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Sound Levels of Power Transformers and Reactors in the UHV Substations

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SUMMARY

Large power transformers and reactors are vital parts for the long distance effective and reliable transmission and distribution of electricity. These units can have higher sound level and can be heard from outside of the substations. Transformer and reactor sound cannot be eliminated. Through proper design and installation – assembly can be reduced. In different countries, the Grids have some restrictions to bring the sound levels in permissible level.
The sources of audible sounds in transformers are core sound (no load sound), load sound in the windings and auxiliary equipment sound, schematic view of them see in the figure 5, [1]. The basic source from transformer core sound is core vibration which is affected from magnetostrictive forces (Maxwell forces), magnetomotive (magnetic) forces (Lorentz forces) and mechanical forces on the core. The sound power levels of air-gapped core reactors are significantly higher than those of loaded transformers.
The load sound is predominantly caused by axial and radial vibrations of the windings. Due to leakage flux stray losses occur additional eddy losses in the structural parts (magnetic shields and tank walls) and within the winding, which create vibration. Basically the loading of transformer has little effect on the sound level. The frequency of load sound is twice the power frequency. Harmonics in load current create vibrations at twice the harmonic frequencies.
Power transformers generate considerable heat because of core, winding, and structural parts losses. The coolant elements are putting the heat out of transformers, which is produced from total losses of transformers. The most common types of cooling are given. Except natural cooling, for all the other cooling methods cooling fans and pumps are using. But these produce also sound. In last decade in using of intelligent monitoring systems have mitigated to reduce of the sound emission of them, and cost optimization.
The main audible sound of the substations comes from transformer and reactor in operation. The substation sound level must be according to the governmental regulations. Large power transformers generate a sound level between 50 to 80 dB. Generally the permissible sound levels in areas of hospitals, nursing houses area 40-45 dBA, areas with apartment buildings, recreational areas outside cities 45-50 dBA.
IEC 60076-10-1 Edition 2. Determination of sound levels- Application Guide is giving detail information for test environment and procedure of the audible sound level of transformers.

KEYWORDS

Audible sound level, Transformers, reactors, sound source, core sound, load sound, vibration, substations

CORE SOUND (NO LOAD SOUND)

The predominant source of transformer and reactor sound level is the core. The basic sources of the core sound are magnetostrictive forces, magnetomotive forces and mechanical forces on the core.
The core sound occurs by a phenomenon called magnetostriction which is a property of ferromagnetic materials.

The magnetostrictive materials develop mechanical deformations in an external magnetic field, see figure 1. These deformations generate a vibration sound of cores, audible 'hum'. Hum is of low frequency, fundamentally 100 Hz or 120 Hz depending on the source frequency. The sound is usually air borne, and vibration is ground borne. They are extremely connected. Oil is incompressible; air and gas transmit the audible sound very effectively [1].

Magnetostriction phenomenon is formulated by coefficient of $\boldsymbol{\varepsilon}$ [2]

$$\boldsymbol{\varepsilon} = \frac{\Delta \boldsymbol{l}}{\boldsymbol{l}}$$

Where ($\boldsymbol{l}$) is the length of the lamination sheet and ($\boldsymbol{\Delta l}$) denotes its change.

Ferromagnetic materials have this phenomenon which attributed to rotations of small magnetic domains in the materials. The orientation of these domains by the imposition of the magnetic field creates a strain field [3]. The magnetostriction forces are much higher than magnetic forces. Rotational flux occurs at a T-joint in the middle limb and top/bottom yoke in the core sheets of the 3-5 limbs transformers, (Figure1), [4].

