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NOISE CONTROL FOR A BETTER ENVIRONMENT

Noise measurement diagnostics for large electric machines

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ABSTRACT

In the field of power engineering, much attention is paid to low machine failure rate and minimisation of shutdown periods that are always associated with major financial losses. That is why methods of non-destructive testing of the power generating equipment under operation are preferred to regular inspections under shutdown periods that often do not reveal any machine defects. This paper presents a diagnostic method for checking the mechanical condition of transformer frame and core and electric generator stator. The method is not intended to replace the conventional diagnostic measurements or tests, but to make possible early detection of places and the likely causes of future defects. It may be used in combination with other diagnostic methods to identify potential weaknesses in large electric machines and equipment where the condition, in particular compression force and its uniformity, of the magnetic core is of great importance.

Keywords: Non-destructive diagnostics, Noise measurement, Large electric machines
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1. INTRODUCTION

Electric machine diagnostics comprises many different methods, procedures and tools. The operational reliability of any large electric machine with rating up to several hundreds of MW depends, among other things, on the homogeneity and integrity of the magnetic core. At the moment, there are no suitable tools or methods for monitoring this important mechanical parameter of the machine. The conventional non-destructive techniques used in this area are based on measurements of electrical quantities or bearing vibrations during the machine operation. Such techniques have their inherent limitations regarding sensitivity and scope of the identifiable defects. Noise diagnostics represents a new approach to the issue of monitoring the mechanical condition of electric machines in that it offers, in a way superior to other diagnostic methods, the possibility to identify potential defects in the early stage of development.

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2. GENERAL KNOWLEDGE AND ASSUMPTIONS

The method of noise diagnostics has been developed on the basis of general acoustic phenomena and the knowledge of principles upon which electric machines operate. The method is primarily intended to monitor the condition of the magnetic cores of transformers and generator stators. It is expected to find application with large electric machines and equipment where the machine size and dimensions render use of the conventional non-destructive methods rather impractical.

The initial inspiration for the method development was T. C. Rathbone's work [1] where the so-called Rathbone Chart related the mechanical condition of electric machine to vibrations of specific frequencies measured at the machine surface. This observation is believed to have established a basis for monitoring the development of mechanical condition of an electric machine through a series of comparative measurements. In practical situations, the issue of selecting correct measurement spots is of importance; with large machines, the number of required measurement positions is naturally very high. That is why non-destructive tests based on vibration measurements are predominantly used on the machine bearings only.

Upon the assumption that the machine noise is a direct representation of the machine vibrations in a gaseous environment, it should be possible to identify changes in the mechanical condition of the machine by monitoring its operational noise.

Using an omnidirectional microphone (which is particularly advantageous with axially symmetric machines), it is possible to record the machine noise within a certain spatial angle. Compared to the spot-vibration sensing technique, this noise-picking method implies great practical simplification of the measurement arrangement. The advantages and shortcomings associated with this approach will be discussed below.

3. THEORETICAL BASIS OF THE METHOD

It is obvious that forces acting within electric machines are related to the machine vibrations and the emitted noise. Nevertheless, not all emitted noises can be attributed to the mechanical condition of the machine. It is therefore reasonable to assign various types of noise to categories regarding their origin:

- Electromagnetic noise;
- Mechanical noise;
- Ventilation noise.

3.1. Noise of electromagnetic origin

Noise of electromagnetic origin is a typical feature of any electric machine in operation. It originates due to vibrations of the machine frame, core and other machine parts caused in turn by the action of electromagnetic forces and the magnetostriction phenomenon. The frequency spectrum of the noise of electromagnetic origin is of a discrete nature where the key frequency values can be readily determined. For the purposes of this study, we will consider the noise of magnetostriction origin and the noise caused by electromagnetic forces separately.

