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Selected Topics in Electrical Machines

(KEV/VPS)

Electromagnetically excited noise and vibration in electrical machines

(Study text)

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Symbols and abbreviations

Symbol	Unit	Explanation
B	T	Magnetic flux density
c	-	Any integer
e	-	Zero or even integer
f_{1X}	Hz	Rotor rotational frequency (mechanical)
f_{ecc}	Hz	Frequency of eccentricity-excited vibration
f_L	Hz	Machine supply frequency
f_p	Hz	Pole passing frequency
f_{Qr}	Hz	Rotor bar passing frequency
f_s	Hz	Slip frequency (frequency of rotor field)
k_e	-	Coefficient denoting eccentricity type and level
n	min^{-1}	Revolutions per minute
p	-	Number of pole-pairs
Q_r	-	Number of induction machine rotor bars
s	-	Per unit slip (for induction machines)
t	s	Time
Δp	N/m^2	Surface force density
μ	H/m	Magnetic permeability
ξ	rad	Angular position along stator bore

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Abbreviations

1X	Rotor rotational frequency (mechanical)
2L	Twice line (supplying) frequency
2X	Double rotor rotational frequency
e-NVH	electromagnetically-excited Noise, Vibration and Harshness
UMP	Unbalanced Magnetic Pull

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Introduction

Noise and vibration are a common, although usually unwanted, manifestation of the operation of machinery or units. They arise as a result of production tolerances and imperfections, or defects, poor assembly or setting up of machines on a supporting base. Increased vibrations and noise are also a manifestation of various device faults. Their monitoring and subsequent analysis can therefore be used in technical diagnostics. Noise and vibrations very often arise from the essence of the very principle of the machines' operation, accompanying physical events or as a direct consequence of their primary function, or the chosen production technology.

In electric rotating machines, the variable electromagnetic field is a source of magnetic forces, which, in addition to the desired torque, excites the vibrations of the stator stack. Vibrations are then transmitted to the frame or to other structural parts of the machine or drive, from where they are emitted into the surrounding environment in the form of noise (radiation of acoustic energy). This principle is shown schematically in Fig. 0.1, where a whole series of energy transformations can be traced.

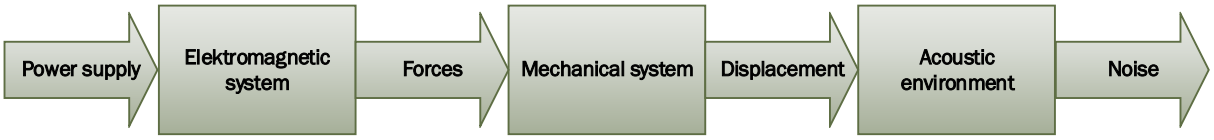


Fig. 0.1: Electric energy to acoustic energy conversion in electrical machines. [1]

The machine is powered by electrical energy, which is converted (among other things) into magnetic forces in the machine's electromagnetic system consisting of a winding and a magnetic circuit. The action of these forces can be divided into three directions in the cylindrical coordinate system – tangential, radial and axial. Tangential forces mainly create torque, but they also cause bending stress on the stator teeth, which, together with radial and axial forces, cause vibrations of the machine's stator (mechanical) system. Stator system consists of the stator stack (lamination), winding including insulation system, the frame of the machine and possibly also structural parts that serve to fix the stator package in the frame (columns, etc.). Vibrations cause deformation of individual structural parts, while structural parts surrounded by an air environment are a source of acoustic energy emission, i.e. noise.

The origin and action of magnetic forces, their contribution to the generation of noise and vibrations as well as other causes and principles of the generation of electromagnetically excited noise and vibrations (*e-NVH - electromagnetically-excited Noise, Vibration and Harshness*) in electrical machines are described in more detail in the following sections of the text.