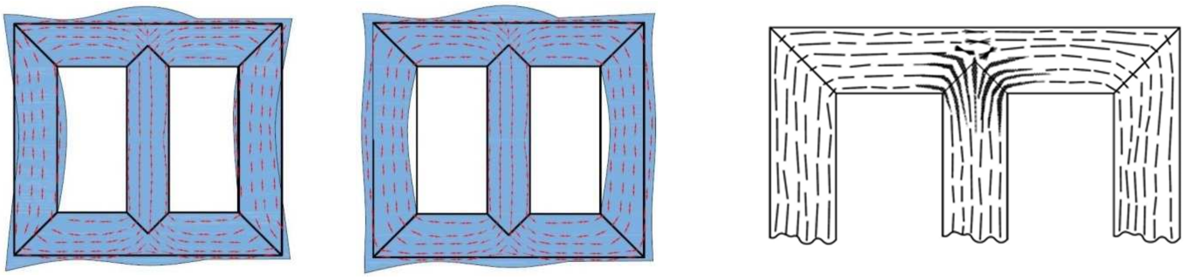
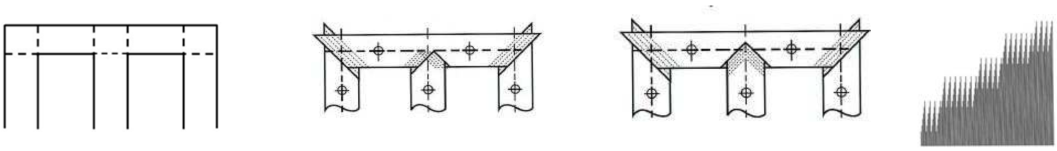


Figure 1. View of magnetic flux and deformation of the transformer core, and rotational flux in a T-joint

The stacking technologies of the core sheets play also an important role. The step-lap stacking of the core sheets reduce sound levels compare with the conventional lap joints (Figure 2 a, b, c). In the joint places the gaps not only affect core losses but also significant core sound level. The increasing of the number of laminations per layer also raises the sound levels [5] [6].



a. Conventional- lap b. longitudinal step-lap c. Cross step-lap

Figure 2. Core configuration, a. Conventional- lap and b-c step-lap stacking's

Mechanical forces on the core occur mainly from clamping arrangement which is essential to hold together the laminations. Clamping parts and clamping torque on the clamping influence the dynamic behavior of the core and play a basic role on the sound level due to magnetostrictive properties of the core laminations. Furthermore, the stacking quality of core has huge effect on no-load sound level performance of the core. However the bonding of core considerably reduces the core sound.

In the last decades due to quality development of the grain oriented silicon steel sheets with high permeability like HIB and laser treated materials; the sound levels of cores are reduced compare with conventional materials [7], [8]. Due to step-lap stacking of those kinds of materials it is possible to reach a reduction of sound level to about 10 dB [8].

In recent years, harmonics in power system are increased significantly with the increasing of nonlinear load.

Most nonlinear loads cause harmonics in the excitation voltage, resulting in an increase in core sound level [9] [10].
In order to summarize, according to these facts, the most significant factors affecting core sound level are: Magnetic forces, material specification (magnetostriction, thickness and coating effect), core configurations, clamping arrangements and harmonics.
Sound level reduction and the saving from no load loss are two important trend of development in power transformers. Reduced core flux density brings the sound level down but increases load losses. In high level of induction it is a risk to generate local saturations which will increase vibrations of the whole structure. The designer can find the optimal value of induction for best solution from the aspect of competitiveness in the market [11], [12]. The best way for that is to use 2-D and 3-D magnetic field modeling for the optimizing core design and minimizing core sound [13]. To predict core sound level was developed a FEM by using COMSOL, Multi physics A/C and acoustic modules [14], [15].

The vibration of the shunt reactor in air- core type occurs mainly due to magnetic attraction force between the winding and yokes located the top and bottom of the winding.
On the other hand, oil- immersed gapped- core reactors are particularly suited for the highest voltages. In this type of reactors, the magnetic field creates pulsating force of the core gap and has a main vibration frequency of twice the power frequency. There is no difference between no- load and load noise in opposite of transformer.
To summarize that, the vibration in reactors occur to magnetostriction forces, magnetic attraction forces (Maxwell forces), electromagnetic forces (Lorenz forces) [16], [17].
The vibration in gapped-core shunt reactor is quite high as compared to transformers. At that reason the impregnation of core packets in the legs must be in vacuum perfectly. The magnetic field creates pulsating forces across air gaps which amount to much tons. Furthermore, the fringing flux effect develops attractive or repulsive force between core packets, which in turn creates vibration. At that reason the spacers in air gaps should be of very stiff material (ceramic discs), see Figure 3.