3.1.1. Noise caused by magnetostriction

This type of noise is predominating with transformers. The magnetostriction phenomenon consists of changes in stress (and dimensions) in ferromagnetic material during the process of magnetisation. On a general level, the dimensional changes imply changes in shape and volume. However, in the realm of technological magnetisation, well below the bend on the magnetisation curve, the volume changes are negligible and the magnetostriction phenomenon can be taken for a one-dimensional (linear) issue. Linear magnetostriction changes grow smaller with increasing temperature; however, within the standard operational temperature range, this relationship can be disregarded. Material properties regarding magnetostriction are expressed by the magnetostriction coefficient ε defined as the relative elongation of a magnetic material sample along a specified axis for a given field intensity. Apart from field intensity (see (1) below), the magnitude of the magnetostriction coefficient also depends on the magnetisation direction, mechanical stress acting on the material and, most importantly, on the technological properties of the material given by its composition and processing.

In general, magnetisation is an even phenomenon, it is its effects are independent of the excitation field polarity. The relationship between the coefficient of linear magnetostriction ε and magnetic field intensity B is given by the following equation:

$$\varepsilon = \sum_{v=1}^{n} k_v B^{2v} \tag{1}$$

where k_v is a constant of magnitude decreasing with the increasing harmonic order v [2].

For magnetic induction $B=B_m sin\omega t$, it is possible to calculate individual harmonic components of the magnetostriction coefficient:

$$\begin{aligned} \varepsilon_1(t) &= \frac{k_1 B_m^2}{2}(1 - cos2\omega t) \\ \varepsilon_2(t) &= \frac{k_2 B_m^4}{8}(3 - 4cos2\omega t + cos4\omega t) \\ \varepsilon_3(t) &= \frac{k_3 B_m^6}{32}(10 - 15cos2\omega t + 6cos4\omega t - cos6\omega t) \end{aligned} \tag{2}$$

From these equations it follows that linear magnetostriction coefficients are pure harmonic functions of frequencies equal to integer multiples of the excitation field frequency. The constants in the equations relate to permanent dilatations in the ferromagnetic material and do not contribute to noise generation.

While linear magnetostriction coefficient ε is defined as the relative material elongation, acting on the ends of transformer core of cross-section S will be fictitious force F the magnitude of which is given by Hooke's law:

$$F = \varepsilon E S \tag{3}$$

where E is modulus of elasticity.

From the above discussion it follows that, as long as the Hooke's law is applicable, the forces acting within the transformer are of harmonic nature with frequencies equal to integer multiples of the excitation frequency. Actions of these forces give rise a noise spectrum with identical prominent frequency components.

3.1.2. Noise caused by electromagnetic forces

This type of noise is common for all rotating electric machines. For the purposes of this study it suffices to consider the electric motor or generator as a simple combination of stator and rotor. Each of these component parts is provided with a winding. The current flowing through the winding generates magnetomotive force whose distribution in time and space can be described by a Fourier series. The same mathematical tool can be used to express the permeance in the air gap between the stator and rotor. This information makes it possible to derive the distribution of the magnetic induction in the air gap and the magnitudes of the radial forces acting on both the stator and rotor.

According to Maxwell, radial force p_r acting on a unit area in the air gap can be expressed as:

$$p_r = \frac{B^2(\alpha t)}{2\mu_0} \tag{4}$$

where $B(\alpha t)$ is instantaneous value of flux density in the air gap at time t and position removed by angle α from the reference position at time t_0 [2].

Upon neglecting the effect of iron saturation ($\mu_{FE} = \infty$), we obtain:

$$p_r = \mu_0 \frac{H^2(\alpha t)}{2} \tag{5}$$

Assuming a specific time and space distribution of flux density in the air gap between the stator and rotor, there will be forces acting on the stator and rotor of corresponding magnitudes and distribution. These forces can cause vibrations of some machine parts and therefore noise. From the machine design it follows that a major part of the noise will be generated by stator vibrations. The stator can be taken for a ring subject on its inner side to the action of forces with specific time and space distribution.

