MEASURING ACOUSTIC NOISE EMITTED BY POWER TRANSFORMERS

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Abstract - This paper proposes a new Measurement Standardization Procedure to measure and quantify the acoustic noise produced by power transformers in audio and video equipment under normal and adverse mains conditions. These conditions and the physical mechanisms that cause the noise are discussed. A new measurement set up and units are proposed to measure and quantify the transformer noise. Examples of measurements on four transformers are given for comparision and illustration.

INTRODUCTION

The aim of this preprint is to propose a new standard procedure for the measurement and quantifying of the acoustical noise produced by power transformers in audio and video equipment under normal and adverse mains conditions.

There is "zero tolerance" among consumers and professional users of audio and video equipment for audible noise of any kind. Nothing is more distressing than the sound of a transformer "buzzing". This is understandable since anyone paying thousands of dollars for a quality system to reproduce music or video wants to hear only music. High end amplifier and studio equipment manufacturers work very hard to ensure the transformers in their products will not make noise under any operating condition. Specifying and selecting a properly designed and manufactured transformer is a critical issue in the design of high quality video and audio products. Power transformers should be dead silent, under no circumstances they should produce any noise.

However, reality is totally different! Transformers may suddenly become noisy. They begin to hum, buzz or rattle, not because they are happy, but because they suddenly operate in a magnetic region where a transformer behaves as an acoustic transducer. This unpleasant feature is known worldwide, and has lead to the need for the development of a new range of "low noise" transformers.

Why does a transformer make noise? Section 1 explains the acoustic noise generating mechanism inside power transformers. Section 2 defines the theory of measuring and quantifying the acoustical power transformer noise. A new set of units for quantifying transformer noise is introduced. A new absorbing type noise test chamber is proposed. Section 3 introduces a measurement setup for emulating adverse mains conditions and defines the calibrated measurement of the acoustical noise levels produced by power transformers under various adverse mains conditions. Section 4 shows and discusses measurements. Conclusions are in section 5.

1 WHY AND HOW POWER TRANSFORMERS PRODUCE ACOUSTICAL NOISE

Transformer noise has two sources: winding vibrations and core vibrations. The single most effective way to reduce windings noise is by having a good quality controlled winding process when assembling them. This research focusses on the cores of normally silent transformers, which make noise under adverse mains conditions. Transformer cores can become noisy as well under specific secondary load conditions which can be translated (transformed) into the adverse mains conditions at the primary as discussed in this paper.

There are three physical phenomena that produce noise in the magnetic core [1-16]:

1. The movement of the 90-degree Bloch walls inside the magnetic domains, frequently called Magnetoacoustic Emission (MAE); see Figure 1.
2. The rotation of the magnetic domains, that is responsible for the bulk magnetostriction; see Figure 2.
3. The Lorentz Force Acoustic Signal (LFAS) causing mechanical forces between laminations of the core; see Figure 3.

MAE occurs in the steep section of the hysteresis loop; see Figure 4. Not much sound is emitted and the bulk magnetostriction is small. The rotation of the magnetic domains is dominant near saturation in the hysteresis loop. The magnetostriction becomes "large" and the core laminations move considerably, thus generating acoustic noise; see Figures 4 and 5.

The rattling of laminations of the core (LFAS) depends largely on the construction of the core. The EI-type cores are more prone to make noise due to their many separated pieces of lamination which mostly are only sturdy clamped at the four corners. In toroidal cores the long role of core band is sturdy clamped everywhere due to the mechanical rolling tension and the pressure caused by the winding tension.

In general: magnetostriction, occurring near saturation of the core, is the main cause of the acoustical transformer noise, while LFAS largely depends on the construction of the core. Due to magnetostriction the core vibrates at the fundamental mains frequency and its harmonics and at core resonance frequencies. In this regard it is important to notice that a noisy transformer means that a) the transformer is badly constructed -or- b) that the transformer is forced to operate in a magnetic region close to or at core saturation.

