THE NOISE OF TWO-SPEED THREE-PHASE INDUCTION MOTORS WITH SQUIRREL CAGE ROTOR

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This paper presents a study of the noise in three-phase two-speed cage rotor, totally enclosed externally cooled induction motors. Investigations include two-speed three-phase induction motors with Dahlander winding connection or separate windings, with rated speeds of 3000/1500, 1500/750, 1500/1000 r.p.m. The investigated motors, manufactured by S.C. Electroprecizia S.A. were placed in a semi-anechoic chamber in order to determine the noise-to-frequency characteristics (spectrograms). This paper is based on the results and conclusions obtained after analyzing these noise spectrograms.

1. **INTRODUCTION**

Investigations have already demonstrated the harmful influence of noise on human health and its negative effects relative to product quality.

The study of the noise produced by two-speed asynchronous motors with squirrel-cage rotor constitutes the object of this paper, with a special focus on determining the main noise sources. The admitted noise level in electric motors (including two-speed motors) is prescribed by the European norm IEC 34-9 and, if lower than the admitted standard limit is declared in the catalogues or web-sites by the motor manufacturers along with other electrical and mechanical characteristics.

This paper is one of a series of other papers [7, 9, 10, 11, 12, 13, 14] in which the authors deal with the problem of electric motors noise.

2. **NOISE SOURCES IN ELECTRIC MACHINES**

Figure 1 presents the sources of noise in cage rotor two-speed three-phase induction motors. These are of several types: aerodynamic, mechanical, magnetic.

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Each of these sources [5, 7], determines a particular type of noise (of aerodynamic, mechanical, magnetic nature). The investigated motors, manufactured by S.C. Electroprecizia S.A. were mounted in a semi-anechoic chamber in order to determine the noise-to-frequency characteristics (spectrograms). Noise analysis of electrical machines is achieved by eliminating noise from several different sources, while trying to acquire the noise from a single source. Noise sources can be separated or eliminated by certain modifications made to the motor.

To eliminate a source, its level must be reduced by at least 10 dB below the global level, in any frequency band. By successive eliminations, the contribution of a specific source in a certain frequency band to the global machine noise can be determined. This can be done as follows:

a) *Motor is driven, fan removed.* The motor without fan is driven from outside the anechoic chamber by means of a driving belt by another motor. The measured noise is the ball-bearing noise L_{mec}.

b) *Motor is driven.* The motor complete with fan is driven from the outside of the anechoic chamber by means of a driving belt by another motor. The measured noise is composed of ball-bearing and aerodynamic (ventilation) noise $L_{mec}+L_V$. By comparing these results with those at a), the aerodynamic noise can be obtained.

c) *Motor is operated, fan removed.* The motor is at no-load, operated at its nominal voltage, the fan is removed. The noise spectrogram contains the magnetic and ball-bearing noise $L_{mag}+L_{mec}$. The magnetic noise results by comparison with the characteristic as indicated at a).

d) *Motor is operated at no-load.* The motor is supplied at its nominal voltage with no load applied to the shaft. The spectrogram will yield the total machine noise L_{tot}.

e) *Motor is at full-load, fan removed.* The motor is operated at its rated load, driving a generator by means of a driving belt. The influence of the load on magnetic and ball-bearing noise can be observed.

f) *Motor is at full-load.* The motor is operated at nominal load and is supplied at its nominal voltage. The influence of the load on the total machine noise can be observed.

The spectrograms were analyzed as follows: Given the mechanical noise level (resulting from test scheme “a”), the ventilation noise resulting from the test “b” can be calculated, considering the addition rule of the noise levels of different origins,

$$L_v + L_{mec} = 10 \times \log\left(10^{0.1 L_V} + 10^{0.1 L_{mec}}\right) \quad (1)$$

Analogously, the magnetic noise was calculated using the results of test “c”.

Test “d” was performed for checking purposes, its result being compared with the calculated value obtained with the formula:

$$L_{tot} = 10 \times \log\left(10^{0.1 L_V} + 10^{0.1 L_{mec}} + 10^{0.1 L_{mag}}\right) \quad (2)$$

Based of the analysis of 108 spectrograms, the following can be deduced:

– aerodynamic noise is dominant in two-speed 3 000/1 500 motors when operated at 3 000 r.p.m.; ball-bearings of inadequate type or incorrectly mounted may generate significant ball-bearing noise;

– magnetic and ball-bearing noise is significant in two-speed motors of 3 000/1 500, 1 500/750, 1 500/1 000 r.p.m, spinning at 1 500 r.p.m, while aerodynamic noise level is rather low.