For a general current layer density $A(\alpha t)$ along the machine axis, radial field lines in the air gap, high iron permeability ($\mu_{FE} = \infty$) and a general width of the air gap $\delta\ (\alpha)$, it holds [2]:

$$H(\alpha t) = \frac{[H_0\delta_0 + \int A(\alpha t) d\alpha]}{\delta(\alpha)} \tag{6}$$

From this equation it follows that, in comparison with the idle machine run when the stator current is at the minimum, the overall stress on the stator is greater when the machine is run under load. The magnetic flux in the machine varies with the machine loading (6). At the idle run, when the winding currents are at the minimum, the noise generated in the magnetic core carries information on the core condition. Other noise components appearing in the machine under loading include those associated with the condition of the machine windings. However, this assumption may not hold absolutely; here the dynamic properties of the whole electromagnetic circuit of the machine should be taken into account. From equation (4) it further follows that the main frequency components of electromagnetic forces (and of the noise too) are integer multiples of the machine excitation frequency.

3.2. Noise of mechanical origin

The sources of mechanical noise include friction bearings, gears (if any), unbalanced rotating parts and others. Each of these usually produces a set of frequency components which can be in some cases precisely determined (for example, one of the gear frequencies is given as the product of the rotating frequency and the tooth count), and in other cases not. On a general level it holds that the mechanical noise profile reflects the wide range of the possible noise sources.

3.3. Noise of ventilation origin

In-depth analysis of the ventilation noise shows that the main noise sources include the machine fan, other machine parts with a ventilation function (e.g. the rotor star), and the neck parts of the stator or rotor slots. The noise generated by the air flowing through ventilation openings in the machine frame can also contribute to the overall noise balance, especially in cases where such air flow may cause vibrations of adjacent machine parts. Such noise components are characteristic of the machine size and its internal design. The ventilation noise can be of both discrete and wide-band nature.

The noise-measurement based diagnostic method for monitoring the mechanical condition of turbo-generators, hydroelectric generators and most of large transformers is primarily concerned with the first two types of noise discussed above in Sections 3.1. and 3.2. Such noise originates from vibrations of specific machine parts. Increased vibration is not only detrimental to the key machine parameters such as power, operational reliability, safety or lifetime, but it also may affect the integrity of other machine parts or co-operating equipment. The principle advantage of the noise measurement diagnostics is, based on repeated measurements of selected sections of the machine noise spectrum, the possibility to identify undesirable development in the mechanical condition of the machine under test and the associated potential failure risks.

4. THE METHOD FOUNDATIONS

If, according to Rathbone [1], mechanical condition of an electric machine is related to the vibration amplitudes measured at the machine surface (see table 1), then we may expect a corresponding relationship with respect to emitted sound power W. With acoustic power W given by equation (7) and the sound power level L_W by equation (8), it can be shown that the change in the sound power level ΔL_W (9) is a function of only Δv because the rest of the equation (8) is constant, always assuming that area S is kept constant. We are primarily concerned with changes in the sound power level as the proposed method essentially works on the basis of relative changes.

$$W = p_{ef} \cdot v_{ef} \cdot S = v^2 \cdot \rho \cdot c \cdot S \cdot s \tag{7}$$

where p_{ef} is sound pressure, v_{ef} particle velocity, S the measurement area, v surface velocity, ρ mass density, c sound velocity and s sound radiation efficiency. Equation (7) holds for plane sound waves.

$$L_W = 20\log\left(\frac{v}{v_0}\right) + 10\log\left(\frac{S}{S_0}\right) + 10\log(s) - 34 \tag{8}$$

where the reference values of measurement area and surface velocity are $S_0 = 1$ m^2 and $v_0 = 10^{-9}$ m/s.

$$L_W = 20\log\left(\frac{v}{v_0}\right) + k \tag{9}$$

Table 1: Data from Rathbone chart for frequency 50 Hz

Mechanical condition (run) of machine under test	Curve	v [m/s]
Extremely smooth	f	0,00110
Very smooth	e	0,00188
Smooth	d	0,00314
Very good	c	0,00550

Table 2: Change in sound power level ΔL_W

v (m/s)	L_W [dB]	ΔL_W [dB]
0,00110	120,8+k	-
0,00188	125,5+k	4,7
0,00314	129,9+k	4,4
0,00550	134,8+k	4,9

If changes in mechanical condition can be established at sound frequency of 50Hz, the same changes should be identifiable at other typical frequencies. As shown in (7), changes in acoustic power can be determined on the basis of surface vibration or acoustic pressure measurements. According to our observation, a change in the sound power level of approximately 5dB (see table 2) corresponds to specific changes identified in Rathbone Chart (see table 1).