The main reason why the transformer is noisy may be a combination of the above given causes. Anyway, the device has become noisy and the amount of acoustical noise produced should be measured to determine whether or not the produced noise level is acceptable.

2 MEASURING AND QUANTIFYING ACOUSTIC TRANSFORMER NOISE

It is not so difficult to measure the amount of noise produced by a transformer. First, we need to isolate the noisy device from the environmental noise, to be sure that we are only measuring the transformer noise and not the environment noise. This means that a "silent" room or isolating chamber should be constructed. Transformers in general are not freely floating in the air, but sturdy mounted in cases. Each of those cases is different in shape and construction and each case will contribute in a different way to the total amount of noise produced. Therefore a "standardized" case should be defined on which the transformer under test should be mounted. A calibrated microphone is needed plus some calibrated pre amps and so on. A minimal measurement time length should be defined and related to the lowest frequency to be measured. Noise level and the distance -r- to the noisy product are related and consequently the distance between microphone and transformer should be defined. The noise signal in the time domain needs to be converted (by means of FFT) into the frequency domain. For each frequency, there should be a weighting factor, coupled to the sensitivity of the ear, to determine the perceptibility of the noise. There should be a clear definition of the mains conditions: is the mains "clean" or "distorted" and in what way and how do distortions affect the noise produced and measured as indicated above.

Figure 6 and Photo 7 give an impression of a suitable sound isolation chamber. The character of this design is such that the internal reflections of the transformer noise are absorbed by the chamber. The microphone detects the acoustical transformer noise only in one direction; from the transformer directly to the microphone.

In this regard an assumption is made: the frequency region of interest appears to be below 10 kHz. The reasoning for this is found in the lower sensitivity of the ear at higher frequencies and in our measurements; they show little sound energy emitted above 10 kHz. Consequently the minimal wave length of the noise equals 3.4 cm (340 m/s divided by 10 kHz). The overall dimensions of the transformers of interest are smaller than 20 cm (2 kW power range and smaller). Therefore, beam forming (lobing) of the emitted sound will occur at high frequencies. One might ask under such conditions whether the emitted sound energy should be measured (reflective sound chamber) or the sound pressure level (only in one predetermined direction in an absorbing sound chamber). Our measurements on many toroidal transformers indicated that acoustical beam forming occurs. Especially the high frequency sound is emitted into the transformers rotational symmetrical axis direction, where the microphone is placed. This microphone position ensures that the noise is measured under the "worst case" condition. It is our opinion that this condition should be the standard for measuring transformer noise. When noise is heard and this noise is directed to our ear, we should measure this maximum noise level. Consequently we can accurately measure the noise in an absorbing type of sound chamber, under the stringent condition that the microphone is placed on the "worst case" spot.

A "standard" metal case is emulated inside the sound chamber, by placing the noisy transformer on a metal plate, thickness of 2 mm, dimensions 40 by 40 cm, with the edges folded over 90 degrees downward. The edges give the plate its stiffness and this emulates the mounting plate of a transformer in a case. At the four corners of the plate, rubber supports are mounted to allow for free movements of the plate. Figure 6 shows the detailed construction. When we measure the noise in this way, we actually measure the noise from the transformer plus the noise emitted by the plate, beamed in the vertical direction right into the microphone placed above. This configuration indeed is "the worst case" situation where the maximum sound pressure level is measured due to lobing of the noise.

The distance to Sound Pressure relation from microphone to noisy transformer is well known for the "far field" condition, where a doubling of the distance -r- will cause a 6 dB drop in the Sound Pressure Level. For practical reasons we measure at a standard distance of 0.5 m. Assume that we measure at a certain frequency a Sound Pressure Level of 32 dB. At 1 meter distance, under the "far field" condition, the noise level will be 6 dB lower at 32 - 6 = 26 dB. In fact, at any reasonable distance -r- in the "far field", the noise level can be measured and converted to a level at 1 meter by means of the well known formula 2-1.

