Measuring No – Load and Load noise of Power Transformers using the Sound Pressure and Sound Intensity Methods – Part – I: Outdoors measurements

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Abstract: The subject of deciding on the most appropriate method of determining the true sound power level of a power transformer has been discussed through the transformer industry for decades. It is the objective of this 2 – Part paper to identify magnitudes of the contributions to the inherent difference in power transformer noise level measurements when using the Sound Pressure method versus when using the Sound Intensity method. The paper presents results of comprehensive outdoors and indoors measurements made of the frequency spectrum and total noise of a large number of power transformers using the two measuring methods. In Part – I of the paper, results of the outdoor measurements made on the total noise produced by three power transformers in low ambient / no sound reflections locations are presented. Results of the indoors measurements made on 48 power transformers of 12 – 336 MVA power ratings are presented in Part – II of the paper. Appropriate conditions for accurate indoors measurement of transformer noise when using the Sound Intensity method have been derived. Modifications to the existing IEC and IEEE Industry Standards of transformer noise testing are proposed.

Keywords: Power Transformers, Transformer Noise, Sound Power Measurement, Sound Intensity, Sound Power

I. Introduction

Indoors measurement of the true noise level of a transformer is critical, especially when requirements for low and ultra – low noise levels are to be met. It is even more critical when the levels of individual frequency components of transformer noise are to be guaranteed. The IEC Standard, [1] – [2], allows using the Sound Pressure method, provided appropriate corrections are made for sound wall reflections and ambient noise. It also allows using the Sound Intensity method, provided the difference between the measured values of the sound pressure and sound intensity levels in dB (A) is less than, or equal, 8 dB. Presently, the IEEE Standard [3] allows the Sound Pressure method only, provided a correction is made for the ambient noise under specific ambient noise conditions. The IEEE Standard does not allow corrections for the sound wall reflections. In addition, the ambient noise conditions, as required by both the IEC and IEEE Standards, are often not feasible to meet when measuring Low and Ultra Low noise power transformers.

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II. Review of Previous Work

As mentioned above, the subject of deciding on the most appropriate method of determining the true sound power level of a transformer has been discussed through the transformer industry for decades. Some attempt has been made in the late eighties to evaluate the accuracy of the Sound Intensity method, [4] – [8]. This work was mostly part of an effort by a CIGRE Working Group to determine the conditions for appropriate transformer sound power level measurement using the Sound Intensity method.

In reference [4], outdoors measurements of the total noise level, in dB (A), were made on power transformers in operation using both the Sound Pressure and Sound Intensity methods. These transformers were located in different levels of ambient noise. The conclusion was that the Sound Intensity method gave consistent results under variable test conditions. The authors recommended that transformer noise ratings be determined using the Sound Intensity method as it better measures the true noise level of the transformer.

In reference [5], Dr. Reiplinger, of Siemens, investigated methods to improve the measuring accuracy of the total transformer noise in dB (A). He used three different techniques, simultaneously, to measure the sound level of a 7.8 MVA transformer in three different test rooms with different ambient noise conditions and different sound wall reflections characteristics. The conclusion of this effort was that the Sound Intensity method was the only method that could eliminate the acoustic near – field error, the sound wall reflections error, and the error caused by ambient noise.

In reference [6], Pauwels investigated using the Sound Intensity method to measure the total noise of a 100 KVA distribution transformer when tested in different test rooms and with different, but controlled, ambient noise conditions. The authors concluded that the Sound Intensity method gives accurate results when the difference between the measured Sound Pressure and Sound Intensity is 4 – 7 dB (A). They also concluded that using the triggered Sound Intensity method, larger differences between pressure and intensity levels could be accommodated with maintained high accuracy.