5. EFFECTS OF MECHANICAL DETERIORATION ON THE MACHINE NOISE SPECTRUM

5.1. Defects in mechanical integrity of machine parts

As demonstrated above, as long as the core stress is within the limits of the Hooke's law, the noise spectrum includes frequencies of electromagnetic origin and magnitudes that are integer multiples of the excitation frequency. Should the noise spectrum contain prominent amplitudes of higher odd harmonics (150Hz, 250Hz etc.), it will be indicative of stress on some machine parts outside the realm of the Hooke's law. In other words, occurrence of higher odd harmonic frequencies shows that we are dealing with nonlinear stiffness of the machine or a part thereof. This condition can be explained as a situation where the forces acting on some machine parts exceed the magnitudes of the friction forces keeping the adjacent parts in fixed positions with respect to one another, and such parts start to rub (e.g. individual core sheets or winding in a slot) against one another. The degree of risk associated with such condition shall be assessed based on the spot or area of occurrence, relative values of the noise signal amplitudes in individual frequency components and changes of these phenomena with respect to the previous measurements. Figure 1

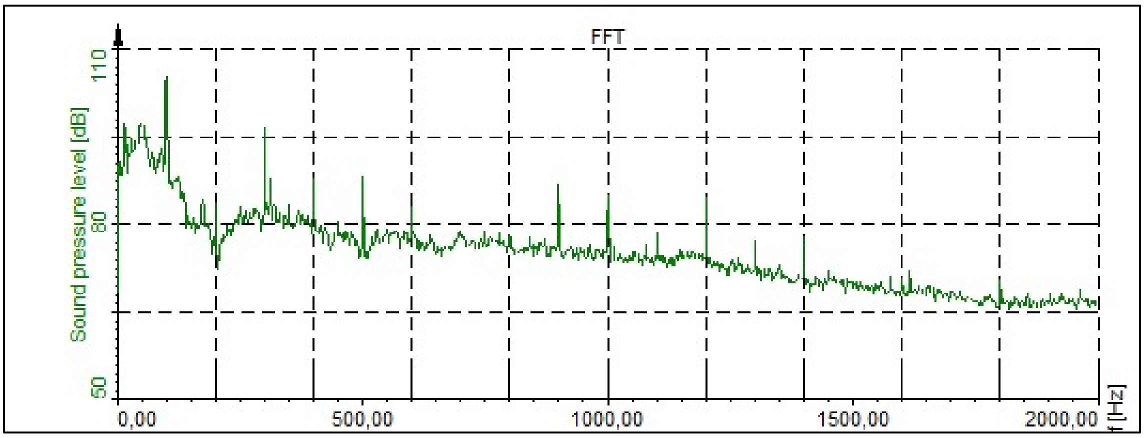

Figure 1: Typical frequency spectrum of hydro generator without signs of loosening in magnetic core circuit of stator

shows an example of the noise spectrum of an electric generator where the harmonic frequencies of magnitudes equal to integer multiples of the excitation frequency testify to the predominantly rigid structure of the machine subject to stress within the elastic deformation zone. On the other hand, the noise spectrum shown in Figure 2 is an example of a machine with defects in the magnetic core compression. Here the occurrence of higher odd harmonics indicates the condition of nonlinear stiffness of the machine body. This kind of defect is typical of all electromagnetic machines and equipment that have been in operation over a certain period of time.

