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ASPECTS OF DESIGN OF POWER TRANSFORMERS FOR NOISE REDUCTION

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Abstract - *Power transformers are in the category of capital equipment of power plants and high voltage electricity distribution networks. Factory ABS Minel Transformers in Ripanj designs and produces (manufactures) power transformers with power up to 400 MVA and voltage level up to 400 kV, by using modern methods of calculation and design. Producers (manufactures) of power transformers perform certification of characteristic types of their products in accredited laboratories and by doing that they gain significant advantage in international tenders. Moreover, international standards prescribe functional characteristics which must be laboratory tested (before delivering each transformer to the customer) at delivery moment of each transformer to the user (customer). Lately, the customers increasingly insist on requirements in respect to noise level of transformers, which are sometimes more strict than those requirements prescribed by the standard, in order to protect working and living environment.*

This paper analyzes the influencing factors and points out the engineering solutions that are applied in design phase (in order) to reduce the noise of power transformers.

1. INTRODUCTION

Power transformers belong to the category of capital electric power equipment for each power system. There are several types of power transformers that determines their application: single phase and three phase power transformers, transformers with and without regulation, start up transformers and distribution transformers, transformers for voltage levels of 110 kV, 220 kV, 400 kV and higher voltage levels of above 1000 kV, transformers with power of 8 MVA, 12 MVA up to 725 MVA and 1000 MVA. Start up power transformers are mounted on hydro and thermal power plants and are directly associated with the generating aggregate, while distribution power transformers are installed in high voltage transformer substations like those of 400 kV/110 kV or 110 kV/35 kV.

The beginning of development of power transformers starts with the 80-ies of XIX century and is directly related to the transmission of alternating current from the production site to the end user. The pioneering contribution to development of power transformers was made by:

- P.N. Jablochkoff (П.Н. Яблочков),
- L. Goulard and J.D. Gibbs,
- S.Z. de Ferrari,
- W. Stanley,
- O.T. Blathy, M. Dery and K. Zipernowsky.

Engineers from Hungarian GANZ-a (Bláthy, Dery and Zipernowsky) got three patents in 1885 for distribution of electrical power using shielded transformer with magnetic core. Since then, transformer as a term is being used and industrial production of alternating current transformers begins.

Although the construction of power transformers in its basis hasn't been changed notably since 1885 until today, some of the significant development results have been achieved in recent decades (Figure 1) in the area of application of new materials, reduction of losses, increment of power and voltage levels, regulation, production technology, testing and maintenance of transformers. All that influenced on the fact that power transformer as we know it today is a modern product whose service life often exceeds 40 years of usage.

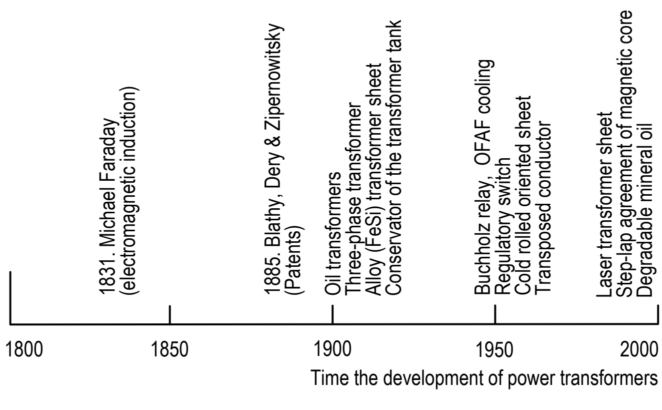


Fig.1 *Development hystory of power transformer's construction*

Today, in addition to functional requirements, very high standards related to protection of human environment are being posed to transformer's constructors. The biggest problems are mineral oils used as dielectric in transformers, which are flammable and eco unfriendly. That's why, in the last ten years, new environmentally better and harder flammable silicone oils, synthetically and natural esters have been developed. Transformer's noise is very important exploitation characteristic of power transformers, which is measured in any final test with methods prescribed by the standards IEC 60076-10 (2001) and IEEE Std C57.12.90

(2006), and at the same time the recommended values of the permitted noise levels by NEMA - National Electrical Manufacturers Association Standards TR1 (1998) must be met. Recommended values of the permitted noise levels of power transformers are defined depending on the power of the particular transformer, test voltage and cooling method (Table 1). With the increase of power of power transformer also increases the permitted noise level (Table 2).

Table 1 *Permissible noise level for 100 MVA transformer with ODWF cooling*

Test voltage kV	350	450	750	900	1175	1300
Permissible noise dB	78	80	81	82	83	84

Table 2 *Permissible noise level for 300 MVA transformer with ODWF cooling*

Test voltage kV	350	450	750	900	1175	1300
Permissible noise dB	83	85	86	87	88	89

Revitalization of hydropower plants, thermal power plants and transmission distribution networks and high voltage transformer substations is usually based on installation of new power transformers with modern construction, which meets all the requirements of international standards. The only Serbian factory of power transformers – ABS Minel Transformatori in Ripanj manufactures power transformers with power of up to 400 MVA and voltage level of up to 400 kV based on its own construction solutions, for EPS (Electric Power Industry of Serbia), EMS (Electric power networks of Serbia), and as well for markets in the region, the European Union, Russia and countries of the former republics of the Soviet Union and countries of north Africa [1]. Currently in the realisation phase is the largest project in the field of electric power in Serbia, the revitalization of HE „Bajina Bašta“ project, which is executed by the Austrian company Andritz Hydro. Within revitalization of all four aggregates of hydro power plant, already two power transformers of power 112 MVA, voltage level of 242/15.65 kV, have been installed. These transformers were designed and manufactured in ABS Minel Transformatori factory in Ripanj, while remaining two power transformers are in production phase (Figure 2).