– magnetic noise is dominant in two speed motors of 1 500/750 r.p.m., spinning at 750 r.p.m. and of 1 500/1 000, spinning at 1 000 r.p.m., but is accompanied by ball-bearing noise in certain cases. There is no aerodynamic noise.

The noise level is different for each speed of two-speed motors.

The tests “e” and “f”” have shown that when the motor is at load, the noise level increases with 5–10 dB.

As an example, for the two speed motor 1.1/0.29 kW–1500/750 r.p.m motor, the following results were obtained:

→ 1500 r.p.m: test a) 70.1 dB, b) 70.9 dB, c) 74.7 dB, d) 76.2 dB, e) 79.1 dB, f) 79.2 dB.

→ 750 r.p.m: test a) 47.1 dB, b) 47.6 dB, c) 53.6 dB d) 53.8 dB, e) 55.1 dB, f) 55.1 dB.

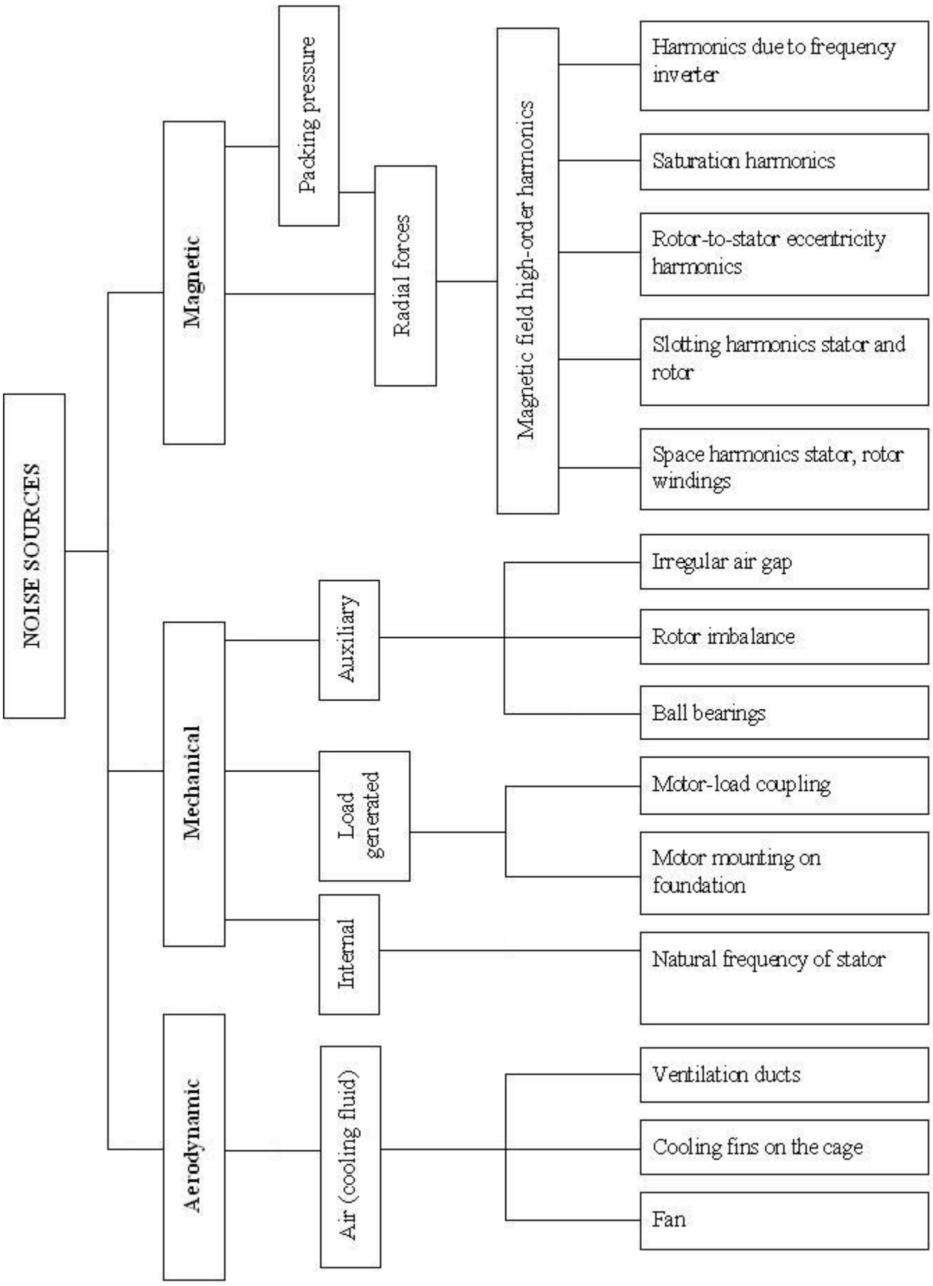

Fig. 1 – Noise sources in two-speed electric motors.