There are many reasons to consider noise and vibration already in the design of electrical machines. The most important ones are described below:

- **High power / torque density** currently required in electromobility especially, is associated with a higher saturation of the magnetic circuit of the machines and thus a higher excitation of vibrations from the magnetic forces in the machine.
- **Material savings lead to less robust constructions** which often result in lower stiffness of structural parts and can therefore more easily induce vibrations.
- **Robust design** to ensure a long service life and fault-free operation of an electrical machine is not only related to dimensioning in terms of the electromagnetic utilization of the machine or thermal-ventilation calculation. Equally important is the dimensioning of the structural parts of the machine with regard to their mechanical stress, whether in terms of the torque transmitted along the shaft, the bearing load capacity or the structure's ability to withstand vibrations.
- **Health and environmental aspects** are relevant regarding the exposure of people or animals to noise and vibrations. Hygienic limits are established in this area, which set the maximum permitted levels of noise and vibration for different environments and times of the day or night.
- **Comfort** of passengers in vehicles or personnel operating machinery with an electric drive is related to vibrations, which should not be transmitted to the interior of the vehicle, and especially to the overall acoustic performance of the drive, which should not be disruptive. In this case, it is more about the composition (spectrum) of the noise than its absolute level and its perception by the human ear (psychoacoustic measures).

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1 Overview of noise and vibration sources in electrical machines

Sources of noise and vibration in rotating electrical machines can be divided according to their location into internal and external. That is, whether the vibrations are excited directly inside the machine or originate in other parts of the assembly (drive) or in the surrounding environment. From the point of view of the cause of noise and vibrations, it is possible to further divide them into electromagnetic, mechanical, aerodynamic and electronic sources (see Fig. 1.1). Some of them occur naturally in the machine and either can be suppressed or at least mitigated by various design measures (e.g. slot skewing) or their occurrence must be accepted. Other sources of vibration and noise are faults arising during machine operation. Some faults, e.g. unbalanced magnetic pull (UMP), may have an electromagnetic cause, but as a result, other mechanical faults may arise (e.g. shaft deflection) and vice versa. [2]

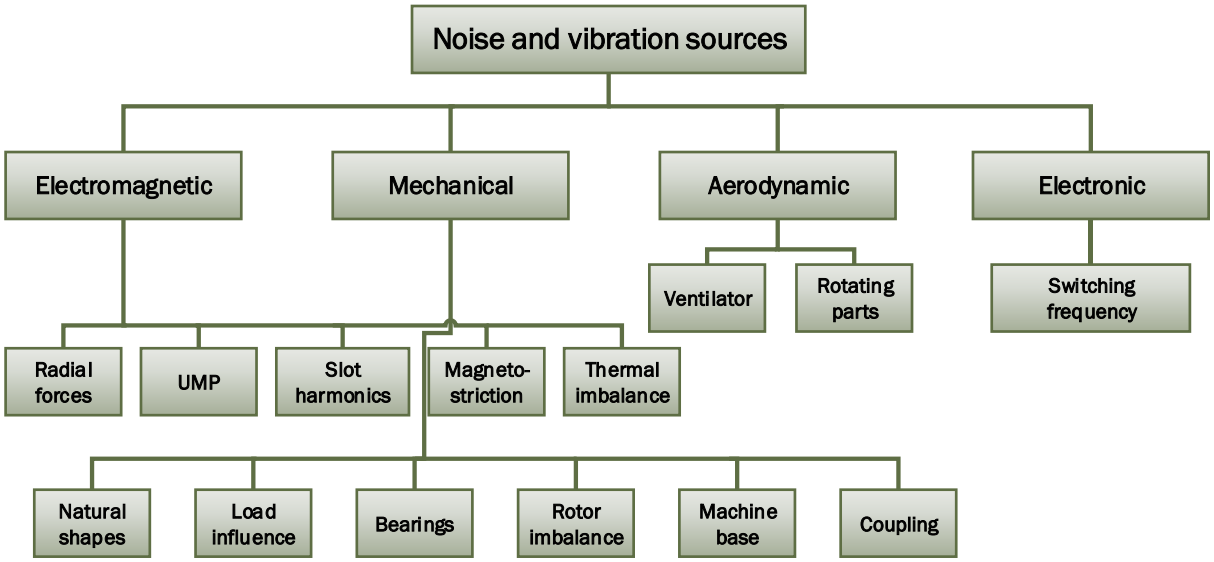


Fig. 1.1: Noise and vibration sources in electrical machines. [2]

Regarding the method of noise propagation, a distinction is then made between noise transmitted by air (*airborne noise*) and noise transmitted by structures (*structure-borne noise*) as shown in Fig. 1.2). Airborne noise can be characterized as the movement of large amounts of air using considerable pressure. Its source can be, for example, air flowing around the fan blades on the machine shaft or large oscillating surfaces (e.g. the machine frame). Structure-borne noise is

transmitted through solid bodies in the form of vibrations and can subsequently be radiated into surroundings as an airborne noise.