Fig. 2 *Step-up transformer 112 MVA on H2 unit of HE "Bajina Basta" manufactured by ABS Minel Transformatori Ripanj*

Power transformers of 112 MVA for hydro power plant „Bajina Bašta“ have been examined by Electrical Engineering Institute „Nikola Tesla“ from Belgrade, together with representatives from several accredited European institutions for high voltage tests, during which functional characteristics have been verified according to the standards as well as noise level which power transformers produce during operational time.

2. NOISE OF POWER TRANSFORMERS

The noise that power transformers produce is defined by IEC 60076-10 (2001) standard and is determined by three basic parameters:

- Sound pressure level method (L_p),
- Sound power level method (L_W) and,
- Sound intensity method (L_I).

Sound pressure level is calculated according to:

$$L_p = 10 \lg \left(\frac{p}{p_0}\right)^2 = 20 \lg \left(\frac{p}{p_0}\right) \quad [\text{dB}], \tag{1}$$

where: p – is the sound pressure [Pa] and p_0 – is reference sound pressure $p_0 = 20 \cdot 10^{-6}$ [Pa].

The sound power level L_W is calculated according to:

$$L_W = 10 \lg \left(\frac{W}{W_0}\right) \quad [\text{dB}], \tag{2}$$

where: W – represents the sound power [W] and W_0 – is reference sound power $W_0 = 10^{-12}$ [W].

Sound intensity level L_I is calculated according to:

$$L_I = 10 \lg \left(\frac{I}{I_0}\right) \quad [\text{dB}], \tag{3}$$

where: I – is sound intensity [W/m^2] and I_0 – is reference value of sound intensity $I_0 = 10^{-12}$ [W/m^2].

The sound level A (L_{pA}, L_{WA}, L_{IA}) is frequency adjusted value of calculated sound level that takes into account nonlinear sensitivity of the human ear to different sound frequencies. Human ear is the most sensitive to frequencies around 1000 [Hz], and is less sensitive to lower and higher frequencies. For a particular frequency of sound level A stands:

$$L_{pAf} = L_{pf} + \Delta L_f , \tag{4}$$

where: L_{pf} - is not adjusted linear value of sound level and ΔL_f – is correction to be taken on the basis of empirical values per octave.

The total noise level in the case of multiple sound sources (L_{WA1}, L_{WA2}, L_{WA3}, ...) can be calculated according to the following formula:

$$L_{WA} = 10 \lg \Sigma 10^{0,1 L_{WAi}} . \tag{5}$$

For n equal noise sources of level the total noise level is

$$L_{WA} = L_{WA0} + 10 \lg n . \tag{6}$$

Measurements of power transformer's noise are performed according to IEC 60076-10 (2001) standard, which describes the measurement procedure in great detail. Measurements are performed during tests for short circuit at nominal current at a distance of 300 [mm], 1000 [mm] or 2000 [mm] from contour – the main radiation plane of transformer's trunk. During tests, mainly sound pressure level L_{pA} and sound power intensity L_{IA} are being measured. The main plane of radiation is imaginary surface that surrounds the transformer's tank and passes through vertical projection of the line around transformer at defined distance (Figure 3). For transformers with natural cooling the measurement points are at a distance of 300 [mm] from the main plane of radiation. For dry transformers, for security reasons, the distance should be 1000 [mm].

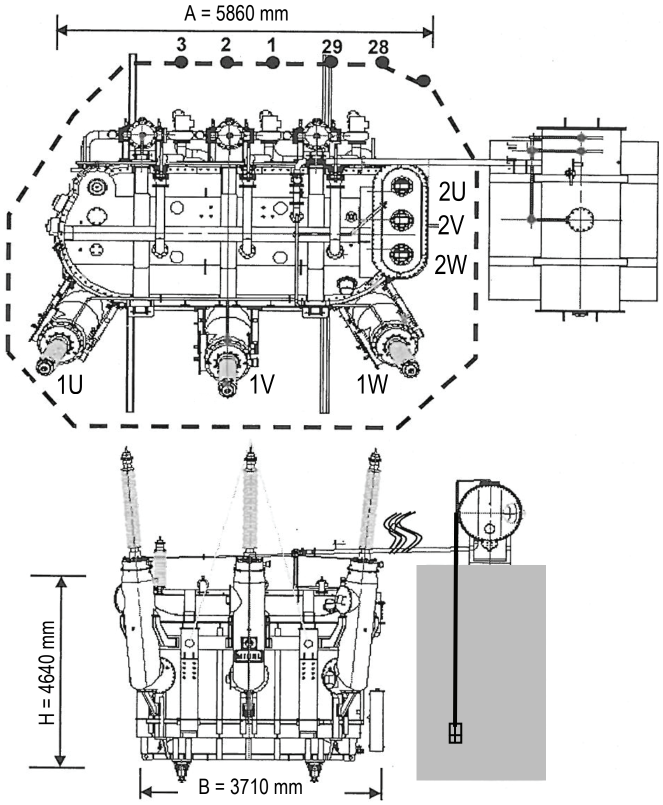


Fig. 3 *Area for noise measurements and placement of measuring points for 112 MVA power transformers*