3. **AERODYNAMIC NOISE**

The principal aerodynamic noise source is the fan. The noise depends on the constructional characteristics of the fan, number of blades, diameter, peripheral velocity, shape and dimensions of the cooling circuit and the speed of the air stream through the system.

Different authors propose different algorithms for the calculation of the noise produced by the fan, some of the formulas being derived experimentally.

In [4], the following formula is recommended for the acoustic pressure, measured in dB (A):

$$L_v = 60 \times \log V + 10 \times \log\left(D_v \times b_v\right) - 24 \times D_V + 12 \tag{3}$$

with the following notations: V – peripheral velocity in m/s; D_v – external diameter of the fan in m; b_v – fan blade width in m.

Other authors [1] indicate a similar formula, but with differences which result from the constants:

$$L_v = 60 \times \log V + 10 \times \log\left(D_v \times b_v\right) + k_1 + k_2 + k_3 + k_4 + k_5 + k_6 \tag{4}$$

Here the empirical constants k are determined as follows:

– k_1 depends on the distance for which the noise is calculated (for a distance of 0.5 m, $k_1 = 5$dB);

– k_2 is determined relatively to the relative flow rate Q_{rel} of the fan;

– k_3 is determined relatively to the diameter D_v of the fan;

– k_4 is determined relatively to the attack angle α_{at} of the fan;

– k_5 is determined relatively to the bending angle of the blades at their external part, β (for radial fans with straight blades $\beta = 0$);

– k_6 depends on the decreasing of the air-borne sound intensity, caused by the motor body or by the fan cover.

To obtain an estimation of the general sound level, the above formula can be simplified as follows:

– for externally ventilated motors:

$$L_v = 60 \times \log V + 10 \times \log\left(D_v \times b_v\right) + k_3 + k_5 + 5\,, \tag{5}$$

– for fans having radial blades, $k_5 = 0$.

By contrast to the relationship found in literature [1, 2, 4], the expression for the calculation of the acoustic pressure in two-speed motors proposed by the authors is identical with the formula determined for single-speed three-phase motors [7]:

$$L_v = 60 \times \log V + 10 \times \log \left(D_v \times b_v\right) + 80 \times D_v + 10.8 \,. \tag{6}$$

Expression (6) was determined based on the experimental results obtained by the authors after testing production motors manufactured by S.C. ELECTROPRECIZIA S.A. [7].

This original expression allows more efficient aerodynamic noise calculation since it can be applied to single and two-speed three-phase motors of enclosed construction, finned aluminium or cast-iron frame, self-ventilated with the fan mounted on the rotor shaft and protected by a fan hood.

The formula (6) was obtained based on the following reasoning:

– in order to reduce the number of the empirical constants and considering the form of expressions (3), (4) and (5) a new calculation formula was derived as follows:

$$L_v = A \times \log V + B \times \log \left(D_v \times b_v\right) + k \,, \tag{7}$$

– for the constants *A* and *B*, their values from expressions (3), (4) and (5), namely A=60; B=10 were preserved and the term *k* was determined as a function $k = f(D_v)$, since tests have shown that the ventilation noise depends considerably on the outer diameter;

– relevant tests were performed on different motor types. For each motor type the value of the term *k* was determined using the formula:

$$k = L_{V,mas} - \left(60 \times \log V + 10 \times \log \left(D_v \times b_v\right)\right), \tag{8}$$

and this value was brought in relationship with the outer diameter of the fan D_v. In this formula, $L_{V,mas}$ has been determined as follows:

- From the spectrograms generated at "*b*" (driven motor), the sum of the mechanical and ventilation noises (L_m+L_v) has been obtained.
- From the spectrograms generated at "*a*" (driven motor without fan) the mechanical noise L_m has been obtained.

Based on these measurements $L_{V,mas}$ was calculated considering the rule of the sum of noise levels of different origin; the points (k, D_v) were used to obtain a graphical representation; thereby resulting that the function $k = f(D_v)$ can be conveniently approximated with a straight line having the equation $k = 80D_v$+10.8. This result was utilized to derive the formula (6).