The work referred to above and further investigations by other authors were summarized in a 1992 CIGRE Working Group report [7]. All measurements at that time aimed at the A-weighted total noise level of the transformer. The conclusion of this work was that the Sound Intensity method gave accurate results measured in total A-weighted sound power levels almost regardless of the test conditions, provided that the measured difference between the sound pressure and sound intensity levels was not higher than 8 dB. After this work, the sound intensity method was included, in 1995, in an amendment to the IEC standard 551 for determining sound levels of transformers and reactors, as an alternative to sound pressure level measurements in cases with disturbing ambient or otherwise difficult test conditions. When the IEC Standard was re-written and issued as IEC 60076-10 in 2001, the Sound Intensity method was included in the main body of the Standard as an equally acceptable test method [2].

III. Components of the Difference Between Sound Pressure and Sound Intensity Measurements

The contribution to this difference has the following three main components:

1. Ambient noise which increases the measured sound pressure level but gives no contribution to the integrated sound intensity measured around the transformer. The ambient noise is partly corrected for in the IEEE and IEC Standards for low levels of the ambient noise. Therefore, this correction can not always be applied when measuring low noise transformers. Also, this correction is truly not sufficiently accurate because, while it presently applies to only to the total dB (A) level, the frequency spectrum of the ambient noise is typically very different from the frequency spectrum of the transformer noise. This is, especially true when measuring the single – frequency (100/120 Hz) load noise of a transformer. Also, these Standards can not correct for load noise of the booth transformer when the booth transformer is located in the test area of the transformer being tested for load noise.

2. Reflected sound from walls and ceiling surrounding the transformer tested. Again, this sound gives no contribution to the integrated sound intensity around the transformer but has a significant influence on the sound pressure measurements. This effect is corrected for in the IEC Standard using the “Room correction K”.

3. Reactive near – field sound close to the transformer. This part of the sound field gives no contribution to the far field sound from the transformer. However, it gives an error when determining sound power levels using sound pressure measurements close to the sound source. This noise component is not corrected for in IEC or IEEE Standards of noise measurements.

IV. Scope and Objectives of the Study Performed

In an attempt to evaluate more precisely the magnitude and factors affecting the contribution of each of the above three components to the measured values of transformer noise, comprehensive indoors and outdoors sound level measurements were made on a large number of power transformers at different distances and at main frequency components of the transformer no – load and load noise. The outdoors measurements were performed on three power transformers in free field conditions and low / very low ambient. The indoors measurements were performed on 48 power transformers of 12 – 336 MVA ratings. The measurements were made using the Sound Pressure and Sound Intensity methods simultaneously. The objectives of the data and analysis presented in this 2 – Part paper are:

1. Identify sources and magnitudes of inaccuracies associated with measuring transformer noise.

2. Evaluate and quantify the contributors to the difference between measured values using the Sound Pressure method and those using the Sound Intensity method.

3. Evaluate the relationship between Sound Pressure measurements, with the allowed IEEE and IEC corrections, versus measured values using the Sound Intensity method.

4. Develop appropriate conditions and procedure for accurate measurement of no – load & load noise of power transformers using the Sound Intensity method under different test environment and conditions.

V. Outdoors Sound Measurements

Presented below are results of detailed outdoors sound level measurements made on three different power transformers at different distances from the transformers. In these measurements, wall reflections are completely avoided and ambient sound was low enough to have little or no influence, at least in the near – field measurements. The following sections of the paper include description of the transformers tested, the tests performed, measured data, discussion of the data, and conclusions from this data.

A. *Measurements performed on a 16 MVA transformer*

This transformer is part of a small substation outside a small town in Sweden. The station has only this transformer and is located in a quiet residential area, refer to Fig. 1 below.

Three complete contours were drawn around the transformer at distances of 1/3 m, 2 m, and 5 m, respectively. In addition, three radial lines were drawn according to Fig. 2 below, with measurement stations at 3 m, 8 m, and 16 m distances from the transformer. On the 1/3 m and the 2 m contours, measurements were made at 16 positions and at two heights. The probe was kept in a fixed position during these measurements. On the 5 m contour, measurements were made at 10 positions. In each measuring position, the probe was swept over an area 1 m wide x 2 m high.

