ORIGINAL SCIENTIFIC PAPER OPEN ACCESS

A Study on the Vibrations of the Induction Motors Having Squirrel Cage Rotor

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ARTICLE INFO

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DOI: 10.5937/engtoday2300002P

UDC: 621(497.11) **ISSN:** 2812-9474

Article history: Received 9 February 2023; Accepted 1 March 2023

ABSTRACT

In the present paper are examined the vibrations of the induction motors having squirrel cage rotor. The study is performed by means of spectrograms presenting the vibration speed depending on the frequency, drawn up for motors produced by S.C.Electroprecizia Electrical Motors Sacele and on the base of the study of the specialty literature. There have been studied the motors of 3000, 1500,1000 RPM up to 7,5 kW and are proposed measures to reduce their vibration level. Among the possible solutions proposed are using of a waved spring washer between the end shield and the bearing's external ring, the inclination in V or zigzag of the cage's bars at a half of the rotor pitch and reducing the stator field harmonics.

KEYWORDS

Vibrations, Electrical motors, Mechanical vibrations, Magnetic vibrations, Vibrations attenuating, Vibrations dumping

1. INTRODUCTION

Vibrations are an important issue in mechanical and electric domain. When it comes to electrical motors, they have an increased importance, because their presence and magnitude directly influence the behavior of systems they are integrated in. This is why the vibrations of the electrical motors are widely studied. Since the vibrations are a natural phenomenon, they can hardly be eliminated, that is why the most scientific researches focus on the ways and means to attenuate them. Some clear directions the researches target can be identified. One of it is detecting the vibrations. Some outstanding studies can be mentioned here. In [1] is presented a method to be used by the maintenance engineers to detect the faults caused by the vibrations of the induction electrical motors. The paper [2] approaches the using of the difference between the normal noise/vibration and the actual ones to detect faults in working of the electrical motors. A second main research direction approached by researchers is the analysis of electrical motors vibration, for different purposes. In [3,4] the authors emphasize the influence of the non-uniform heating of the winding of the motor on the occurrence of the vibrations. Discrete Wavelet Transform is used in [4] to analyse of the signal/vibrations produced mainly by the bearings of the electrical machines. The diagnosing of electrical motors faults is another domain that captured the attention of the scientists. The works [5, 7] deal with subjects in this area. Different means are used to diagnose the malfunctions of the induction electrical motors: comparing the work of a healthy and faulty motors, the synchronization between two interconnected motors, and sensorless measuring the vibrations, respectively.

Concluding the brief overview of the literature, one may state that detecting, analysing, and diagnose are some main themes of research in relation with the wide domain of vibrations occurred at electrical motors.

Apart from those stated above, the present paper refers to a study performed at an outstanding producer of electrical motors, Electroprecizia Electrical Motors Sacele, Romania. The study targets the induction motors having squirrel cage rotor, of small output, up to 7,5 kW in TEFC construction, and aims to identify ways and means to increase the quality of the products. Motors of 3000, 1500, 1000 RPM are studied. These motors being widely utilized, their vibration level is considered as very important and is usually displayed in the catalogues of the producers among the electric and mechanic characteristics. The vibration level is regulated by the European norm IEC 50034-14 [8]. The study aims to reduce the vibrations of the electrical motors by their construction, not to attenuate the effect of the vibrations by means of dumpers. The novelty of the research consists in using spectrograms to study the vibrations.

2. THE STUDY OF THE CAUSES OF VIBRATIONS AT THE INDUCTION MOTORS HAVING SQUIRREL CAGE ROTOR

Among the sources that cause the electrical motors to vibrate, one can mention:

- electrical unbalancing;
- mechanical unbalancing of the rotor and coupling mean;
- results of a lot of mechanical issues like clearances, frictions, bearings and other;
- results of external influences like foundation, poor aligning of some subsystems;
- resonance, critical speed.