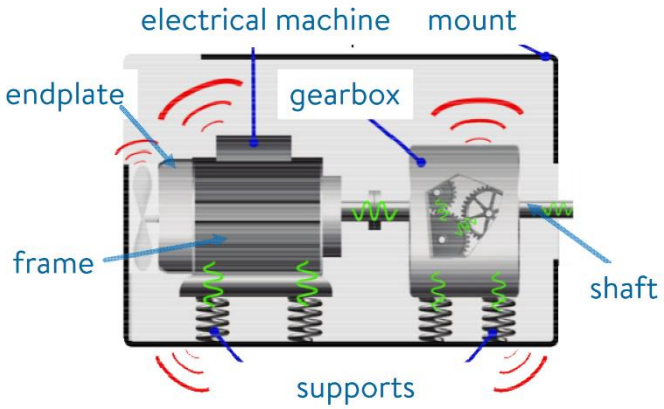


Fig. 1.2: Noise transfer paths in electrical machines – airborne noise (in red), structure-borne noise (in green). Source: EOMYS Engineering

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2 Electromagnetic sources of noise and vibration

2.1 Radial magnetic forces

Noise and vibrations excited by magnetic forces belong to the internally excited ones. The value of the magnetic forces acting on the stator and rotor of the machine is derived from the square of air gap flux density waveform in the machine. The radial component of flux density has the most significant effect on the value of vibrations, or forces. However, certain vibrations are also excited by the tangential component, which at the same time causes bending stress on the teeth, and possibly also by the axial force component, which arises in machines with skewed stator or rotor slots or skewed permanent magnets on the rotor. Assuming that the magnetic circuit of the machine is made of ideal iron, the surface force density in the radial direction can be simply calculated as [3], [4]

$$\Delta p(\xi,t) = \frac{B^2(\xi,t)}{2\mu_0}, \qquad (1)$$

where $B(\xi,t)$ is magnetic flux density in a specific time instant t and a specific angular position along stator bore ξ and $\Delta p(\xi,t)$ is corresponding surface force density (or a specific magnetic pull).

Magnetic forces act at the interface of materials with different permeability – in the case of electrical machines, it is the interface between ferromagnetic material (electrical steel sheets) and air. The action of the forces is in the direction of the material with lower permeability, i.e. into the air, and the result is an attractive force between the stator and the rotor.

The force action is concentrated almost exclusively on the tooth tip surface normal to the air gap – so the radial direction prevails. The force acting on the tooth surface adjacent to the slot is negligible. This is due to the significantly higher flux density magnitude in the air gap compared to the flux density inside slots. The above mentioned can be seen from Fig. 2.1, where surface force density vector distribution on the stator tooth of an induction machine is depicted. The total force acting on the individual teeth of the stator and rotor of the same machine at a specific time instant can be seen in Fig. 2.2. The figures come from a finite element analysis of an 11 kW induction machine.

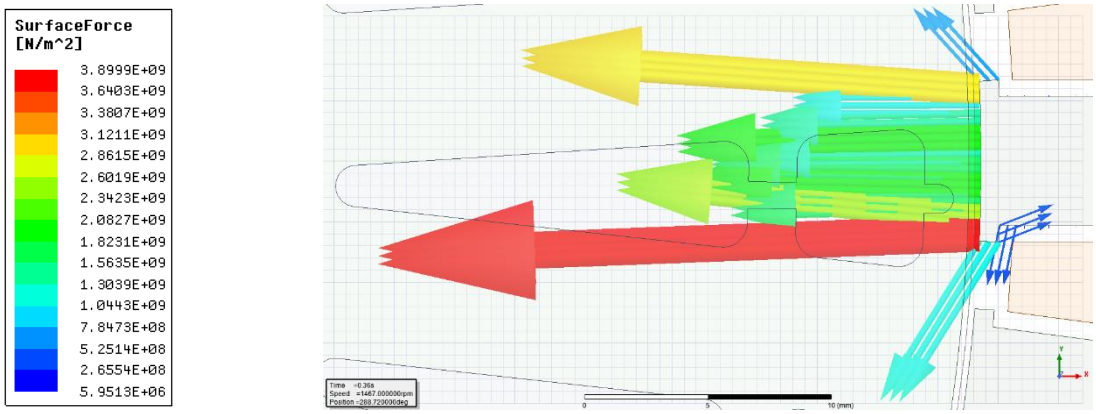


Fig. 2.1: Surface force density vectors acting on a single stator tooth.