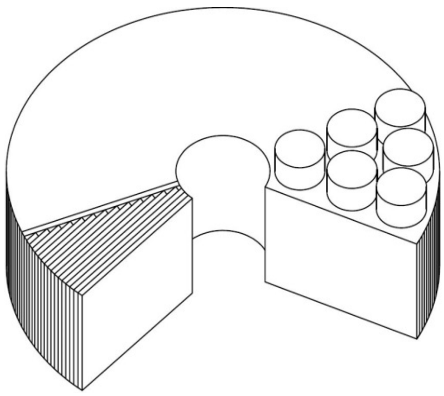


Figure3. Gapped core package with radially laminated core segment and ceramic spacers

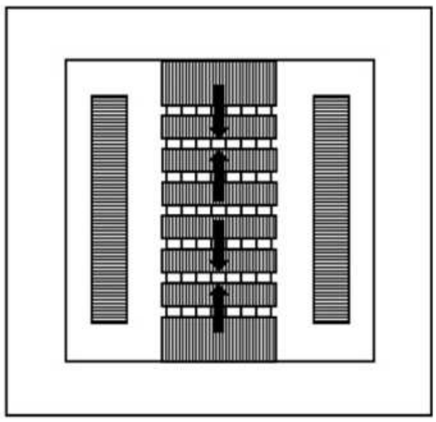


Figure 4.Maxwell forces in gapped core reactor

The yoke clamping structural parts also create vibration. The total vibration of the active part is transferred to the tank. So we can express that, due to all these mechanical stresses the main source of the gapped- core reactor sound power is the core. So that sound power levels of shunt reactors are significantly higher than those of transformers when loaded [18].
The vibration of active part is transferred to the tank walls through mechanical contact at the bottom and through the oil. Very often the tank walls set up a pattern of vibration [19]. These elements reduced the vibration originated from active part. Tank vibration levels are especially specified for reactors but not for transformers. Average vibrations shall not exceed 60 microns peak to peak. It is very important to have high degree of dimensional accuracy during manufacturing the core to obtain reactance and phase currents within permissible limits.
Nowadays, it is used with success computational approach FEM for reactor sound level calculation.

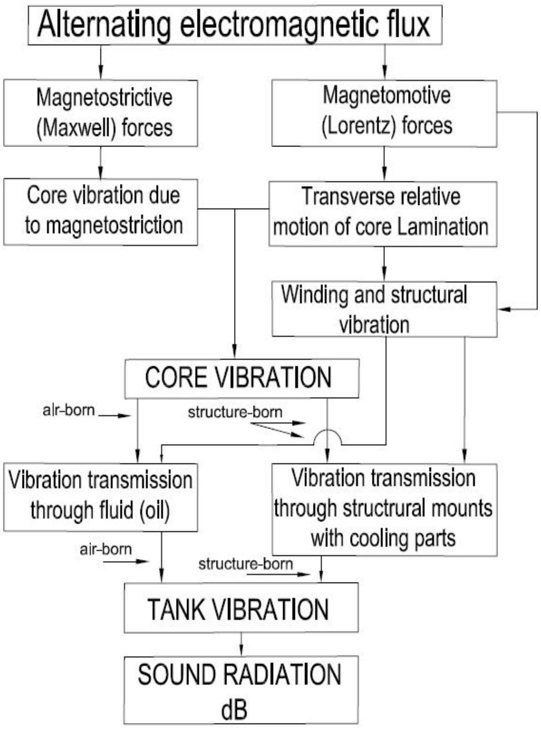


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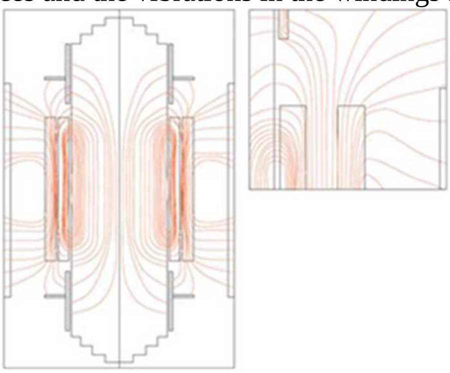
Figure 5. Schematic view of audible sound generation and transmission path in transformers / reactors

THE LOAD SOUND IN THE WINDINGS

The load sound is mainly caused by axial and radial vibration of the windings. The load current is generated by stray field of the winding which has electromagnetic forces (Lorentz forces), see figure 5. Leakage flux creates the stray losses, see the figure 6. These are additional eddy losses in the structural parts and within the windings. According to the experiences radial vibrations are not big contributor to the winding sound level. But, the compressive Lorentz forces create axial vibrations which can be a major source of sound, if the windings are not proper supported. Winding vibration is transmitted via the winding clamping structure and via insulation oil to the transformer tank. [20], [21], [22] Figure 7. In the last decade by applying FEM (finite element model), the analysis of electromagnetic forces and the vibrations in the windings so that load- sounds are carried out [23].



a b

Figure 6. a- Leakage field in the transformer, b-linkage of axial/ radial flux to the yoke beam

On the other hand due to stray fluxes these forces create vibrations in the structural parts (magnetic shielding and tank). Not proper designed magnetic shielding can be a significant source of sound. The mechanical resonance in the mounting structure can have also a significant effect on the vibration.