2.1. The vibrations of mechanical origin.

The three-phase induction motor samples produced by S.C. Electroprecizia Electrical Motors Sacele were equipped with SKF bearings with C3 clearance. From the previous measurements can be noticed that the vibration level increases with the frame sizes, outputs, and rotational speeds. The vibration and noise level is influenced by the following factors:

- the utilized bearing type (with normal or increased clearance C3);
- the machining tolerance of the adjacent parts tp the bearings (end shield and shaft);
- the mounting technology applied for the bearings;
- the construction type of the motor housing and end shields (aluminum, cast iron), namely the mass and rigidity of these parts;
- the unbalancing of the rotating parts.

The sources of the mechanical unbalancing are non-homogeneousness of the material constituting the rotating part, construction, machining and mounting flaws. Causes of the non-homogeneousness can be bubbles and porosity in the cast parts, non-uniform density of the material in different places and others. Among the construction flaws producing a displacement of the center of gravity from the axis of rotation, one can mention the asymmetric distribution of the masses and orifices, non-uniform thickness of the walls of hollow parts, the existence of non-machined external, internal or side surface portions, wrong design of machining tolerances or fitting tolerances of the assembled parts, causing radial or axial runouts, the rotation speed close to the critical speed, the perturbation of the distribution symmetry of the masses due to the keys a.s.o. The unbalancing may also be caused by non-respecting the machining tolerances, the deformations of the machined parts due to internal stresses of thermal origin [9]. Very important is the flexure of the shaft and radial runout of the spindles.

Among the mounting flaws can be enumerated the radial runout caused by the internal non-uniformity of the bearings, the asymmetric distribution of the masses due to the mounting by screws of the combined rotating parts, the radial runout caused by the keyed assemblies, the bending of the shaft caused by the non-coaxiality in the case of rigid mounting, deformations of the parts due to uneven heating or cooling in the case of warm pressing. The rotating parts unbalancing can occur due to the deformations caused by the non-uniformity of the thermal fields and by the differences between the thermal dilatation coefficient of the materials composing the complex assembling. The unbalancing can also be produced by the displacement (for example of the windings by electrical machines under the action of centrifugal forces), by the non-uniform corrosion and by the wearing of the parts under the action of external factors. The displacement of the center of gravity from the rotation axis causes centrifugal forces of unbalancing origin.

2.2. The vibrations of magnetic origin

In the air gap of the induction motor besides the main magnetic field, producing the torque on the shaft, a lot of superior harmonic fields appear. These fields have a parasitical character, and substantially worsen the motor's characteristics, because they cause supplementary losses, noticeable as worsening of the starting torque and by radial forces.

The main sources of the superior harmonics of the magnetic fields in induction motors are the distributed windings in the slots, the presence of slots by both parts of the magnetic circuit, the saturation of the magnetic core and different admitted or accidental asymmetries occurred in the fabrication process (eccentricity of the rotor from the stator). The vibrations and noise of magnetic origin of the induction motors is mainly an effect of the interaction between the superior harmonics of the stator's magnetic field and those of the rotor's ones. Caused by these interactions (tangential, radial, and even axial), magnetic forces appear, acting on the laminations, on the housing, and on the rotor, producing their oscillation. In the case of the motors the magnetostriction phenomenon can be neglected.

Among the radial forces, the strongest are those of unilateral magnetic attraction of the first order, labeled with P in Figure 1, which appear due to the interaction between certain harmonics in the stator and others in the rotor, when their order differs by one unit (r=1). These forces are a very strong source of vibration and noise. The noticed most important noises and vibrations must be attributed to these rotating unilateral magnetic attraction forces, which are rotating.