Fig. 1 – 16 MVA, 50 Hz, 3-phase, 55/11 kV, OFWF/OFAF

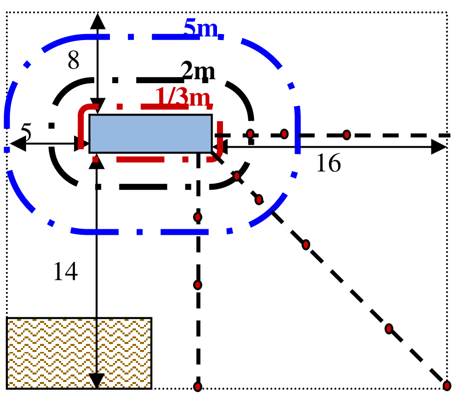


Fig. 2 – Substation indicating measuring positions

The measurements were performed using a Bruel & Kjaer (B&K) Real time analyzer type 2144 together with a B&K intensity probe equipped with a 50 mm spacer ideal for the 80 – 1250 Hz frequency range, which is the range of interest for measuring total noise of Power transformers. All measurements were done using the 1/3 octave resolution.

Presented, in Fig. 3 below, is the measured average frequency spectrum on the contour encircling the transformer at 1/3 m from the transformer. It can be seen from the figure that the difference between the sound levels measured using the Sound Pressure method and the Sound Intensity method is small, especially, for the main frequency components of the noise of this 50 Hz transformer; namely, at 100 Hz, 200 Hz, and 300 Hz. This is because of the relatively low ambient noise levels at these frequencies. This observed difference between the pressure and the intensity measurements is a result of the near – field reactive sound which is included in the sound pressure measurement at this contour. Note that the appreciable noise measured at the 630 – 1000 Hz frequency range is caused by the forced oil / water cooling system.

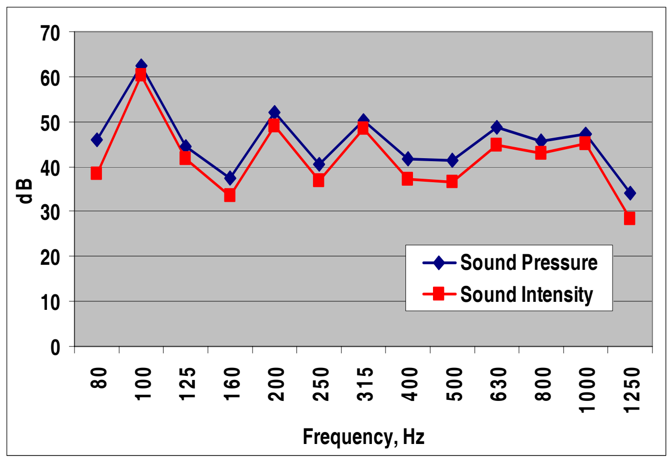


Fig. 3 – Frequency spectrum of the 16 MVA Transformer measured at the 1/3 m contour

A summary of Sound Pressure and Sound Intensity measurements at the 3 different contours around this transformer are given in Table I below for the three main components of the transformer noise.

Distance	Sound Level, dB	100 Hz	200 Hz	300 Hz
1/3 m	L_P	62.4	52.0	50.3
	L_I	60.2	49.1	48.5
	$[L_P - L_I]$	2.2	2.9	1.8
2 m	L_P	56.9	47.3	44.9
	L_I	55.9	45.5	43.3
	$[L_P - L_I]$	1.0	1.8	1.6
5 m	L_P	53.7	42.1	40.1
	L_I	52.1	39.8	37.3
	$[L_P - L_I]$	1.6	2.3	2.8

Table I – Measured noise levels at the 3 characteristic frequencies of the 16 MVA Transformer