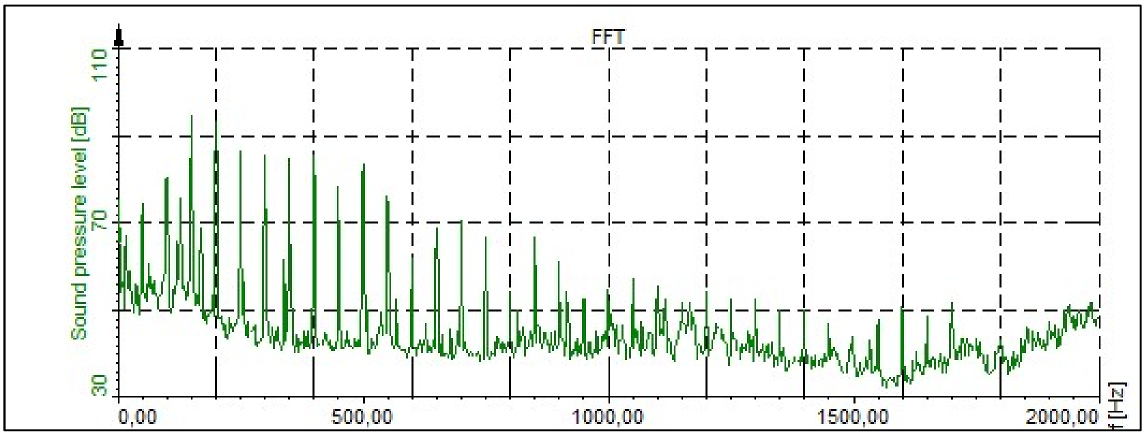

Figure 2: Typical effect of loosening in magnetical circuit in the core of transformer accompany with increased subharmonic frequencies in the noise spectrum

5.2. Rotor eccentricity

As the magnitude of the first harmonic of the noise signal of the electromagnetic origin depends on the size of the air gap between the stator and rotor, height of the magnetic core yoke and the characteristic frequencies (dynamic properties) of the machine, any variations of said magnitude detected in the direction along the machine axis may testify to changes in these machine parameters. Should similar trends in the changes of the magnitudes of the first harmonic of the noise signal of the electromagnetic origin and that of the first harmonic of the rotational frequency of the generator under test be established, the reason for this behaviour will likely be the rotor eccentricity. In cases of suspected non-circular rotor motion, various noise signal harmonics should be subject to analysis.

5.3. Other mechanical defects

Similar noise-measurement diagnostic methods and procedures can be developed and applied to assess integrity of other machine parts or those of the co-operating equipment (e.g. gearwheels and gearwheel sets, current collector systems, turbine blade fitting and others).

6. COMMENTS TO METHOD APPLICATION

The noise diagnostic method consists of processing noise signals recorded by omnidirectional microphones located approximately 30cm from the machine surface. The measurement points shall be selected with respect to the size and type of the machine under test. Figure 3 shows typical measurement point positions along the machine. To facilitate correct identification of the noise sources, the measurement points should cover not only the generator but also its co-operating equipment found in the immediate vicinity such as the turbine, exciter or current collector equipment.