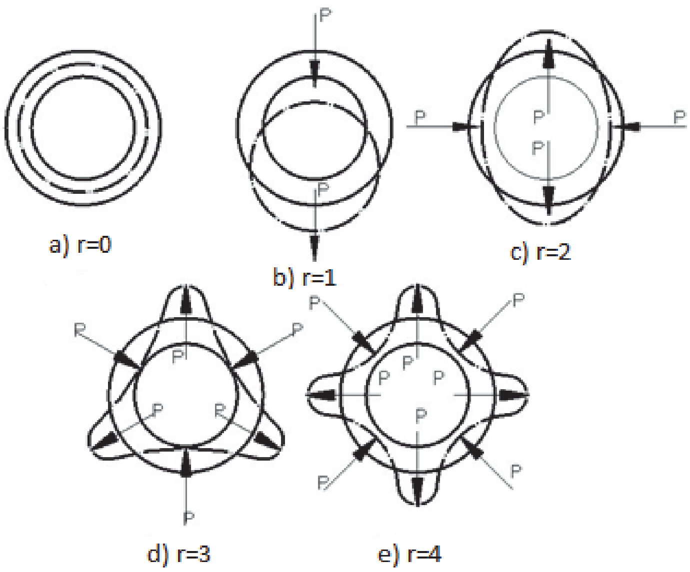

Figure 1: The oscillation orders of the stator (spatial distribution of the forces).

When r =1, 2, 3, 4 the deformations appear in the stator [10,11]. The distribution is presented in Figure 1 c, d, e. When the orders of the interacting harmonics differ by 2 units, unilateral magnetic attraction forces of order 2 will result, but these have a very low intensity, and so on. The higher is the order, the smaller are the vibrations. The stator's rigidity depends on its geometrical dimensions and also on the order of the deformation. (proportional with r ≥2). Therefore, for the producing of magnetic noise and vibration, mainly the magnetic forces of low order are important, because for these the amplitudes of the dynamic deformation become maximal. For small induction motors, the order is considered as being low, when r ≤ 4.

To producing magnetic noise and vibration, the resonance phenomena contribute considerably. When the frequency of the magnetic forces acting on the stator becomes close to the own frequency of the stator, the deformation amplitude will increase intensely [10,11].

3. ANALYZING THE VIBRATIONS BY MEANS OF SPECTROGRAMS

The study of vibrations of induction motors having squirrel cage rotor have been performed by means of the spectrograms. The diagrams of vibration speed [mm/s] depending on the frequency, have been drawn up. The subject of the study were three motor types produced by S.C.Electroprecizia Electrical Motors, Sacele: frame size 71 : 0,37 kW-1500 RPM, frame size 71 : 0,37 kW-3000 RPM, and frame size 80 : 0,55 kW-1000 RPM. For each motor are drawn up 5 spectrograms in the accessible points foreseen in IEC 6003414 [8]. In Figure 2 are displayed the pointsX1, Y1, Z1. The points X2, Y2, and Z2 are symmetrically placed at the other end of the motor. The measurements have been done in the accessible points X1, Y1, Z1, X2, Y2.

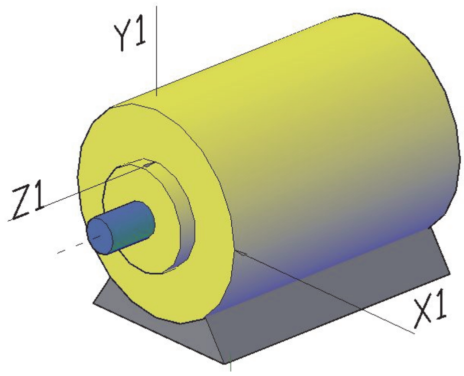

Figure 2: The measuring points to collect data for the spectrograms

The block diagram of the measuring setup is shown in Figure 3, where have been noted:

M - the motor;
VTR – the vibrations transducer;
FA – the frequencies analyzer (Bruer & Kjaer type 2112 [12]);
R – the recorder (Bruer & Kjaer type 2305 [13]).

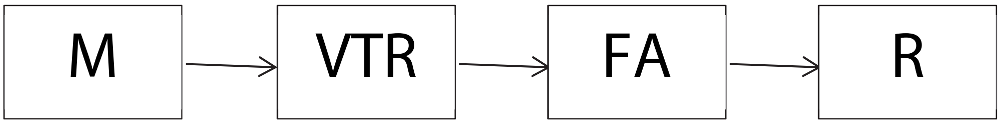

Figure 3: The setup pf the measurement

In Figure 4is presented a sample of a spectrogram. The placement of the measuring points are displayed in it, and it is labeled the point to which corresponds the spectrogram. Some peaks can be observed on the graph.