L_P = Sound Pressure measurement

L_I = Sound Intensity measurement

It can be seen from the table above that the difference between Sound pressure & Sound Intensity measurements is 1.8 – 2.9 dB at the 1/3 m contour, 1.0 – 1.8 dB at the 2 m contour, and 1.6 – 2.8 dB at the 5 m contour. The reduced differences at the 2 m contour are a demonstration that the near – field effect in the sound pressure is smaller at 2 m distance than at the 1/3 m distance. At the 5 m contour, the difference starts to increase again as the noise level of the transformer decreases with distance. Hence, ambient noise adds more to the noise level measured using the Sound Pressure method but not to the measured noise level using the Sound Intensity method. This is even more evident in Fig. 4 below which presents measured values of the 100 Hz dominant component of the noise of this transformer at the 2, 4, 8, 16 and 36 m contours. The level at each distance point is an average of all measurements performed around the transformer at that distance. The figure demonstrates how that the noise level of the transformer measured using the Sound Pressure method includes the 1 – 2 dB near – field reactive sound when the measurement is made at 1/3 m of the transformer, no difference at distances as far as 16 m from the transformer but includes a higher error due to the ambient noise at farther distances from the transformer.

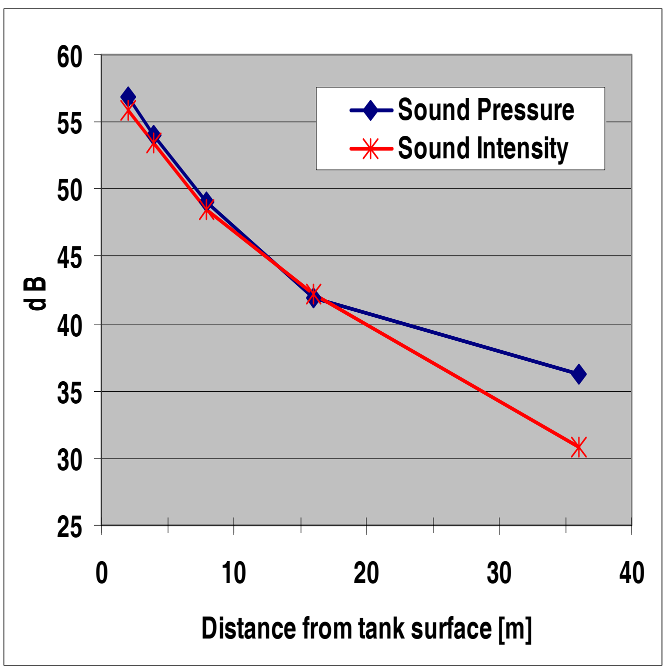


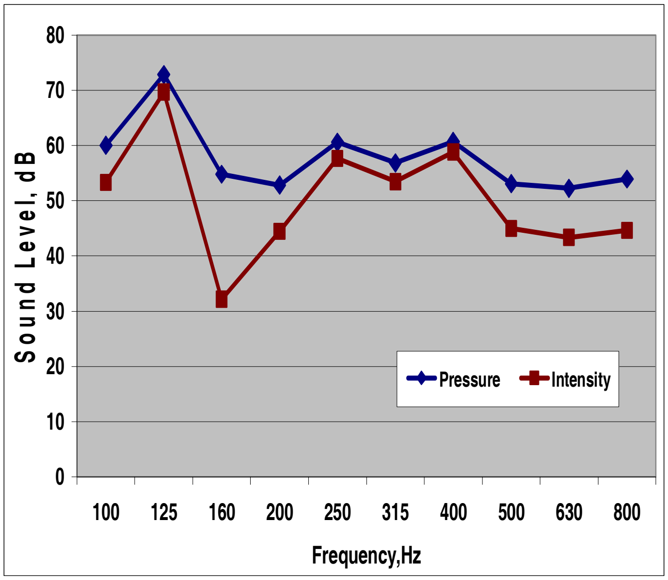
Fig. 4 – Measured 100 Hz frequency component at different contours around the 16 MVA Transformer