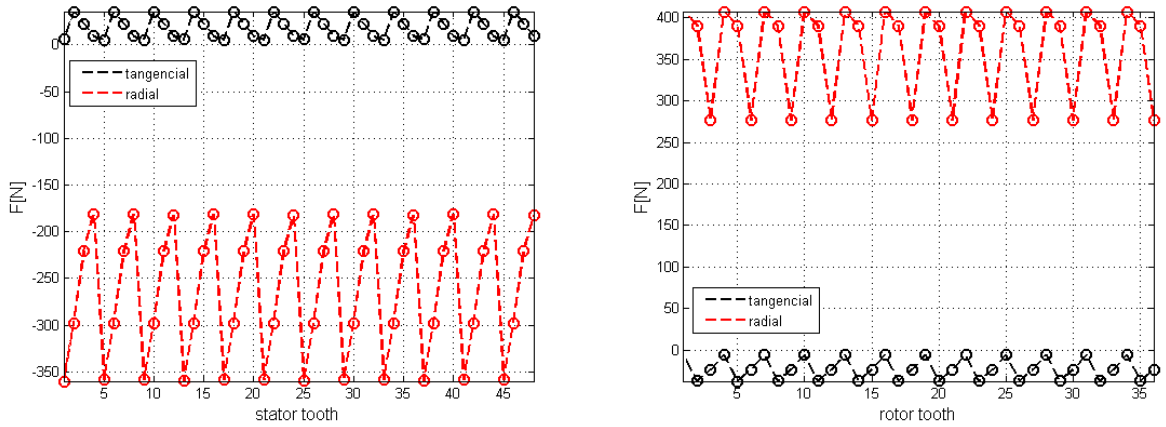


Fig. 2.2: Radial and tangential force values acting on stator (in the left) and rotor (in the right) teeth.

The magnitude of the forces acting on the stator teeth changes in time and space together with the air gap flux density according to (1) and it is these time-varying forces that excite the vibrations of the teeth, which are further transmitted through the yoke to the machine frame.

The frequency of the vibrations fundamental caused by magnetic forces is due to the square of the flux density in (1) at twice the frequency of the supply voltage / current (*twice line frequency*) and is denoted as *2L*. In the case of a sinusoidal waveform of the magnetizing current, and thus of the air gap magnetic flux density, the resulting force in each flux density period has two maxima - in the positive and negative half-wave. This means that the vibrations excited by this force oscillate at a frequency equal to twice the frequency of the supply voltage. This fact is clearly visible in Fig. 2.4.

Therefore, a certain level of vibration at this frequency naturally occurs also in machines in a perfect technical condition, and the vibration rise at this frequency is typical for some faults causing asymmetry of the magnetic circuit (e.g. static eccentricity or inter-turn short circuit of the winding).

Magnetic forces at *2L* (see below) also act on the stator end-windings. For this reason it is necessary to bind end-windings well and, in the case of larger machines, support and fasten them using a combination of binding ring and winding supports in order to prevent end-winding vibrations as much as possible. End-winding vibrations, especially in the case of bar coils, cause abrasion of the bar insulation at the slot end (manifested by white dust) and in extreme cases the insulation may fail (see Fig. 2.3).

Performing vibration diagnostics of two-pole synchronous and induction machines, attention must be paid to compliance, or proximity (in the case of IM), in frequencies *2L* and the second harmonic from the rotor rotational frequency *2X*.



