measures the sound radiated into the 'far field' and is therefore recommended to apply whenever possible.

Closely linked to the effects described above is the definition of the measurement surface S pre-set by standards. The natural measurement surface for the sound power level determination as per equations (1) would be, as shown in Fig. 1, an enveloping hemisphere. As the measurement distance is however in close vicinity to the test object, this approach does not reflect the measurement situation and cannot be used. Approximated formulations for S have subsequently been introduced to the industry and proven to match the reality sufficiently. They nevertheless inhere also some uncertainty. Two approaches are used:

$$S = 1.25 \cdot h \cdot l_m, \quad S = (h + x) \cdot l_m \qquad (2)$$

with l_m being the length of the measuring path, h being the height of the test object counted from the reflecting plane and x being the measurement distance – all quantities given in meters. The first approach is applicable only for a measurement distance of 0.3 m while the second approach is valid for all measurement distances up to 30 m. More background information is provided in [6].

1.3. Complexity of tank vibrations and their impact to sound level measurements

While in the previous section the sound level uncertainty due to the measurement conditions is discussed, Figure 2 is intended to illustrate the complexity and uneven distribution of tank vibrations. Do such vibration patterns have potential to introduce uncertainty to sound level measurements?

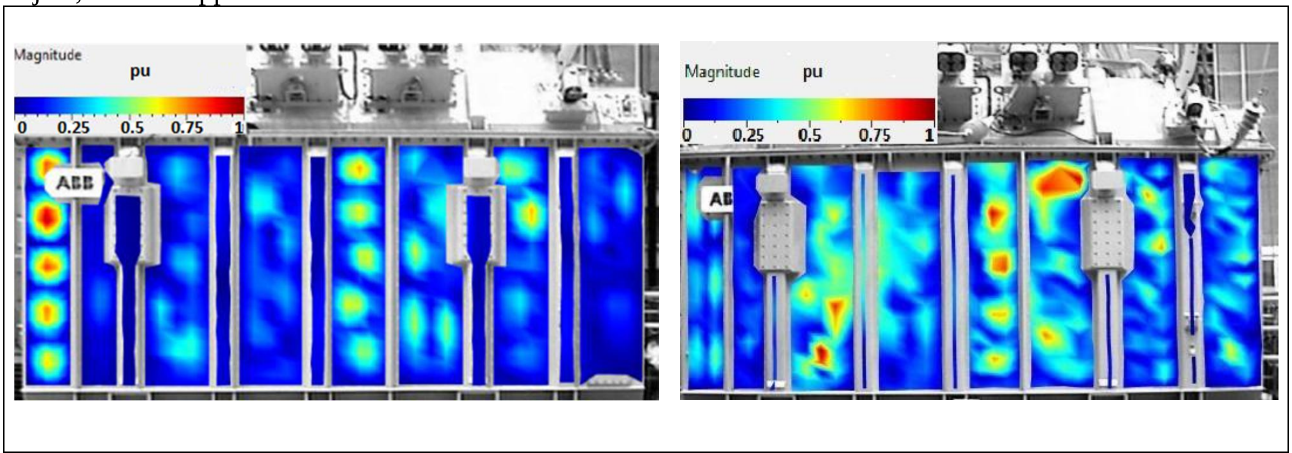

Figure 2. Tank vibration pattern measured in load (left) / no-load condition (right) at acoustically dominating frequencies of 100 Hz / 300 Hz

2. Sound level uncertainty due to selected variations during the measurement

While the sound power level of a transformer is a unique device characteristic, its determination by measurement is influenced by many factors. Some of them will be discussed based on manifold measurements performed in the test laboratory of the ABB Transformer Factory Lodz. This test bay offers good acoustic conditions in respect to dimensions relative to the investigated units, has a rectangular shape with a plane reflecting surface and side walls which are entirely covered with sound absorbing material, resulting in a low (negligible) background noise level. Excitation devices are all located in a separate room. Measurements are taken with the B&K 2270 sound meter. Well-suitable acoustic conditions and equipment is essential to perform reliable acoustic studies.

2.1. Measurement procedure: Surface scan versus path walking

As per explanations in respect to Fig. 1, the more measurement points are taken on the measurement surface and averaged out, the more reliable will be the sound measurement. The non-homogeneous distribution of tank wall vibrations as shown in Fig. 2 obviously supports this statement, specifically if the measurement distance is small – 1 m here. In order to learn about the uncertainty introduced by the standard requirement to measure the sound level along a path of one or two selected heights only, standard measurements were compared with sound measurements performed using a surface scan. One transformer side (tank wall) was selected for the investigation and the continuously averaging measurement sound meter option selected. For both measurements, the sound probe was moved continuously. In case of the surface scan, probe moving was executed such to cover all regions of the tank wall equally. Results are shown in Fig. 3; clearly indicating that the standard requirement in respect to the path selection is fully representative for the sound radiation of the lower (accessible) region of the transformer – for both, no-load and load condition. Differences are all within a dB.