For transformers with forced cooling measurement points are at a distance of 2000 [mm] from the main plane of radiation. Measurement points are approximately evenly spaced along the edge of the transformer (with step up of 1000 [mm]) provided that there must be no less than 6 measuring points, regardless of the size of the transformer. For transformers with a height of transformer's tank less than 2500 [mm] measuring points are at the half height. For power transformers of greater height measurement positions are at two heights (one at 1/3 and the other at 2/3 of the total height).

3. SOURCES OF POWER TRANSFORMER'S NOISE

Power transformers as fundamental systems for transformation of electricity from one voltage level to another, in the phase of transmission or electricity generation they have several sources of noise, of which the most important are:

1. Magnetic core – where vibrations occur due to the effect of magnetic forces (magnetostriction)
2. Windings – where vibrations of the conductors occur due to electrodynamics magnetic forces and
3. Aerodynamic and hydraulic noise of the cooler – which is generated by the operation of pump units for water cooling or fans for air cooling.

Magnetostriction is a phenomenon that results in a change of dimensions of material being in the magnetic field, and in the case of transformers it results in changes of dimensions of transformer's sheet of magnetic core. The changes are in few μm/m for typical transformer's sheet. The value of magnetostriction depends on magnetic induction (Figure 4), type of transformer's sheet and mechanical strains that arise due to the effect of electromagnetic forces. Magnetic forces are generated within the joints of pillars and yokes of magnetic core.

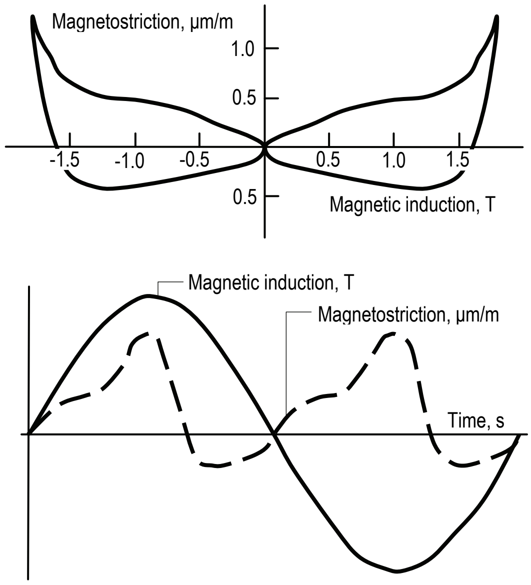


Fig. 4 *Correlation of magnetic induction and magnetostriction*

The frequency of the first harmonic in vibrations of magnetic core' sheets is twice the value of frequency of electrical distribution network, i.e. 100 [Hz] for network of 50 [Hz]. Besides the first harmonic, there are significant amounts of higher order harmonics which resulted as multiplication of pitch frequencies with even numbers of frequencies of distribution network (200, 300, 400 [Hz]).

Noise level of magnetic core is calculated using the following empirical expression:

$$L_{WA}(\text{core}) = k_1 \lg G_{Fe} + k_2 B + k_3 \quad (7)$$

where: G_{Fe} - is the mass of magnetic core, B – is induction inside the core, k_1, k_2 – are empirical coefficients, k_3 – is empirical coefficient that takes into account the type of transformer's sheet, type and construction of the core, frequency, design of transformer's tank.

Electromagnetic forces inside winding conductors, produce axial and radial winding vibrations with pitch frequency twice the frequency of electrical distribution network (i.e. 100 [Hz] for network of 50 [Hz]). Higher order harmonics are insignificant. That noise inside the windings is called load noise, in contrast to the magnetic core noise called the no-load noise. Additional noise is produced by vibrations of terminals from the windings.

Winding noise level for certain load can be calculated using empirical expression:

$$L_{WA}(\text{windings}) = k_1 + k_2 \lg S_r + 40 \lg \alpha \quad (8)$$

where: S_r - is nominal power of transformer, k1 and k2 – are empirical coefficients, α – represents relative load (load current / nominal current).

Aerodynamic noise of the fan significantly contributes to the total noise level of the transformer. The level of fan noise depends on: the speed of fan blades rotation, blade size, construction and number of blades, the ways of setting the fan on the cooler. The frequency spectrum of fan noise is considerably wider than the one belonging to magnetic core. Frequency of the first harmonic is calculated according to the formula:

$$f_1 = n\ N_b \quad (9)$$

where: n - is the number of revolutions per second, N_b - is the number of fan blades.