Fig. 2.3: White powder coming from insulation abraded from end-windings due to vibration and friction (in the left); winding insulation failure due to end-winding vibrations (in the right) [5]

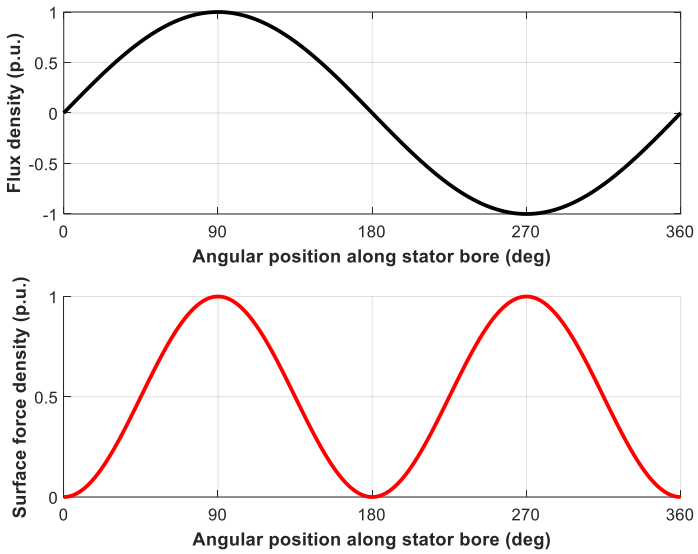


Fig. 2.4: Single period of magnetic flux density and radial force density waveforms (two-pole machine, slotting neglected)

2.2 Unbalanced magnetic pull (UMP)

If the machine is symmetrical from an electromagnetic point of view, the magnetic forces acting around the machine circumference are in balance and the rotor is not additionally stressed. However, in case of magnetic field asymmetry, unbalanced magnetic pull (UMP) is created. UMP acts in the direction of the resultant force and causes additional stress on the rotor and bearings. This can lead to premature bearing wear, shaft deflection and, in extreme cases, to a collision between the rotor and the stator.

The aforementioned asymmetry can be caused, for example, by the geometrical asymmetry of the magnetic circuit (eccentrically placed rotor, elliptical stator or rotor, shaft deflection, uneven distribution of slots along the stator circumference, etc.), winding asymmetry (e.g. different number of turns, inter-turn short circuit or broken rotor bar of IM) or asymmetry of the power supply. The unbalanced magnetic pull can be static or dynamic, depending on whether it always acts in the same direction or changes its direction over time (depending on the rotation of the shaft). This is explained below using the example of static and dynamic eccentricity (see Fig. 2.5).

In the case of eccentricity, the air gap length is not uniform around the entire circumference of the machine. The air gap is more saturated in the spots where the air gap is smaller, and thus a larger magnetic force also arises in this direction, which causes unbalanced magnetic pull.

Eccentricity can be static (SE), dynamic (DE) or mixed. While in the case of static eccentricity, the position of the smallest air gap length is constant in time and the UMP magnitude and direction can be considered constant, at least in the first approximation, in the case of dynamic eccentricity, UMP direction change over time together with the smallest air gap length position.

Static eccentricity can be represented as a rigid shaft mounted into the stator with a slight offset from the stator axis. The rotor thus rotates around its own axis, which, however, is not identical to the axis of the stator. This condition can cause deflection of the shaft (especially in machines with longer shaft) which should, however, still have the same position.

On the other hand, dynamic eccentricity is mostly caused by the deflection of the rotor already in production or caused by the thermal imbalance of the rotor. In that case, the direction of unbalanced magnetic pull changes together with the revolving rotor and causes vibrations of the shaft as well as the stator of the machine at multiples of the mechanical rotation frequency of the rotor *1X* according to (2).

For induction machines, in the case of DE, sidebands shifted of the pole passing frequency (3) can be formed around the rotational frequency and twice line frequency. In (3), f_s is slip frequency of the machine [6].