B. Measurements performed on two 250 MVA Transformers

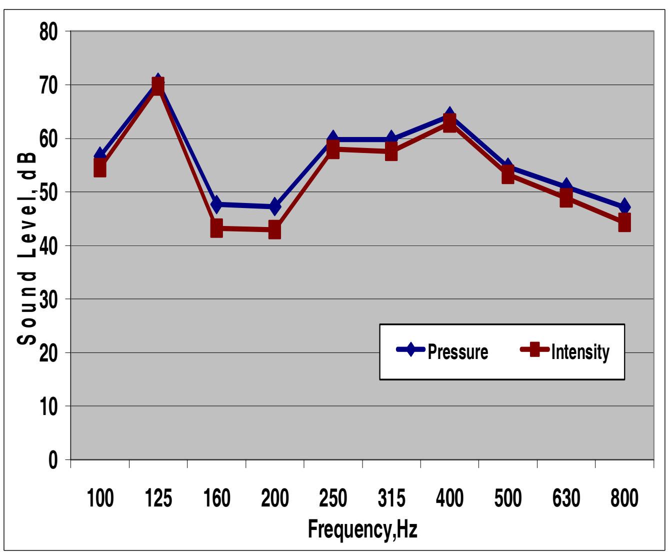
Comprehensive sound pressure and sound Intensity measurements were made on two 250 MVA, 230 KV, 60 Hz, Auto – transformers located in the Arizona desert, hence a relatively low level of ambient noise and free field conditions (absence of sound reflections). The two transformers are of different designs, manufactured by two different manufacturers, and are located in two different substations. The measurements were made at night. One of the substations, however, had a little higher ambient noise than the other as it was located about ½ mile from a freeway. The load on the transformers was 102 and 107 MVA, respectively. Both transformers were operating at about 103 % rated voltage. The measurements were made at contours of 1/3 m, 2 m, and 4 m around one transformer (26 x 2 measuring stations) and at 1/3 m, 2 m, and 5 m around the other transformer (29 x 2 measuring stations). Measurements were also made at one measuring line at distances up to 16 m from the transformer. Fig. 5 shows a photograph of one of the two transformers.

Fig. 5 – Photograph of one of the two 250 MVA transformers tested

A sample of the measured data is presented in Fig. 6 (a) and 6 (b) below at 1/3 m and 2 m distances from the transformers, respectively. The figures demonstrate that the difference between the measured values of the pressure and intensity levels is lowest at all three main frequency components of the transformer noise, namely, 120 Hz, 240 Hz, and 360 Hz. The magnitude of this difference is practically the same for all the frequency components of the transformer noise and it is in the range of 1 – 2 dB. At other frequencies, this difference is 6 – 15 dB for transformer – 1 with the higher ambient noise, Fig. 6 (a), and 3 – 5 dB for transformer – 2 with the low ambient noise, Fig. 6 (b). The difference is caused by the contribution of the ambient noise to the measured sound measurements but not to the sound intensity measurements.



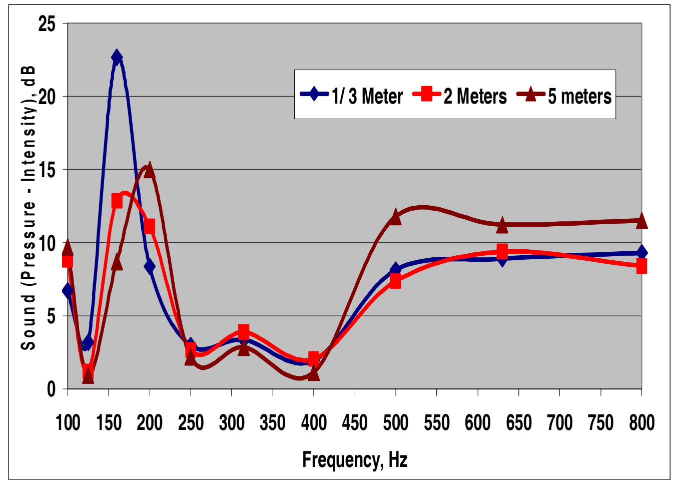
(a) At 1/3 m contour around transformer – 1