Transformer's noise level resulting from the fan noise can be calculated according to the formula:

$$L_{WA}(fan) = L_{WA,0} + 10\ lg\ n \quad (10)$$

where: $L_{WA,0}$ – is the noise level of one fan (determined under real operating conditions - the fan on the cooler) while and n - is the number of fans.

The total transformer's noise level is calculated by adding the noise from all sources (magnetic core, windings, fans) with the assumption that all noise sources are independent.

4. DESIGNING THE MAGNETIC CORE IN ORDER TO REDUCE NOISE

There is a multifunction correlation between electrical values and acoustics indicators when designing and calculating the magnetic core of power transformer. While estimating the design parameters of power transformers, various solutions are possible with different values of induction, where increased induction means smaller dimensions of magnetic core, and thus the smaller dimensions of transformer itself. Decreased induction, lower magnetic flux requires a larger amount of material needed and thus the higher transformer's price for smaller nominal power. But also, by reducing induction for every 0.1 [T] magnetostriction and noise of transformer's core reduces for 3 - 4 [dB]. By reducing the induction, noise reduces as well, but at the same time the price of the transformer increases, so designers must find the optimal value of induction from the aspect of competitiveness in the market.

Nowadays, transformer's sheets of 0.23 [mm], 0.27 [mm] and 0.30 [mm] thickness are mainly used when manufacturing a transformer. When applying high quality types of transformer's sheets (HiB-superoriented or ZDKH sheets) with increased price of magnetic core, it is possible to reduce transformer's noise for approximately 3 [dB]. In order to minimize magnetization and idle current losses, and also the noise level, today as a standard solution is used step-lap mode of angular overlap of transformer's pillars and yokes while stacking the magnetic core (Figure 5).

Step-lap lap has several steps unlike the classic lap in one step, which reduces the noise of the magnetic core for up to 6 [dB]. At lower inductions (1.3 - 1.5 [T]) with step-lap lap even greater noise reduction can be achieved (Figure 6). Vibrations of transformer's sheet, which creates noise of magnetic core when magnetic flux passes through it, can be reduced by tightening the magnetic core.

Tightening of yokes with screw connection of the side metal profiles leads to fixing the transformer's sheets in yoke, while tightening of pillars is done by polymer tapes (Figure 7). Half-polymerized poliglas tape is used for tightening the magnetic core, because later while heating the magnetic core it gets fully polymerized and shortened, which leads to very strong tightening of transformer's sheets in pillars of magnetic core. Heating at 140 ^{0}C for 120 minutes polarizes the half-polymerized tape.

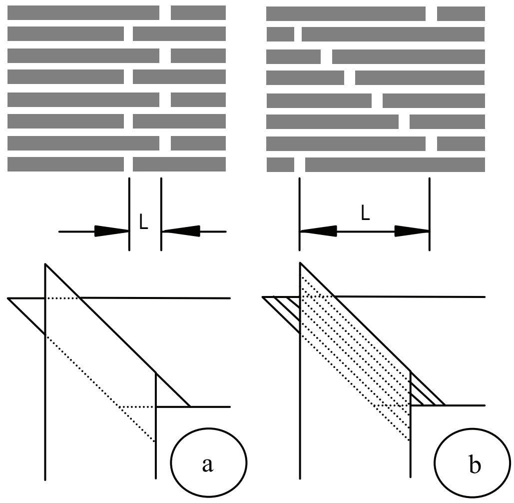


Fig. 5 *Classic and step-lap method for stacking transformer's sheets a) classic method – 1 step, b) step-lap method – 6 steps*

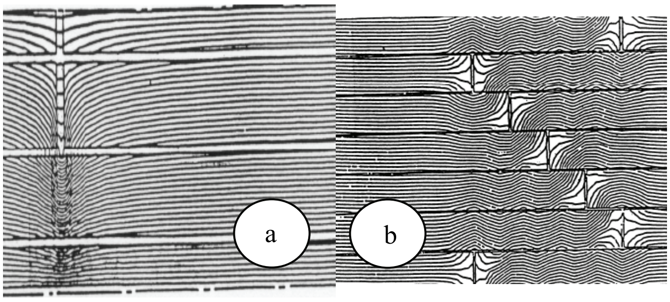


Fig. 6 *Magnetic forces in the area around the overlap of transformer's sheets between the components of pillars and yokes of magnetic core:*
a) classic method, b) step-lap method

Fig. 7 *Tighten pillars of magnetic core with yoke being taken off in the assembly process*

By tightening the yokes of the magnetic core with screws made of anti-magnetic material (Figure 8) there is one part of transformer's sheet on the upper surface that remains not tighten because of the yoke's circular cross section (Figure 9). The flat surfaces of the lower yoke are coated with epoxy or wood glue, in order to reduce vibrations of the sheet's ends which are not tighten. The upper yoke must be dismantled because of repair, thus the flat surfaces of the upper yoke are not coated with glue [2].