$$SPL_{\boldsymbol{at\ 1\ m}} = SPL_{\boldsymbol{at\ r\ m}} + 20\log r \tag{2.1}$$

We tested at three frequencies whether or not the "far field" condition is vallid in our actual noise test chamber. Figure 8 shows the Sound Pressure Levels of 200, 650 and 2000 Hz as function of the distance -r-, to be compared with the shown ideal 20log(1/r) "reference". For 200 Hz, at an equal or larger distance than 50 cm, the "far field" behaviour is found, while for 650 and 2000 Hz, within the accuracy of the measurements, the ideal "far field" behaviour is closely matched. For frequecies above 200 Hz we therefore safely can use the "far field" formula's for predicting Sound Pressure Levels at distances larger than 0.5 m.

Figure 9 shows an example of the noise spectrum measured at 0.5 m distance from a typical noisy transformer. In this case the time to frequency domain conversion is performed by the LibertyAudioSuite system, but similar results were measured with the MLSSA system. It is clearly visible that at each frequency the level is different. To standardize the measurement, a frequency weighting curve is needed for, taking the acoustic properties of the ear into account. There already exists such a weighting function. Figure 10 shows these standardized Balanced Noise Criterion Curves (abreviated to NC-curves), which are internationally accepted for the weighting of acoustical noise levels in studio's and working and living environments. Table 1 shows some noise levels as they occur in different environments. In these NC-curves it is clearly visible that the ear is not very sensitive at low frequencies, while the very high frequency sensitivity loss is not accounted for. In our specific case this is no problem and needs no further study due to the little amount of very high frequency sound emitted by noisy transformers.

The noise levels measured and the NC-curves can be combined into one picture as shown in Figure 11. In this specific example, the transformer produces at 0.5 m (our distance of measurement) less noise than the NC-30 curve. This means that we can quantify the noise by: NC30 [dB,0.5m] or NC24 [dB,m], the later having the advantage of using SI-units, and is therefore preferable.

VENUE	NCB-curve
Broadcast and recording studios	10
Concert, recital, opera halls	10-15
Large auditoria, churches	<= 20
Small auditoria, cinemas	<= 30
Meeting and conference rooms	<= 30
Bedrooms, hospitals	25 - 40
Private offices	30 - 40
Classrooms and libraries	30- 40
Small conference rooms	30 - 40
Living rooms	30 - 40
Large office or reception area	30 - 40
Retail shops, restaurants	30 - 40
Lobbies, labs, drafting rooms	40 - 50
Maintenance shops, kitchens	45 - 55
Shops, garages	50 - 60
No hearing-damage risk	<= 70

Table 1: NCB curves at different locations. S&VC September 1999, pp.60)

The distance relation as expressed in formula 2-1 is a clear part of the noise measurement. But the distance from listener to the noisy transformer in the listening environment plays the same important role. When a noisy piece of equipment is placed several meters away from the listener, the noise level at the listening spot will be smaller than the level at 1 meter. Rearranging formula 2-1 expresses this relation:

$$SPL_{\boldsymbol{at\ r\ m}} = SPL_{\boldsymbol{at\ 1\ m}} - 20\log r \qquad (2.2)$$

Formula 2-2 is valid under "far field" condition up to the critical distance D_c where the level of direct sound and the level of reverberant sound are equal. See for more details Figure 12. Because it is impossible to know each listening environment, we propose to standardize the noise specifications for the 1 meter distance mentioned. For any particular application the actual noise level can be calculated at the listener spot at a distance r from the noisy transformer using formula 2-2 with the restriction of $r < D_c$.