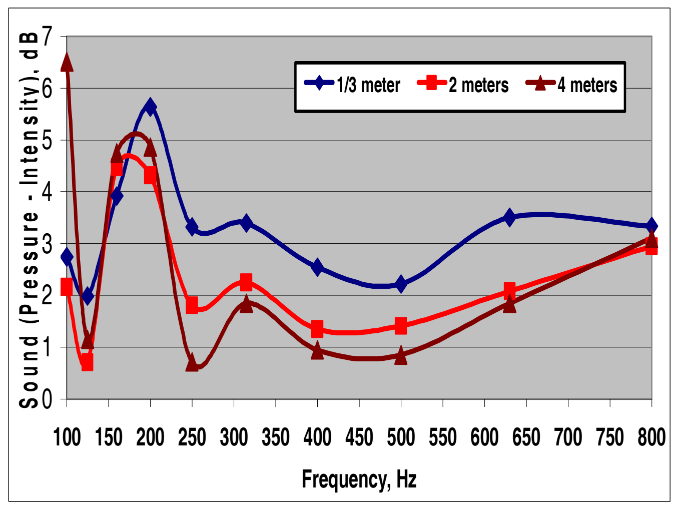
(b) At 2 m contour around transformer – 2

Fig. 6 – Measured frequency spectrum of the noise of the 250 MVA transformers

This is more evident in Fig. 7 showing again that at 1/3 m from the transformers, the difference between sound pressure and sound intensity measurements at the main frequencies of the transformer noise is consistently in the range of 2 – 3 dB. At a distance of 2 m from the transformers, the difference decreases to be in the 1 – 2 dB range. This difference decreases to be < 1 dB at the higher distances of 4 m and 5 m. At these contours, the sound pressure measurements are practically equal to the sound intensity measurements.