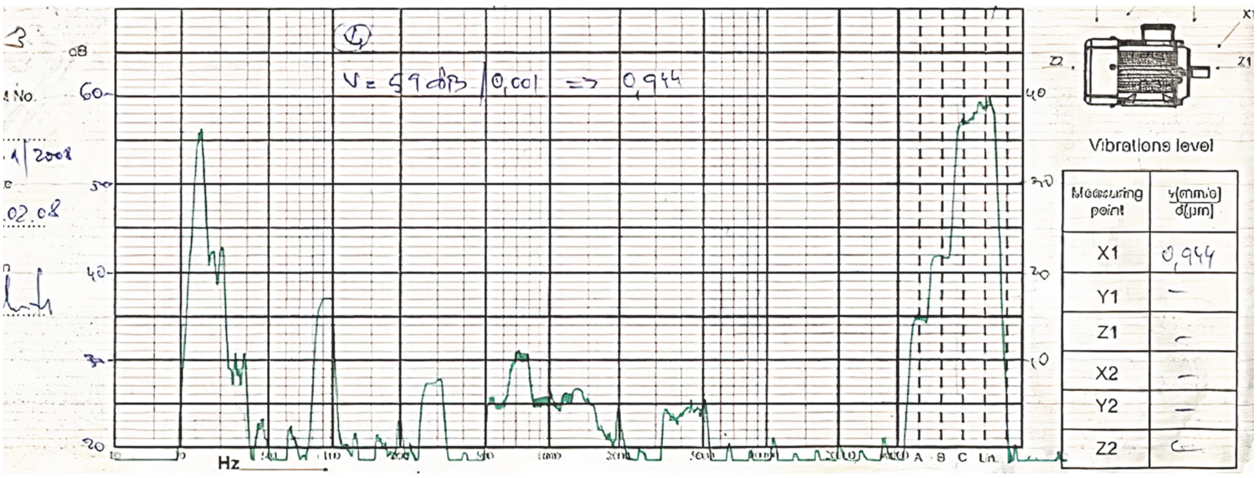

Figure 4: The spectrogram in measuring point X! for the motor 0.37kW-1500 RPM

The global values of the vibration, resulting from the spectrograms, are synthesized in Table 1

Table 1: The vibration speed for different motors

Measuring point	The vibration speed [mm/s]		
	0.37kW-3000 RPM	0.37kW-1500 RPM	0.55kW-1000 RPM
X1	1.99	0.944	0.398
Y1	1.99	0.168	0.562
Z1	0.45	0.562	0.126
X2	0.25	1.00	0.299
Y2	0.473	0.106	0.200

It can be noticed that the values are generally higher for the 3000 RPM motor, followed by the 1500 RPM and the 1000 RPM motor. Though the diagrams include frequencies up to 40000 Hz, it can be noticed that the vibration peaks appear only up to 5000 Hz. By all these motor types the most noticeable vibration peaks appear below 100 Hz, but there are some peaks also at higher frequencies. For example, by the 1000 RPM motor, there is a noticeable peak at 700 Hz. The maximum allowed vibration level according to IEC 60034-14 [8] is 1,6 mm/s. At the motor 0.37kW-3000 RPM, after a careful balancing of the rotor, the values of the speed vibrations measured in the points X1 and Y1, which initially displayed overcoming values of 1.99 mm/s decreased as low as 0.85 mm/s, and 0.9 mm/s, respectively

4. METHODS FOR REDUCING THE VIBRATIONS

Obviously, the vibrations affect negatively the working of the electric motor itself, as an ensemble, and of its components. That is why their intensity must be decreased to the lowest level possible. Usually, this is done by using dampers, in fact, the best way to solve the problem is not to attenuate the effect of the vibrations, but to reduce them by the conception and construction of the motor (eliminating them completely is, unfortunately, almost impossible)

4.1. Reducing the vibrations of mechanical origin

The elimination of the oscillations produced by the action of centrifugal forces of unbalancing origin is realized by balancing the rotor [13], that is by improving the distribution of the masses of the rotating part by increasing or partially diminishing the mass in certain places. In order to evaluate the balancing degree, the notion of specific unbalancing is utilized. This is the ratio between the value of the unbalancing and 1 kg from the rotor's mass.