Fig. 8 *Tighten magnetic core*

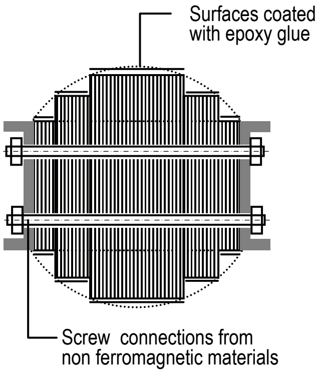


Fig. 9 *The intersection of tighten yoke of magnetic core*

In order to reduce the noise of magnetic core, sometimes the peaks in angles' overhang of magnetic core are being cut, since they are free and they have vibrations due to the flow of magnetic flux. To perform tightening over complete cross section of magnetic core more easily, instead of circular, transformers with rectangular cross-section of magnetic core are rather designed, as one of the solutions to reduce noise. When completed active part of the power transformer is placed in the transformer's tank, it gets further secured with anti-vibration elements that are placed between the magnetic core and the transformer's tank. Besides the fact that reinforcement provides stability of the active part during transport, it also reduces the transformer's noise for about 2 [dB].

5. DESIGN OF WINDINGS FROM THE ASPECT OF TRANSFORMER'S NOISE REDUCTION

With the development of modern methods of CAD design, significant improvements in the design and construction of the transformer's windings are accomplished, using 3D modelling, and especially through simulations and 3D FEM modelling of electrical, electromagnetic and thermal phenomena in transformer's windings, and in different working conditions (Figure 10).

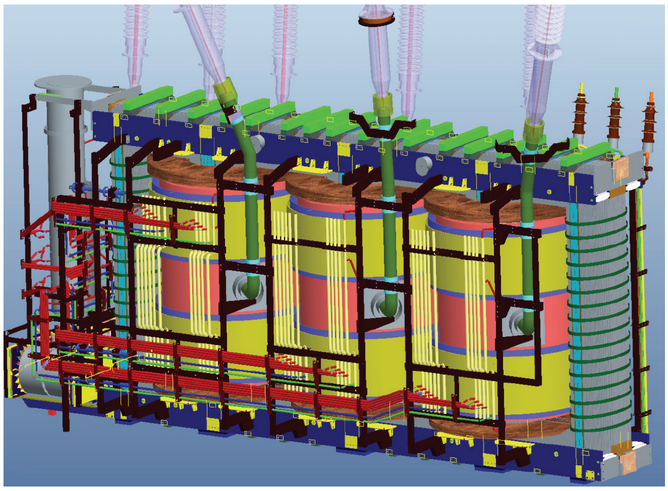


Fig. 10 *CAD project of active part of power transformer*

Windings placed on magnetic core together with the terminal part of the conductors represent the active part of transformer, that is placed in the transformer's tank, which performs drying in vacuum and pouring the transformer's oil. Electrodynamics forces in the windings are with very high intensity, and they create vibrations of conductors in windings that are spaced apart from each other due to oil flow and more intensive cooling. Moreover the terminals are also exposed to vibrations, therefore they firm especially within the active part of the transformer (Figure 11).

Fig. 11 *The active part of power transformer*

By applying modern methods of CAD design, the analysis of electrodynamics forces in windings are carried out, which are correlated with the voltage level of current flow. Electrodynamics forces are particularly intense at short-circuit voltage when they can completely deform windings of the transformer (Figure 12). Modal analysis provides the definition of modal parameters of windings as a mechanical structure, and those are the resonant frequencies, suppression and modal shapes [3].

Resonant frequency is the frequency at which the dynamic excitation creates a critical reaction of windings structure. It is important to identify the resonant frequency because the excitation that is even close to the structural resonance frequency, also produces an adverse effect for the windings.

In most cases, the dynamic excitation generates vibrations of the windings that have high amplitude and can cause damage to the isolation, or in extreme cases - short-circuit voltage, till breaking the conductor and total damage of the windings (Figure 13).

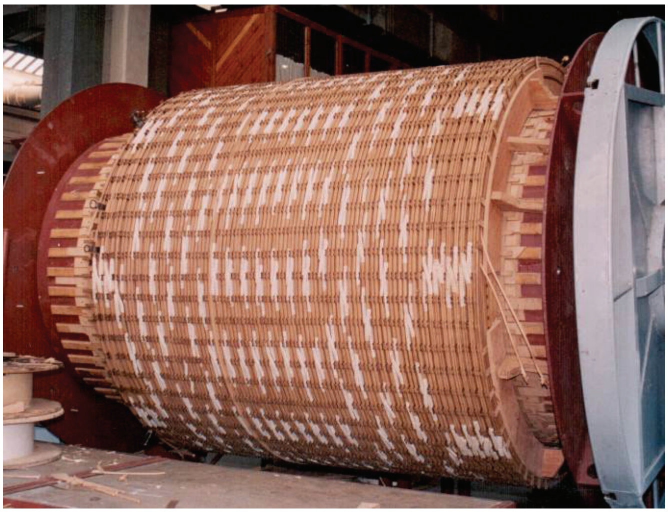


Fig. 12 *Making the windings for 112 MVA power transformer on horizontal winding machine*

Fig. 13 *Deformation of windings due to short circuit*

As the resonant frequencies are associated with the stiffness of the windings, dynamic parameters can be compared with the analytically calculated stiffness and thus they can correct the analytical model of the windings. Winding technique also achieves the suppression effect that allows rapid energy dissipation of vibrations, i.e. windings quickly return to its original condition upon termination of action of dynamic load (Figure 14). Modal shapes represent a way of deforming, moving windings that vibrate at a resonant frequency and make noise (Figure 15).