2.2. Measurement procedure: Path walking (walk-around) versus point-by-point

Historically, the so-called point-by-point procedure was the only measurement procedure offered by standards and was triggered by the technical capabilities of available sound meter: Data processing simply took time and required to measure the sound level stationary, i.e. in discrete points. Modern sound meter are working much faster, allowing the sound probe to move continuously up to a certain speed, defined in [1],

Figure 3. Sound level measurements using two different continuous measurement procedures

without introducing erroneous measurements. Fig. 4 shows measured sound levels from three transformers for a comparison of the two measurement procedures.

Figure 4. Sound level measurements as per IEC: walk-around versus point-by-point procedure

The sound level difference between the two procedures is not distinct and can go in both directions, i.e. the point-by-point sound level can be higher or lower than the walk-around sound level. It deviates here in the range of ±2 dB. Please note that such numbers can be sometimes exceeded; result of other tests. The sound level difference between the procedures indicates a certain impact of the complex tank wall vibration patterns, Fig. 2. It seems that the measurement simplification from a surface scan to path moving (walk-around procedure) does not affect the accuracy, the reduction from path moving to a limited number of measurement points (point-by-point procedure) however does somewhat.

Based on the results presented here but also with findings in before section, it must be concluded that the walk-around procedure is more accurate than the point-by-point procedure – simply because it measures the average sound level of the entire path (i.e. many more points). It clearly should be preferred whenever possible. In respect to uncertainty it can be stated that the walk-around procedure does not introduce uncertainty while the point-by-point procedure does – about ±2 dB can be assumed.

2.3. Repeatability

The variation of measured sound levels of repeated measurements is an indicator for the measurement quality, i.e. room conditions, device stability, measurement execution, and is seen as an internal assurance measure for reliable measurements. Fig. 5 shows the sound level variation for repeated measurements and was found to be very small / negligible.

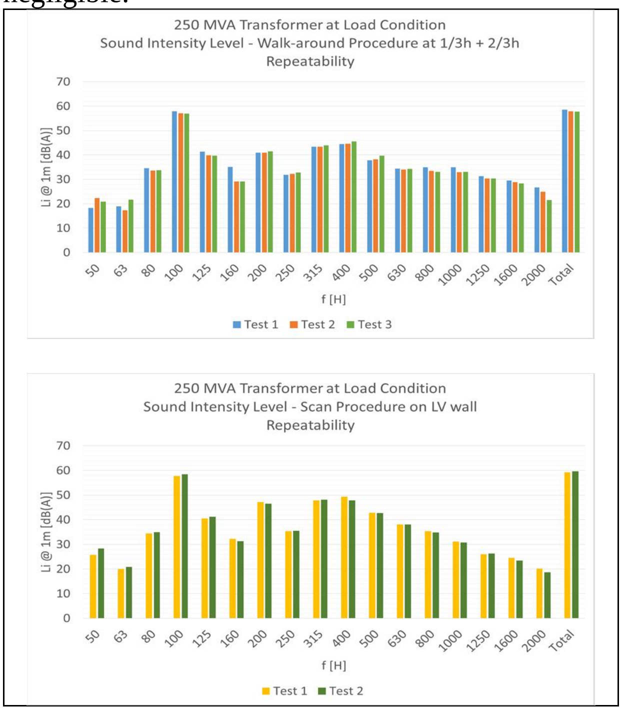

Figure 5. Repeated sound level measurements using surface scan and walk-around procedure

Note that the presented results are received while the transformers were sitting in an unchanged position in the test lab. It of course would be of interest to perform a repeatability test on a transformer being relocated to another position in the same test lab after a first test. Also of interest would be the investigation of different support structures, subject of future work.

2.4. Measurements along an incomplete path – circumferential variation of the sound level

As explained in chapter 1, it is essential to include as much as possible of the measurement (enveloping) surface to the sound level measurement. One of the standard requirements to obey this request is to measure the sound level around the entire test object, i.e. along the entire (closed) path. There are however sometimes situations that do not at all or only allow this in a modified manner (change in measurement distance and height) and such must be handled with care. If the sound radiation in the inaccessible region is not comparable with that along the accessible path, this may introduce an error to the determined sound power level because the measured sound level L_p or L_I would be not representative for the entire path. In order to better understand and approach the uncertainty of such a situation, sound level measurements along parts of the measurement path were performed on two selected transformers. Both units have a distinct circumferential variation in their sound radiation and allowed access to the full measurement path. The reasons for the circumferential variation in the sound radiation of certain transformers are design related and are not subject of this paper.