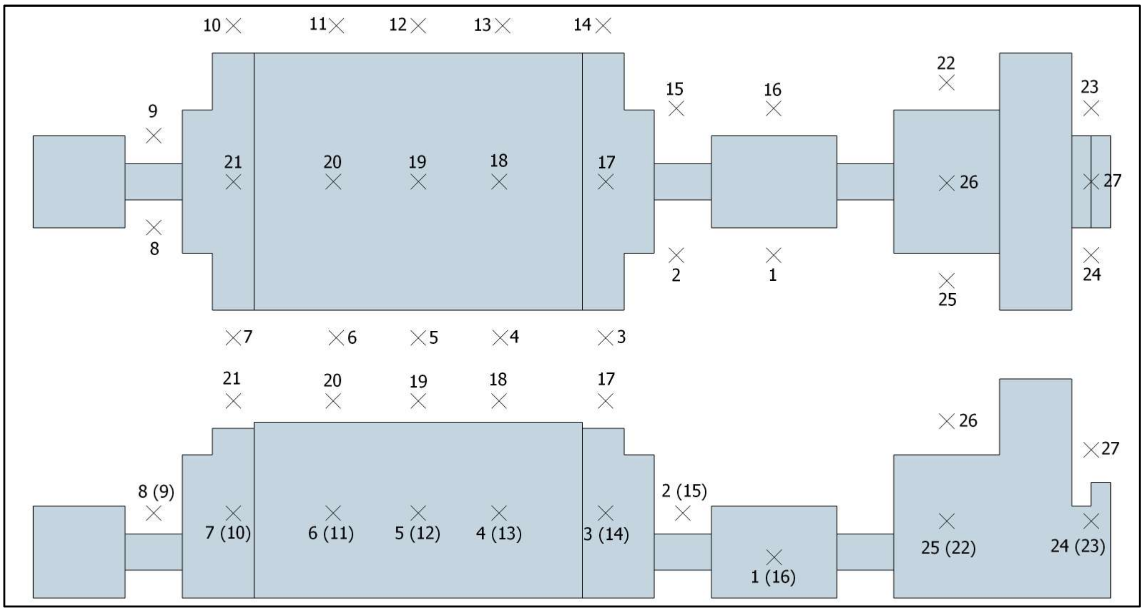

Figure 3: Typical position of measurement points

In each measurement point, the sound pressure level values are measured and the respective mean values calculated. Any change in the mean values is the first indicator about a change in the mechanical condition of the machine. However, there are situations where the changes in the mechanical condition do not produce any change in the mean values of the sound pressure level. These are situations where the sound pressure value is given by the sound component of a certain dominating frequency that does not change while the changes in other sound components of other frequencies do not affect the mean value in a significant manner. To avoid the risk of incorrect conclusions, the time record of the sound signals at each measuring point is stored and subsequently subject to FFT analysis to determine the respective frequency spectra. The final assessment of the mechanical condition of the machine is then based on evaluation of the signal amplitudes of individual frequency components and their changes in time.

Most noise-diagnostic measurements intended to identify major machine defects and potential malfunctions are carried out with the machine under rated load. In some cases, additional measurements at idle run or mechanical mode of operation (applicable to rotating machines only) may be needed to derive more detailed information on the irregularities disclosed earlier.

If the same or very similar signs of the magnetic circuit disintegration are established with a machine under rated load and in the idle run, it can be assumed that the problem lies in the magnetic circle of the machine. If there are no indications of a defect with a machine running idle, we should look for a problem associated with the machine winding. In the cases of rotating machine, it is sometimes necessary to separate the noise components of mechanical and electromagnetic origins. For these purposes we use the so-called mechanical operation of the generator under test where the generator driven by the turbine is disconnected from the grid and the excitation equipment. Under this operational mode, the noise component generated by the electromagnetic forces is kept at the minimum (depending on the degree of de-excitation) while the mechanical noise component will prevail.

7. METHOD PROS AND CONS

7.1. Advantages

- **Application ease** – the method execution does not disturb the normal equipment operation
- **High sensitivity** – the method facilitates early identification of potential equipment weaknesses with direct benefits to the equipment maintenance and repair action planning

7.2. Weak spots

- In repeated measurements, it is necessary to ensure that the operational conditions of the machine and the measurement device arrangement and setting are identical
- The test results make it possible to identify a (potentially) defective machine part but not the precise spot of irregular function

8. FUTURE STEPS

As a comparative diagnostic method, the noise measurement and assessment technique may find application in various fields of technology. In every such new application area, it will be necessary to identify the initial/default equipment state, its characteristic frequencies and the noise effects of equipment defects. In the realm of power industry where the noise-measurement diagnostics is well established, the logical extension of the application sphere is steam and hydraulic turbines. Potential opportunities are also seen in diagnostics of gearboxes, compressors or other electric-driven machines where the specific operational noise frequencies can be monitored, compared and evaluated.

9. CONCLUSION

Compared to the conventional non-destructive diagnostic methods, the noise-measurement diagnostics offers, among other things, the benefit of early warning in the area of magnetic core disintegration.

On a more general level, the method is based on the assumption that behaviour of selected mechanical parts of a machine is indicative of the overall machine condition where changes in the manifestation of such behaviour may help identify the causes of the changes in the machine condition.

After more than 20 years of the method testing and application in Czech power plants, the noise-measurement diagnostic method has been included among the internal regulations concerning preventive inspections on electric machines operated by ČEZ GROUP. Presently the method is patent protected in Czech Republic (patent file No 17466006.8/EP17466006, the Czech title: “Diagnostika magnetického obvodu elektrických strojů“), and the patent protection procedures are pending in several other European countries.

10. REFERENCES

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