Transformer's windings are exposed to the radial and axial component of the electrodynamics force. Radial component burden the inner winding on pressure, and external winding on strain. In order to increase the conductor's resistance to pressure, the isolation mounts are being set – lattices that rely on the isolating cylinder, while inside the cooling axial channels at the appropriate distance inserts are being placed. Parts of windings are loaded like a beam with continuous load that makes the deflection.

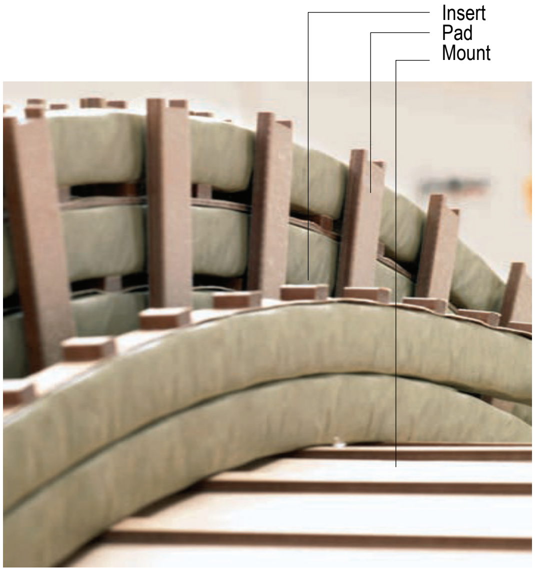


Fig. 14 *Isolation elements that provide rigidity and vibration resistance of conductor in winding*

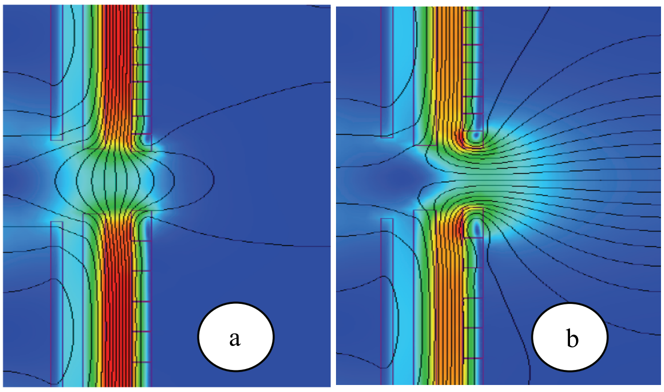


Fig. 15 *Dispersion magnetic field in the space between the windings:*
a) due to harmonics in the phase,
b) due to harmonics in anti-phase

The required number of mounts and inserts is determined by dimensioning of the windings, along with the choice of their size from a series of standardized dimensions, which will provide tightening of conductors that will be less than it is allowed (Figure 16). Mounts causes the local deformation of conductors, which should be also taken into account in the calculation process. Axial forces tend to compress and shift the winding from the current focus (Figure 17). To ensure the durability of the winding's isolation, due to the axial forces, in cooling radial channels of the windings an appropriate number of isolation pads of adequate dimensions are being placed. Dimensioning comes down to determining the required number of pads and the selection of their width from the range of standardized sizes. Specific winding's straining reduction is achieved by increasing the conductor's size, or increasing the transformer's impedance, which increases the amount of used material, and thus the price of the transformer.