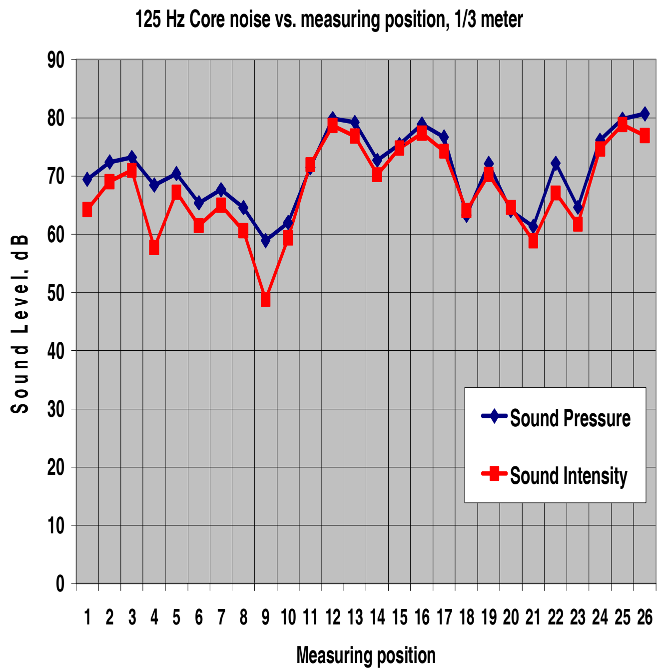
(a) Transformer with higher ambient



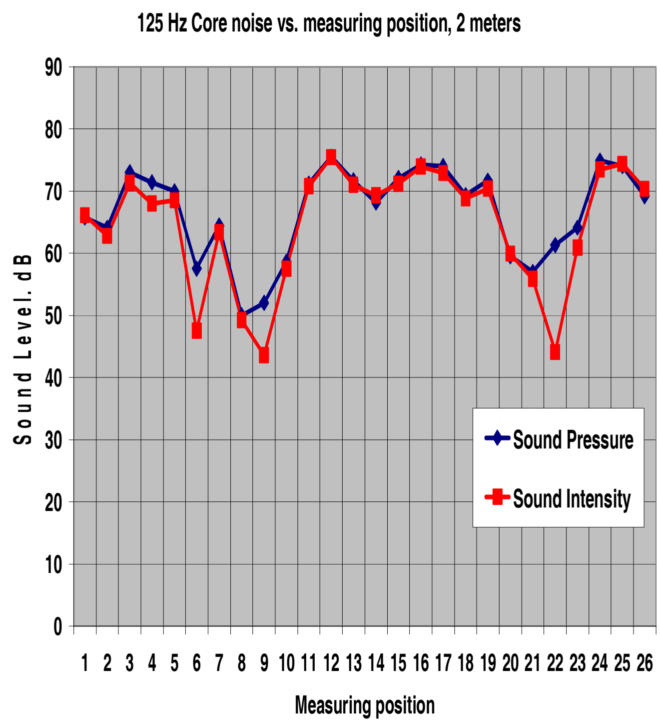
(b) Transformer with lower ambient

Fig. 7 – Difference between sound pressure & sound intensity measurements around the 250 MVA Transformers

These differences are consistent with data plotted in Fig. 8 (a) and 8 (b), where actual detailed measured values of the 125 Hz frequency component of the transformer noise around the transformer are presented at the 1/3 m and the 2 m contours, respectively. It is interesting to see, in Fig. 8 (a), that the difference between the sound pressure and sound intensity measurements is lowest where the measuring points are across from the radiators and is highest where the measuring points are closest to the transformer tank. Fig. 6 – 8 confirm that the contribution of the near – field reactive sound to the sound pressure measurements of the main frequency components of the noise of these transformers is in the 1 – 2 dB range and the contribution of the ambient noise is minimal in the case of one transformer and small in the other.



(a) Measurements at 1/3 m contour



(b) Measurements at 2 m contour

Fig. 8 – Measured 125 Hz noise component around the 250 MVA transformer having the lower ambient noise

VI. Accuracy of Sound Pressure & Sound Intensity Measurements Versus Distance from Transformer

In Fig. 9 below, values of the 125 Hz noise component of the 250 MVA transformer, with the low ambient noise, measured along one line at a number of distances from the transformer are plotted. Again, the figure shows a 2 dB difference between sound pressure and sound intensity measurements at 1/3 m and almost identical values at distances > 2 m up to 16 m from the transformer. This is another indication that the near – field effect is about 2 dB and that there is, practically, no contribution of either the near – field effects or the ambient noise to the sound pressure measurement of this frequency component at farther distances. The apparent 2 dB abnormal difference at the 4 m measurement was caused by a sudden noise external to the transformer occurring at the time the measurement was made at that measuring station. Fig. 7 (b) earlier showed that this difference is < 1 dB when the averages of the pressure and intensity measurements around the transformer are used.

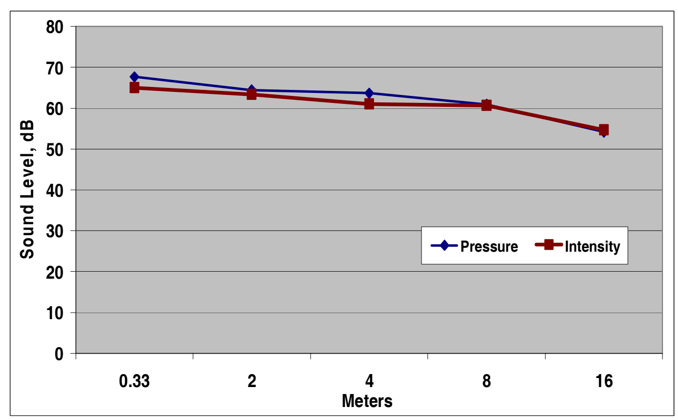


Fig. 9 – Measured 125 Hz noise component at different distances from the transformer having the lower ambient noise

VII. Accuracy of the dB (A) Level Measurements

Fig. 7 showed that, at frequencies other than the transformer noise frequencies, the difference between the sound pressure and sound intensity measurements is high because it is compared with basically a very low level of sound level produced by the transformer. The ambient noise, having frequency components different than those of the transformer, results in even larger errors when measuring the total dB (A) level of a transformer using the Sound Pressure method.