The electromagnetic forces are proportional to the square of the load current. That means the sound level depends on winding parameter because of the winding displacement variation and the current flow induced the electromechanical vibration. The vibration of the winding is transmitted via winding clamping structure to assembled active part and via insulation oil to the transformer tank.

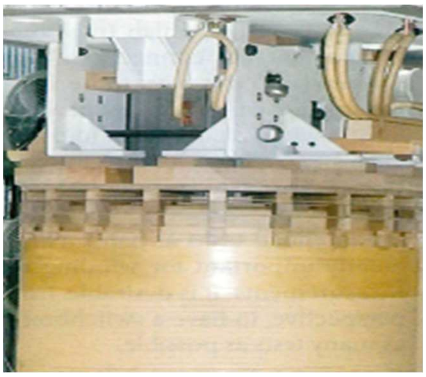


Figure 7. Clamping parts

Due to leakage flux the stray losses occur additional eddy losses in the structural parts and within the winding, which create vibration. The geometry of winding, type of conductors (CTC, continuously transposed conductors) and used material in structural parts influence also the stray losses and vibration. Additionally, the terminals can have also vibrations, therefore they must be to take into account [24] [25]. Effective tank and yoke shielding are provided which control stray losses in structural parts to a great extent.

If the assemble quality of the magnetic shielding not proper can have negative effect for sound level. It is very important that, the shunts must be rigidly anchored to the tank walls.

The frequency of load sound is twice the power frequency. In special type of power transformers (as example rectifier transformers) is the presence of harmonics in load current can create vibrations at twice the harmonic frequencies. These increase the sound level. Furthermore current harmonics are major source of increase in sound levels in HVDC transformers.

Basically the loading of transformer has little effect on the sound level. In many such cases, the difference between load and no load sound level, at identical flux density is usually max. 2 dB.

Generally, the transformer sound levels are almost proportional to the mass of the core and winding. The condition monitoring of the winding and core vibration gives substantial information. The vibration signal analysis method is one of the effective methods for that.

THE SOUND OF THE AUXILIARY EQUIPMENT

The major factor for the generation of the transformer heat is copper loss I^2R, beside the various losses like eddy current, hysteresis losses in the core, and in the other metallic structural components. The coolant of the transformer is air, mineral oils, synthetic oils, vegetable oils, water and gas. The most common types of cooling methods are as follows:

Air natural (AN), air forced (AF), oil natural air natural (ONAN), oil natural air forced (ONAF), oil forced air forced (OFAF), oil forced water forced (OFWF), oil natural water forced (ONWF).There are basically two types of transformer, dry type and oil immersed type. Dry type transformer is cooled by air natural (AN) and air forced (AF) method. Oil immersed type transformer is cooled by oil air cooling methods (ONAN) , (ONAF), (OFAF) , and oil water cooling methods (OFWF) and (ONWF) [26].

Cooling fans and pumps create mostly broadband sounds coming from forced flow of air or oil. All circulations with pumps and fans have big influence on the sounds coming from the cooling systems. The fan sound is a function speed and circumferential velocity. Aerodynamic sound of the fan significantly contributes to the total sound level of transformer. Blade design, tip speed, number of fans and arrangement of radiators are important influences for the fan sound output. The cooling fans blow air over radiators or coolers. The radiators also contribute to increase the sound level due to transferred tank vibrations transmitted through cooler pipes that connect it to the tank (structure- borne vibration). Nowadays the cooling system are controlled in an improved way by continuously variable speed- controlled fans (air- forced cooler technology), which optimize noise and losses [27].

The using of the intelligent monitoring and control system has many benefits which are reduction of sound emissions, optimization of hot spot temperature, cost optimization and many others. Basically the sound of the auxiliary equipment in transformers and oil- immersed type reactors has not any difference. Both of them have similar cooling system.