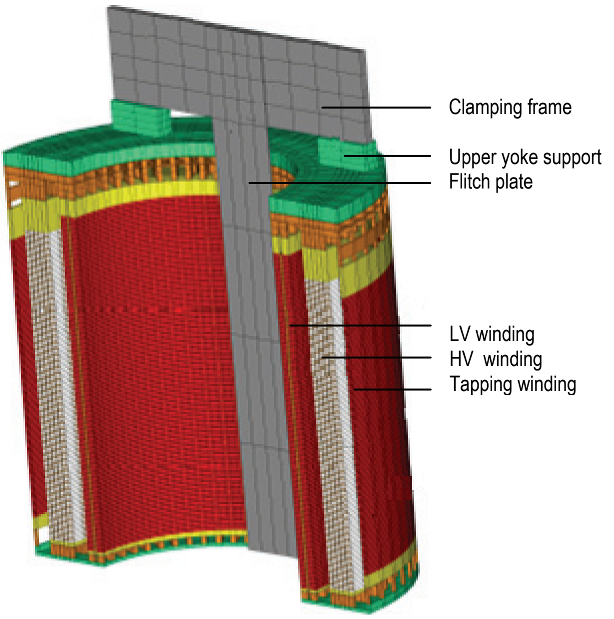


Fig. 16 *Solid model of transformer's winding*

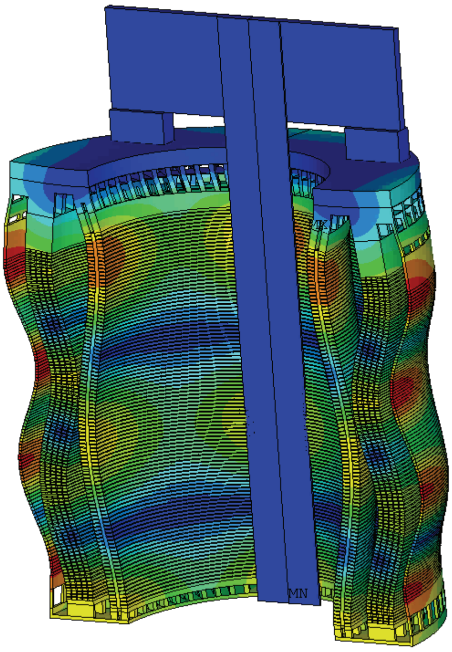


Fig. 17 *Analysis of strainings by MFE method*

Although industrial production of transformers exists already one century, there is still not enough theoretical and practical knowledge about effective measures that can be used to reduce the noise of power transformer's windings. Reducing the noise in transformer's windings is the subject of many scientific research projects, which are carried out in the development laboratories of large companies - manufacturers of power transformers (Siemens, ABB), through researches based on sophisticated numerical methods of modelling (Figure 18).

For large power transformers special kind of transposed conductors for making windings are being made in order to reduce losses in the windings and winding's noise reduction (Figure 19). Transposed conductor consists of several individual specially twisted conductors that provide the same length of the conductor, regardless of the different diameters on windings.

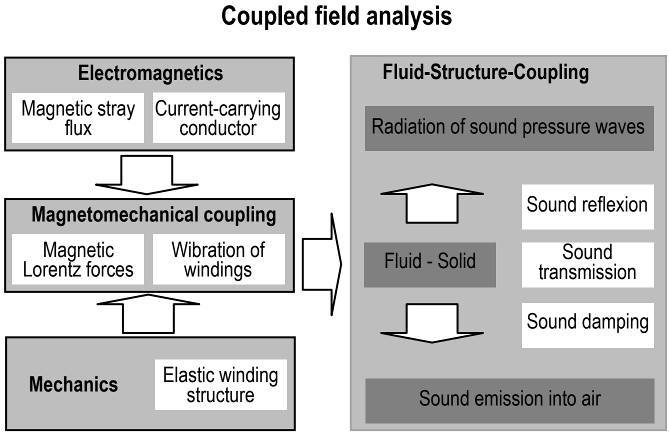


Fig. 18 *Engineering analyzes of windings noise*

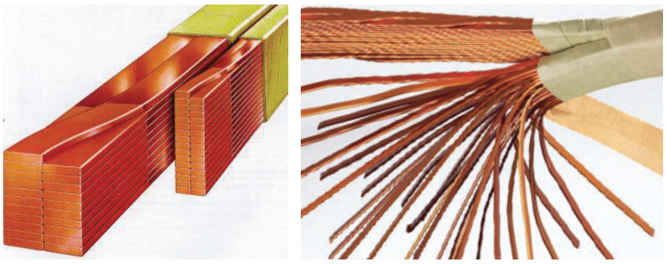


Fig. 19 *Transposed conductors for making windings*

There are still a lot of phenomenological events that are not fully explored in the field of noise generation in the power transformer's windings, so they are still the subject of ongoing researches [4].

6. FAN'S NOISE REDUCTION

Fans are used as an additional transformer's cooling system meaning that they increase the capacity of the cooling system for transformers (Figure 20).

Fig. 20 *Fans on the power transformer*

Fan's noise reduction is achieved with fewer numbers of rotor's revolutions of the fan, but at the same time it reduces the cooling capacity, thus the commonly used fans are with greater number or with larger dimensions blades, in order to compensate the reduced cooling capacity (Figure 21). Reducing fan's noise can be determined according to the empirical formula:

$$\Delta L_{WA} = 70 \lg(D/D_0) + 50 \lg(n/n_0), \quad (11)$$

where: D – is a diameter of the fan, n - number of revolutions per second, p - the number of motor poles.