The squirrel cage rotors of induction motors are balanced on special balancing equipment (Electroprecizia Electrical Motors utilizes equipment produced by the company Schenck Austria [14]).

The main method to reduce the vibrations is the balancing of the rotor, but also the utilization of bearings of high quality, correctly mounted in accurately machined end shields. The strengthening of the end shield's wall by means of strengthening internal ribs also contributes to the reducing of the vibrations. A device and method to balance rotating parts is presented in literature [15].

4.2. Reducing the vibrations of magnetic origin

The reducing of the field's harmonics has an important role in the reducing of the vibrations of magnetic origin and is realized by the following methods [16, 20]:

- choosing the appropriate slot numbers for the stator and rotor;
- sinusoidal winding for the stator;
- inclination of the slots, usually by the rotor;
- increasing the air gap.

The ratio of the stator and rotor slots has an essential influence on the radial forces and implicitly on the vibrations and noises. The choice of the number of slots must have in view many criteria. A small number of slots is optimal from the point of view of the cost of insulating materials, assuring concomitantly a good filling factor. The choice of a big number of slots is preferable for to realize a magnetic field close to the sinusoidal form.

By small machines, up to 250 mm diameter it is dangerous to choose slot numbers satisfying the relations below [11,17, 20]:

$$\left|Z_1 - Z_2\right| = 0,1,2 \tag{1}$$

$$\left|Z_1 - Z_2\right| = p,\ p \pm 1 \tag{2}$$

$$\left|Z_1 - Z_2\right| = 2p, 2p \pm 1, 2p \pm 1 \tag{3}$$

$$\left|Z_1 - Z_2\right| = 3p, 3\,p \pm 1 \tag{4}$$

In order to meet the request for a machine with normal functioning, without vibrations and noise, it must not appear a resonance between the frequencies of the radial magnetic forces for a slip s=0 and the fundamental frequency of the stator, according to the equations [11, 17, 20]:

$$f_0 = \frac{8.4 \times 10^4}{R_a} \sqrt{\frac{q_j}{q_j + q_z}} \tag{5}$$

$$f_r = f_0 \frac{h\, r\left(r^2 - 1\right)}{2\sqrt{3} R_a \sqrt{\left(r^2 - 1\right)}} \tag{6}$$

where:

- f_0 – the frequency of the radial force [Hz];
- R_a – the mean radius of the stator yoke [mm];
- q_j – the mass of the stator yoke [kg];
- q_z – the mass of the teeth [kg];
- f_r – the resonance frequency of the stator [Hz];
- h – the height of the stator yoke [mm];
- r – the order of the radial force.

Considering all relations must be avoided, resulted the optimal recommended slot numbers for induction machines.

As it is known, the magnetic forces producing vibrations, can be reduced when the superior harmonics of the magnetic intensity are eliminated and with this scope windings with shortened pitch can be utilized, or the rotor slots are inclined from the cylindrical surface's generatrix line. By an appropriate inclination, different harmonics can be eliminated, like also by shortening the winding pitch.

The magnetic induction in the air gap [17] has superior harmonics, both caused by the repartition of the winding in the slots, causing a non-sinusoidal curve of the magnetic intensity and magnetic induction, and also due to the air gap's non uniformity resulting from successive presence of the teeth and slot openings in the magnetic field.