This is demonstrated in Table II below. The measured values of the total noise level of the transformer with the very low ambient noise (Transformer – 2), using the Sound Pressure method, are 1.0 dB higher than the Intensity measurement at the 1/3 m contour, and practically the same at the 2 m and 4 m contours. This confirms that the near – field effect in this transformer is about 1.0 dB. Therefore, for this transformer, neither this effect nor the effect of ambient is existent at the 2 and 4 m contours. For Transformer – 1, with the relatively higher ambient noise, sound pressure measurements are higher than the intensity measurements by 3.1 dB at the 1/3 m contour, 3.2 dB at the 2 m contour, and 4.4 dB at the 4 m contour. With a 1.0 dB near – field effect, the errors contributed by the ambient noise to the Sound pressure measurements on this transformer are 2.1 dB at the 1/3 m contour, 3.2 dB at the 2 m contour, and 4.4 dB at the 4 m contour. Above demonstrates the large error included in the Sound Pressure measurements of the dB (A) level as the frequency content of the transformer noise is not the same as the ambient noise. As, typically, ambient noise includes higher frequencies than the transformer noise frequencies, the error would be expected to be higher when measuring the dB (A) level using the Sound Pressure method as compared to the Sound Intensity method.

Transformer #	Measured Quantity	Measuring Contour		
		1/3 m	2 m	4m
1 Low Ambient Level	L_P	61.7	60.4	59.3
	L_I	58.6	57.2	54.9
	$L_P - L_I$	***3.1***	***3.2***	***4.4***
2 Very Low Ambient Level	L_P	62.7	61.0	58.0
	L_I	61.7	61.0	58.2
	$L_P - L_I$	***1.0***	***0.0***	***-0.2***

Table II – Values of total noise level, in dB (A), of the two 250 MVA transformers measured at three different contours
$\mathbf{L_P}$ = Sound pressure $\mathbf{L_I}$ = Sound Intensity

VIII. Conclusions

Outdoors measurements presented in this paper demonstrated that the difference between measured noise levels of power transformers, using the Sound pressure method and those using the Sound Intensity method, is caused by the following components which are not part of the sound power produced by the transformer. Hence, these represent errors in noise levels measured using the Sound Pressure method:

1. Near – field reactive sound when measurements are made at the 1/3 m contour. This error is in the range of 1 – 2 dB.

2. Ambient noise whose effect is greater at frequencies other than those of the transformer noise. Hence, the error is greater when measuring the dB (A) level of transformer noise.

The data demonstrates that, when the ambient noise level is low compared to the transformer noise level and the measurements are made at distances > 2 m, the transformer noise levels measured using the Sound Pressure are practically identical to those measured using the Sound Intensity method.

These results also confirm conclusions from previous work (as reported in references [4] – [8] of this paper) that the Sound Intensity method is the more accurate and consistent method of measuring the true noise level of a transformer. In Part – II of this paper, this conclusion will be confirmed even more for indoors measurements of transformer noise. However, appropriate conditions, developed in the paper, would need to be met for accurate noise measurements using the Sound Intensity method.

IX. Acknowledgements

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X. References

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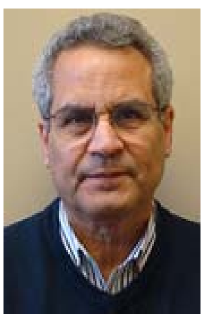
XI. BIOGRAPHIES



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