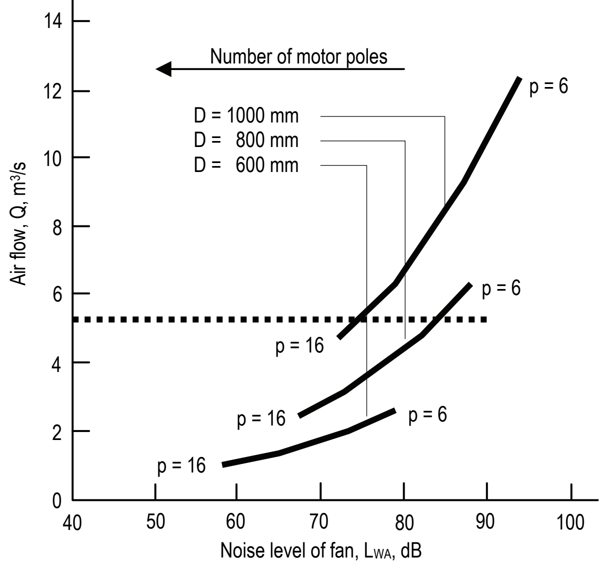


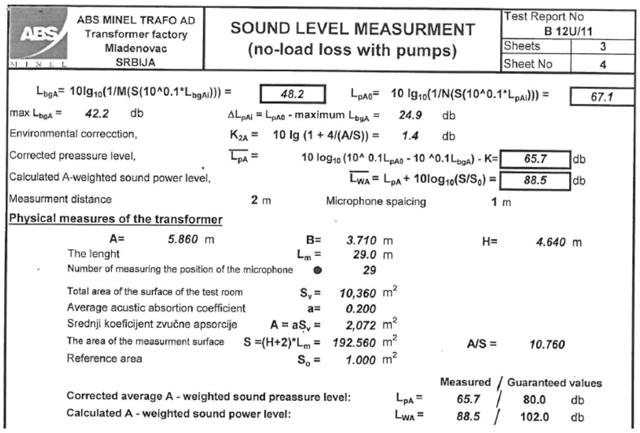
Fig. 21 *Noise level depending on the diameter of the rotor, the number of poles and the cooling capacity of the fan*

In addition to this, reducing fan's noise can be achieved through balancing the rotating masses, quality bearing and stable structure for binding the fan with housing of the radiator for cooling.

7. CONCLUSION

Around thirty years ago, as part of the then known Institute for Machine Tools and tooling (IAMA) in the framework of scientific research program VIBEX - Protection against noise and vibration, within living and working environment, one of direction for the research was the protection of the transformer's noise in urban areas. These surveys also included the distribution transformers that are installed in transformer substations 10/04 kV in inhabited areas. Usually the solution for reducing the noise and vibrations was sought through elastic reliance of the transformer's active part, also with complete transformer substation's isolation techniques with special anti-acoustical materials. Termination of existence of the Institute IAMA and its orientation to the study program of industrial production of machine tools and computer control systems, the research program for protection against noise and vibration has entered into stagnation.

At that time, the noise and vibration studies haven't been focused in the area of large power transformers, which are designed at the factory Minel Transformers in Ripanj according to Westinghouse license. Today in the development of power transformers standards in the field of noise are imposed by major companies from most developed countries in the world, that's why the designers from Minel Transformers factory have developed original methods for calculation and design solutions that fully provide the permissible level of noise and all other functional characteristics required by international standards (Figure 22).


ABS MINEL TRAFO AD
Transformer factory
Mladenovac
SRBIJA

SOUND LEVEL MEASURMENT
(no-load loss with pumps)

Test Report No B 12U/11
Sheets 3
Sheet No 4

L_{bgA}= 10lg$_{10}$(1/M(S(10^0.1*L_{bgAi}))) = 48.2 L_{pA0}= 10 lg$_{10}$(1/N(S(10^0.1*L_{pAi}))) = 67.1
max L_{bgA} = 42.2 db ΔL_{pAi} = L_{pA0} - maximum L_{bgA} = 24.9 db
Environmental correcction, K_{2A} = 10 lg (1 + 4/(A/S)) = 1.4 db
Corrected preassure level, $\overline{L_{pA}}$ = 10 log$_{10}$(10^ 0.1L_{pA0} - 10 ^0.1L_{bgA}) - K= 65.7 db
Calculated A-weighted sound power level, $\overline{L_{WA}}$ = L_{pA} + 10log$_{10}$(S/S_0) = 88.5 db
Measurment distance 2 m   Microphone spaicing 1 m

Physical measures of the transformer

A= 5.860 m   B= 3.710 m   H= 4.640 m
The lenght L_m = 29.0 m
Number of measuring the position of the microphone ● 29
Total area of the surface of the test room S_v = 10,360 m^2
Average acustic absortion coefficient   a= 0.200
Srednji koeficijent zvučne apsorcije   A = aS_v = 2,072 m^2
The area of the measurment surface   S =(H+2)*L_m = 192.560 m^2 A/S = 10.760
Reference area S_o = 1.000 m^2

		Measured	Guaranteed values	
Corrected average A - weighted sound preassure level:	L_{pA} =	65.7	80.0	db
Calculated A - weighted sound power level:	L_{WA} =	88.5	102.0	db

Fig. 22 *Example of a part of the Certificate for noise measurements of 112 MVA power transformer for HE „Bajina Basta"*

Modelling of the magnetic core, windings and solutions for increasing the stiffness of the transformer's active part is a constant challenge to the designers, who are looking for an optimal solution between functional performances, cost of materials and production costs, bearing in mind that in recent times the world market price for power transformers has been significantly reduced compared to the period of 4-5 years ago, despite the fact that all manufacturers are installing the transformer's sheet of the same characteristics, that the copper price is the same for all producers, that we all use Weidmann isolation materials, Nynas transformer's oil and Reinhausen regulators.

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