The slotting harmonics of the magnetic induction, caused by the open slots can be direct $k^*(Z_{1,2}/p+1)$ order or inverse of $k^*(Z_{1,2}/p-1)$ order. The direct harmonics are dangerous, because they produce an important diminishing of the motor's pull-up torque. Because the amplitude of the slotting harmonics of superior order $(k > 1)$ decreases a lot, they can be neglected in comparison with the fundamental slotting harmonics z12/p±1, whose importance is very high, because for q integer, they have a winding factor equal with that of the fundamental of the magnetic induction.

The harmonics produced by the discontinuous distribution of the winding, named teething harmonics, have the same order like those of slotting, the first ones existing independently from the slot's form, while the teething harmonics exist only if the slots are not closed. The slotting harmonics can be much more important than the teething harmonics, which at their high order, present relatively small amplitudes. While the teething harmonics depend on the current in the winding, the slotting harmonics don't depend on the current, having the same value for no-load functioning or loaded functioning.

It was proved both theoretically and practically that can be obtained important decreases of the induced voltage's harmonics, by an inclination of the rotor slots. While the inclination of the slots is an efficient method for decreasing of the slotting harmonics, it leads to an increase of the saturation by a non-uniform axial distribution of the induction, this non uniformity being introduced in the air gap. The disadvantages of the slot inclination consist from an increasing of the stray resistance and reactance, decreasing of the power factor, of the starting torque and of the break-down torque. By some motor types, is noticed an increasing of the starting torque due to the slot inclination, which can be explained by the existence of parasitic torques, which are eliminated by the slot inclination. Other disadvantages are the appearing of axial forces in the bearings and of some transversal currents between the rotor bars of the cage.

The reduction or elimination of the axial forces is realized by the following measures:

- utilization of a waved spring washer between the end shield and the bearing's external ring;
- inclination in V or zigzag of the cage's bars at half of the rotor pitch, in this case being foreseen a central aluminum ring. This method is only rarely utilized due to technological difficulty. It was proved the double favorable action of the inclination to the vibration and electromagnetic noise;
- reduction of the stator field harmonics;
- influences the value of the force waves corresponding to the rotor's field harmonics.

5. CONCLUSIONS

In this paper, an analysis of the vibrations of three-phase induction motors with a squirrel cage rotor is made. This analysis conducts to methods that must be conceived, executed, and checked these motors in order to reduce the vibrations in the limits foreseen in the norm IEC 60034-14.

The analysis was made by the study of spectrograms (vibration speed depending on the frequency) drawn up at S.C. Electroprecizia Electrical Motors Sacele. On the basis of these spectrograms, it was possible to deduct that the vibrations are produced by the simultaneous action of the mechanical and magnetic components. While the noise level is influenced also by an aerodynamic component, the vibrations are not influenced by the aerodynamic component, because the utilized fan being made from plastic material, has a non significant weight in comparison with the rotor's weight. In some cases, aluminum fan is utilized but this is also very light.

From the performed tests resulted that the highest vibration level appears by the 3000 RPM motor, followed by that of 1500, and the lowest ones appear at 1000 RPM.

By the performed tests many methods resulted for the reduction of the vibration. The main method for the reduction of the vibration of mechanical origin is the balancing of the rotor, but also the utilization of high quality bearings, correctly mounted in accurately machined end shield. The modification of the end shield construction by provision of supplementary internal strengthening ribs is also very useful.

The vibration of magnetic origin can be reduced mainly by the following measures:

- appropriate choosing of the stator and rotor slot numbers;
- choosing of an appropriate winding pitch shortening;
- inclination of the rotor slots;
- increasing of the air gap width in order to reduce the influence of the eccentricity;
- utilization of sinusoidal winding.

ACKNOWLEDGEMENT

The present research was supported by the project "Creşterea Competitivității Electroprecizia Electrical Motors prin-dezvoltareaîn parteneriat cu Universitatea Transilvania - Braşov a uneinoifamilii de motoareelectrice, cu eficiențăenergetică de clasăsuperpremium (IE4)/121228/POC/163/1/3".

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