$$f_{1X} = \frac{n}{60} \tag{2}$$

$$f_p = 2pf_s \tag{3}$$

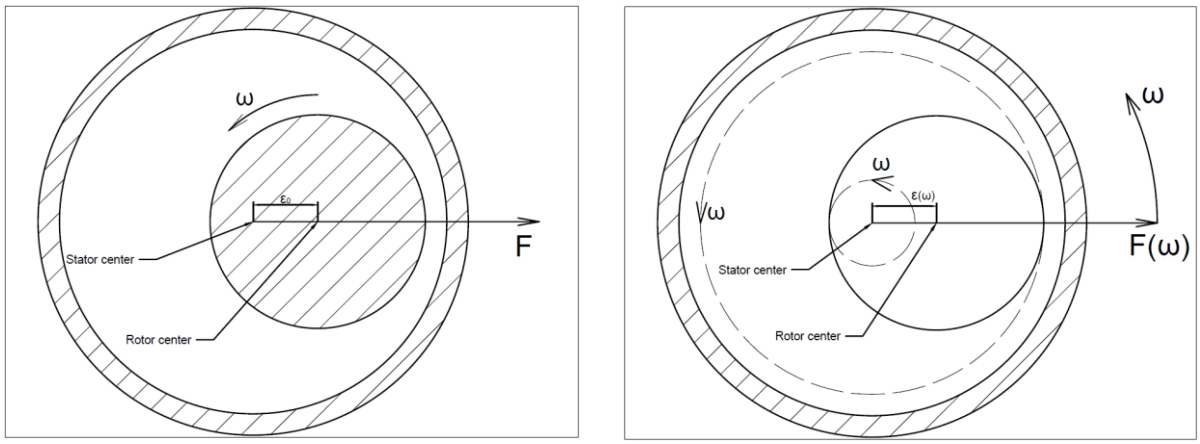


Fig. 2.5: Schematic representation of static (in the left) and dynamic eccentricity (in the right).

Machines with eccentricity can also exhibit high-frequency noise and vibration, the frequencies of which are determined by harmonics of the stator MMF and rotor slotting. According to [7], frequencies of eccentricity related vibration (f_{ecc}) are given by

$$f_{ecc} = \left[\left(cQ_r \pm k_e \right) \frac{1-s}{p} \pm e \right] f_L , \tag{4}$$

where c is any integer, k_e is zero for SE and low integer for DE, s is per unit slip and e is zero or even integer.

2.3 Slot harmonics

Noise and vibrations induced by magnetic forces at higher frequencies are caused by the slotting of the stator and rotor, for that reason they are called slot harmonics or rotor bar passing frequencies. The frequency of the slot harmonics of the rotor is given by equation (5), where n is the number of revolutions per minute of the rotor and Q_r is the number of slots or bars of the rotor. Vibrations from slot harmonics of the rotor are caused by the leakage magnetic field around individual bars. The field is generated by the current induced in the bars and the forces induced by it act on the stator teeth. It can be deduced from (5) that the frequency of slot harmonics is often above 1 kHz and is therefore out of range of standard vibration diagnostic tests. Vibrations induced by slot harmonics are the main source of high-frequency noise in the induction machines, but they do not cause structural changes [6].

$$f_{Qr} = \frac{nQ_r}{60} , \tag{5}$$

Around the rotor bar passing frequency can occur sidebands shifted of $+$ or $-$ $f_{2L}, f_{4L}, f_{6L}, \ldots$.

2.4 Magnetostriction

Magnetostriction is a phenomenon where ferromagnetic materials change their shape or dimensions when magnetized. From a microscopic point of view, during magnetization, the initially randomly oriented magnetic domains of the material align in the direction of the applied magnetic field. During this alignment, the walls between the magnetic domains move, which, together with the alignment of the domains itself, causes a macroscopic change in the shape and dimensions of the material in the order of μm.

During AC magnetization, there is a periodic change in the orientation of the applied field and thus also periodic changes in the dimensions of the magnetic material. These periodic dimensional changes cause **noise and vibrations at *2L* frequency** and its odd harmonics. In rotating machines, magnetostriction is usually not a significant source of noise, or it is masked by other noise sources. On the other hand, in transformers, magnetostriction is the dominant source of noise – it is manifested by a characteristic low-frequency "hum" that increases with the core saturation. Besides core saturation, significant influence on the magnetostrictive noise of the transformer has a lamination pressing force.

2.5 Thermal imbalance

Thermal imbalance is caused by uneven heating of the rotor or more precisely by deflection of the rotor due to uneven heating. Thermal imbalance causes, like other types of imbalance, increased **vibration at rotor rotational frequency *1X***. However, in contrast to the unbalance of rotating masses, thermal unbalance does not manifest itself with a cold rotor and the vibrations gradually increase with the rotor temperature. The cause of the thermal imbalance can be, for example, short-circuited rotor lamination or different conductivity of the squirrel cage rotor bars (some of the bars are cast from another batch).

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Conclusions

The study text provides an overview of sources of noise and vibration in electrical machines and focuses more closely on electromagnetically induced noise and vibration. Other sources of noise, i.e. mechanical, aerodynamic and electronic, are not described in detail in the text and will be briefly addressed during the lecture.

The text is not intended as a full-fledged replacement for the lecture, it is rather a supplement and extension to the lecture slides.

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