Table 1 presents part sound measurements of the four tank sides individually. It can be seen that the side 'Short 2' exposes significantly lower levels than the remaining three sides for both, load and no-load condition. The influence to the average sound level is however moderate: neglecting side 'Short 2' – let us say because of inaccessibility – would increase the average sound level by about 1 dB. If neglecting one of the other tank sides, the impact is even lower and would reduce the average sound level by about 0.5 dB.

Table I. Part sound levels measured on a 250 MVA transformer

Condition	Sound level	LV Side	Short 1	Short 2	HV Side	Average
Load	L_I [dB(A)]	59.6	59.9	52.3	60.1	58.9
	L_p [dB(A)]	61.9	61.8	57.1	62.5	61.3
No-Load	L_I [dB(A)]	61.2	62.8	54.6	61.7	61.0
	L_p [dB(A)]	64.4	66.2	58.7	64.3	64.1

Table II. Total and part sound levels measured on a 160 MVA transformer (60 Hz)

Condition	Sound level	LV+HV+Short 1	Short 2	Measurement as per standard
Load	L_I [dB(A)]	65.2	69.4	66.6
	L_p [dB(A)]	69.6	73.2	70.9
No-Load	L_I [dB(A)]	51.3	50.8	51.1
	L_p [dB(A)]	55.2	55.4	55.2

In summary, significant circumferential variations in the sound radiation impose an uncertainty risk to the determined sound power level, if a limited part of the measurement path is excluded from the measurement. The uncertainty level is practically however not more than ±1 dB. If the sound radiation is circumferentially more or less homogeneous, and external noise (background noise) is negligible (always required), then there is no adverse impact to expect for the sound level measurement when excluding a limited part of the measurement path.

2.5. Measurement distance

The investigations presented so far, primarily addressed the uncertainty of sound levels L_p and L_I measured in the lower region of the measurement surface. If it comes to the uncertainty introduced by the selected measurement distance, the sound power level is of interest. This is, because the sound power level of a transformer is a distinct device quantity and should be independent of the measurement distance. Taking into consideration that the uncertainty of the measured sound levels L_p and L_I is small – as shown in predecessor chapters – the question in focus here addresses the concept: Is the standard approach for the measurement surface S as per second equation of (2) in conjunction with the measured sound level suitable for the determination of the sound power level? If so, the increased surface measure L_S would compensate the decreased sound level L_p / L_I measured at larger measurement distances – refer to equations (1). Figure 6 shows sound level measurements performed at different distances around a 90 MVA transformer in both, no-load and load condition. Because of the large measurement distances, a smaller unit was selected for the test. As expected, the measured sound level decreases with increasing measurement distance.

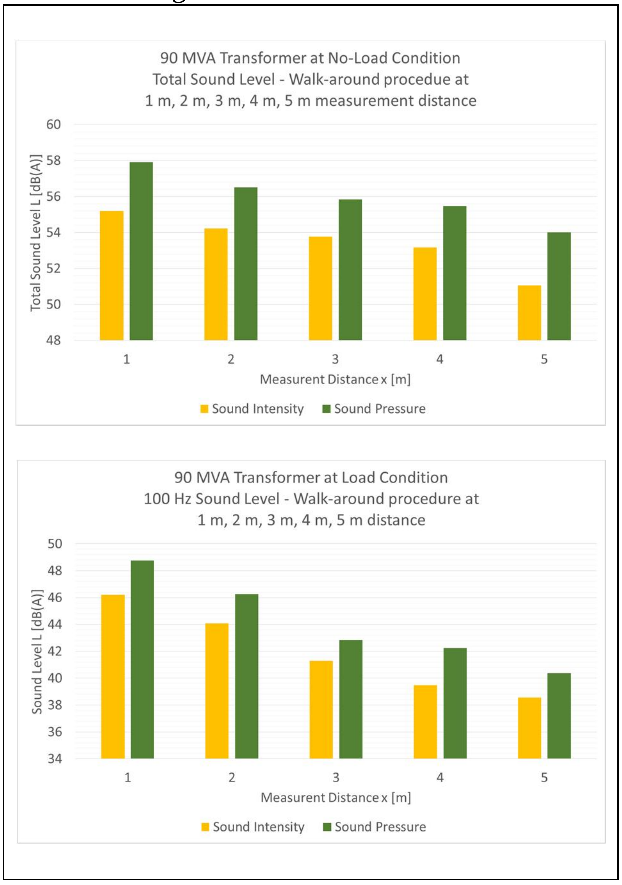

Figure 6. Sound level measurements L_p and L_I at different measurement distances