THE SOUND LEVELS OF TRANSFORMER SUBSTATIONS

The main audible sound of the substation comes from transformer and reactor in operation, see figure 5. Moreover substation sound mainly depends on some factors such as the voltage level, sound source distribution, and building arrangement. Parallel with the expansion of the cities, the urban power loads are increasing also. So these developments become the attention focus of the inhabitant's around the substations. The audible sound levels of the transformers in substations are a function of power and voltage rating of high voltage winding. These types of transformers generate a sound level between 50 – 80 dB. Typical sound level limits at the transformer station property line are; Industrial zone < 75 dBA, commercial zone < 65 dBA, residential zone <55 dBA. According to NEMA ST-20 standard sound levels for small distribution transformers are 40-60 dB. Generally the permissible sound levels in areas of hospitals, nursing houses are 40-45 dBA, areas with apartment buildings, and recreational areas outside cities are 45-50 dBA. (dBA - weighted decibels, A describes; weighted scale which closely follows the sensitivity of the human air). Furthermore, dry type small-medium size transformers are most frequently applied in those places inside buildings [28]. The rooms for these usages must have walls of low sound absorption coefficient. Detailed information is given in IEEE C.57.94 [29]. The Substations depend of voltage level contains a collection of different types of equipment that make audible sound. Transformer sound is a low frequency hum which is associated sounds at harmonic frequencies of 100 Hz and 200 Hz.

Due to expansion of urban area it is a need for more power links. So the new transformer substations need to be increasingly compact, reliable, safe and intelligent. The walls can be of concrete or glass reinforced concrete, brick or steel. The sound of transformer reduced as it tried to pass through a massive Wall. In addition, earth berms or below-grade installation may be effective. Suitable designed and constructed sound barriers can provide several dB reductions from sound level.

Isolation of the transformer from the ground is essential. Because, the sound is usually air borne and vibration is ground borne. They are extremely connected. These effects can be reduced by placing the transformer on anti-vibration mountings-strips of rubber or other resilient material.

The measurements of the sound level at the transformer site can be different, depending on its operating conditions, like load power factor, internal regulation, load current and voltage harmonics etc.

Nowadays, with the development and application of environmental sound level simulation software provides a new idea for substation sound management [30] [31].

The sound problems of HVDC and UHVDC converter stations are more severe than that of HVAC and UHVAC [32]. The large power transformers should be checked and analyzed the consequences of the mechanical impacts appearing during the transportation from the factory to the customer location.

Figure 8. UHV-Power transformer substation

SOUND LEVEL MEASUREMENT

Sound is longitudinal, mechanical wave, and variation in pressure. The sound wave is produced by mechanical vibration of objects, e.g. transformer. Newton's law of mechanics explains the principles of mechanism of disturbance and its generation. IEC 60076- 10 Edition 2. Part 10: Determination of sound levels, and IEC 60076-10-1 Edition 2.Part 10-1 Determination of Sound Levels-Application Guide are giving detail information for test environment and procedure of the audible sound level of transformers. Generally accepted limits of that are in NEMA Standard TR 1-1993(R2000) for transformers and reactors. Transformers sound becomes disturbing when sound level is 3-6 dB above the ambient sound level. The sound can be quantified in the following three ways:

A sound source generates sound power and this cause a sound pressure fluctuation in the air. Sound power (Lw) is calculated in Watt.

1. The sound power level is expressed in decibel (dB) with respect to a standardized reference value :

$$LW = 10xlog\frac{W}{Wo}$$

Where: LW= sound power level (dB), W= airborne sound energy is radiated by a source (W), Wo= reference sound power ($1x10^{-12}$ W).

2. Sound pressure (Lp) is expressed in Pascal (Pa),sound pressure level is also expressed in decibel (dB)

$$Lp = 10xlog\frac{P^2}{Po^2}$$

Where: P sound pressure (Pa), Po= reference sound pressure ($20x10^{-6}$ Pa)
Sound pressure level is measured with decibel meters.

3. Sound intensity level Li calculated according to

$$Li = 10xlog\frac{|In|}{Io}$$

Where In is sound intensity (W/m^2), Io is reference sound intensity Io= $1x10^{-12}\ W/m^2$

Its value is used to locate and rate sound sources.
The sound pressure and sound intensity are used for sound level evaluation. The meaning of them is in subjective manner concerning human hearing. Both of them can be measured directly [33].
The sound level A (LpA, LwA, LiA) is frequency adjusted value of calculated sound level.

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