3 ADVERSE MAINS CONDITIONS AND NOISE MEASUREMENT

We might hope for clean sinusoidal mains voltages with the proper mains frequency. However, reality is different. Sags and surges, spikes, over voltages, DC on the mains, very high frequencies (from computers and GSM phones and radio TV transmitters), lightning residuals, spikes caused by switching on/off of motors, hairdryers switched at lower power with single rectifying diodes causing asymmetrical load to the mains sine wave, such conditions are the reality! And how does the mains transformer react on all this mess? It starts to make acoustical noise. We researched which mains conditions generate noise inside power transformers and found three major causes:

1: The mains 'sinusoid' is not symmetrical. This is identical to a DC-voltage on the mains. A very nice example is: the single phase rectifier used in hair dryers at lower power by means of one series diode. The combination of this rectifier with the actual load resistance and the resistance of the mains wires create an effective DC-voltage on the mains. See Figure 13 for an explanation of this effect of hair dryers.
(It is very easy to test a particular transformer for noise under this "DC on mains" condition. Connect a 100 or 200 W light bulb in series with a proper diode to the same mains socket of the transformer under test and check for transformer noise by listening).
Our measurements indicate that only a few mV-DC can be large enough to bring a transformer into its noisy region. We did many tests to determine the amount of DC-voltage on the mains by means of the light bulb and other loads in series with a diode and by observing the DC content on the mains due to asymmetrical loading elsewhere in our or other buildings connected to the same distribution transformer. We found a DC-component smaller than 100 mV for 120 V at 60 Hz mains. However, by experience we know that bad conditions today surely will be worse tomorrow. We therefore propose to take an extra margin and to use 250 mV-DC as our standard condition for "adverse" mains. (For 230 V at 50 Hz mains, the standard adverse mains condition equals the same 250 mV-DC).

2: Over voltage brings the transformer into its saturation region as well. Example: in Europe the transfer from 220 V to 230 V @ 50 Hz mains voltage takes place in a period of several years, combined with a certain plus/minus deviation. Now suppose, an older 220 V transformer design, having to operate at 230 V (and sometimes in practice up to 240 V). When such a design is constructed with no safety margin of magnetic headroom, saturation will occur at larger input voltages. Our research showed us that 10 % over voltage is a good margin for testing a transformer under conditions of over voltage.

3: Transformers designed for 60 Hz mains frequency can be used in a 50 Hz mains frequency environment. When no magnetic headroom is available, a 60 Hz transformer will saturate at 50 Hz and become noisy. However, it is our opinion that manufacturers clearly should identify on their transformers the mains frequency of safe and silent operation. In this research we assume that all transformers are operating at the right mains frequency of design.

Contrary to popular belief the other effects of mains signal distortion are not included in our list of major noise causes. In the case of sags and surges, a very short momentary saturation of the core can occur. The burst of sound emitted has such a short duration that seldom this will be a problem. Spikes do not produce noise due to their limited time length, and their limited amount of energy will be absorbed inside the conducting shielding inside the transformer. Very high frequencies (Radio and TV, GSM, computers) can not excite the transformer acoustically because it is a mechanical vibrating device with a rather large mass and therefore a limited emitting frequency range. Our measurements showed that above 10 kHz almost no sound is emitted. When considering lower frequency harmonics, for instance the 2-nd and 3-rd ... of the mains frequency: the second harmonic distortion is equivalent to a residual DC-voltage on the mains, while the 3-rd and higher harmonics have a much smaller amplitude than the mains fundamental. This fundamental (50 or 60 Hz) is using most of the magnetic headroom inside the core and is most prone to lead to core saturation. This is not the case with harmonics. The amplitude of the magnetic flux density inside the core is inversely proportional to the frequency of the voltage applied. Harmonics have smaller amplitudes, larger frequencies and consequently create negligible flux densities inside the core. Therefore we omit their influence in audio and video equipment. Above said is certainly not the case for transformers used in switching Triac lighting equipment. However, the study of the effects of such equipment is outside the scope of this research.

Based on above given experience and understanding of the noise generating mechanism inside transformers, we now can define a measurement setup for making "adverse" mains conditions. Figure 14 shows the schematics in a simple form. Through a variac or variable voltage power supply a pure and undistorted mains voltage can be set at the "nominal level" and at a "10 % over voltage level". By means of another variac plus transformer, a rectifying circuit and a buffering capacitor, a "DC-voltage" can be added to the mains voltage.