Table III. No-load sound power level of a 90 MVA transformer determined from measurements at different distances

Measurement distance x [m]	Length of prescribed contour l_m [m]	Measurement Surface Area S [m²]	Surface measure L_S [dB(A)]	Sound Power Level based on Sound Intensity L_{WI} [dB(A)]	Sound Power Level based on Sound Pressure L_{Wp} [dB(A)]
1	24	137	21.4	77.0	79.3
2	30	201	23.0	77.3	79.5
3	37	285	24.5	78.3	80.4
4	43	374	25.7	78.9	81.2
5	49	475	26.8	77.8	80.8

Table IV. Load sound power level of a 90 MVA transformer determined from measurements at different distances

Measurement distance x [m]	Length of prescribed contour l_m [m]	Measurement Surface Area S [m²]	Surface measure L_S [dB(A)]	Sound Power Level based on Sound Intensity L_{WI} [dB(A)]	Sound Power Level based on Sound Pressure L_{Wp} [dB(A)]
1	24	137	21.4	67.6	70.1
2	30	201	23.0	67.1	69.3
3	37	285	24.5	65.8	67.4
4	43	374	25.7	65.2	68.0
5	49	475	26.8	65.3	67.1

3. Conclusions

The determination of transformer sound power levels in test laboratories is described in international standards. Due to practical constraints, the measuring (determination) process is from an acoustic point of view simplified and underlies uncertainties, which have been studied by measurements. As the sound power level is determined as sum of the measured sound level L_I or L_p and the surface measure L_S, both components have to be considered.

The investigation of the measured sound level revealed an uncertainty of not more than 1 dB, when applying the walk-around procedure and following IEC standard requirements. In case the accessible measuring path is circumferentially not complete, the additional uncertainty of ± 1 dB is applicable which gives in total ± 1.5 dB uncertainty in such situations. When applying the point-by-point procedure, an additional uncertainty of ± 2 dB must be considered.

Not explicitly discussed in the paper is the selection of the test method, i.e. sound pressure or sound intensity. It is doubtless that the sound intensity method – if correctly applied and as long as the background (external) noise is negligible – returns accurate sound levels. The sound pressure method always overestimates the sound level and requires corrections, a well-known fact.

Investigations in respect to the surface measure (measurement surface) were done indirectly by performing sound level measurements at several distances between 1 m and 5 m and evaluating the corresponding sound power. The variation of the sound power level – theoretically zero – was found to be around 2.5 dB. This uncertainty is attributed as inherent concept uncertainty because of the methodical simplifications applied to the enveloping principle in respect to both, sound level measurement and surface formula approach.

Based on performed studies, it is concluded that the total relative uncertainty of a determined transformer sound power level under well-controlled test conditions is not more than 3 dB or varies by not more than ± 1.5 dB. Even though the presented investigations have sample character and are statistically not verified, it is clearly anticipated that the results are relevant (based on other studies and experience).

For a reliable determination of transformer sound power levels, the following 'best practice' is recommended:

- Application of sound intensity method
- Application of walk-around procedure
- Acoustic control of test environment, specifically of background (external) noise
- Careful measurement execution as per standard requirements

The addressed factors in this paper have been exemplarily selected. Further parameter should be subject of future work:

- Repeatability when moving the transformer to different places within the test laboratory
- Impact of the support structure
- Sound level in the upper region of the measurement surface
- Impact of tank dimensions versus – measurement distance

References

[1] IEC 60076 10:2016, Power Transformers – Part 10: Determination of sound levels

[2] IEEE C57.12.90, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers

[3] ISO 3746:2010, Acoustics – Determination of sound power levels and sound energy levels of noise sources using sound pressure – Survey method using an enveloping measurement surface over a reflecting plane

[4] ISO 9614:1993 Acoustics – Determination of sound power levels of noise sources using sound intensity – Part 1: Measurement at discrete points

[5] ISO 9614:1996 Acoustics – Determination of sound power levels of noise sources using sound intensity – Part 2: Measurement by scanning

[6] IEC 60076 10-1:2016, Power Transformers – Part 10-1: Determination of sound levels – Application Guide