4. THE MECHANICAL NOISE

The authors have carried out a series of tests on single and two-speed three-phase production motors made by S.C.ELECTROPRECIZIA S.A. equipped with normal and C3 clearance SKF-ball bearings, which allowed the development of a method for mechanical noise estimation.

By analyzing the spectrograms for the driven motor, without fan, it could be noticed that the mechanical noise increases with motor size, power rating and speed. The mechanical noise depends on several factors:

- type of ball-bearings used (normal, or enlarged clearance C3);
- the tolerances of the mechanical parts composing the ball-bearing mount;
- the ball-bearing mounting technique;
- the constructional type of the motor shields (aluminium, cast-iron).

Based on the experimental results, the authors have determined the curves given in Fig. 2, representing the variation of the mechanical acoustic power level $L_{w\,mec}$ in decibels against the power ratings P_N , in kW, for three-phase motors [7]. These are equally valid for two-speed three-phase motors, depending on the running speed of the motor.

Relation (9) will be applied to calculate the mechanical noise of single or two-speed three-phase motors with aluminium structure (housing, shields) with sealed, C3 clearance ball-bearings mounted on parts machined at tolerances in accordance with the specifications of the ball-bearing manufactures.

$$L_{w\,mec} = f\left(P_N, n\right). \tag{9}$$

The values of the mechanical acoustic power level, $L_{w\,mec}$, are obtained from the curves from Fig. 2. The mechanical noise will have different values for the two speeds of the motor thus; relation (9) is applied to calculate the two levels of mechanical noise.

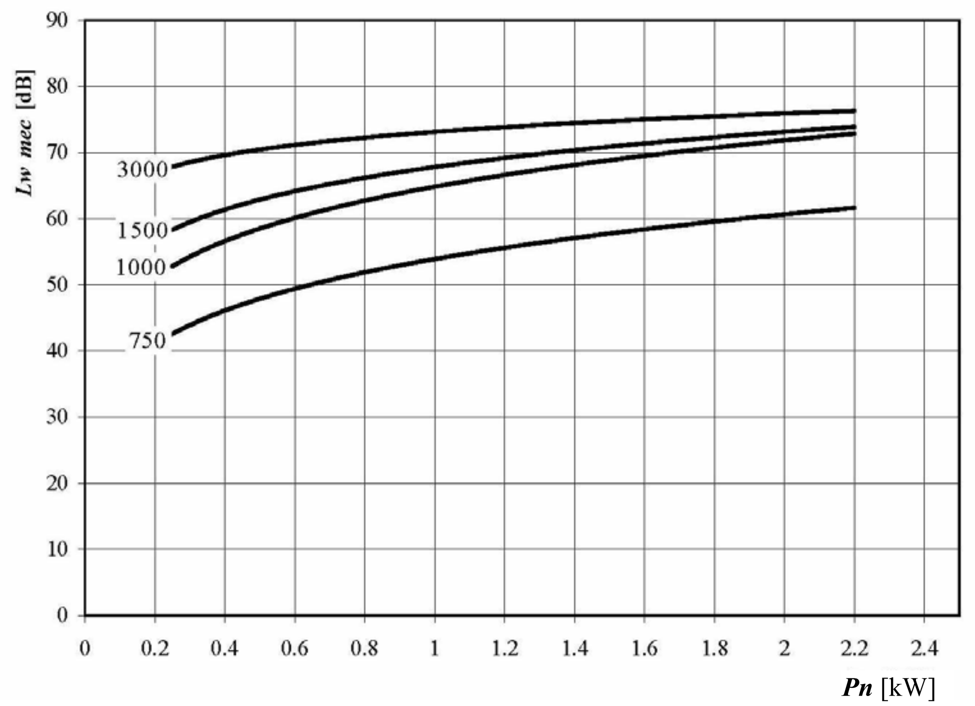

Fig. 2 – Mechanical acoustic power level in single-and two-speed three-phase motors.

5. **THE MAGNETIC NOISE**

It is generally known that the three-phase stator winding of single-and two-speed motors produces a magnetic field that can be decomposed into a direct rotating magnetic field and an inverse rotating magnetic field respectively. Consequently, a three-phase machine consists of two fictitious induction machines, a direct and an inverse one.

The investigated motors were of usual construction, with either one Dahlander-connected winding or with two separate windings. For the case of a single Dahlander winding in 3 000/1 500, 1 500/750 machines, two configurations were considered: normal power steps (D/YY) and air-blower power steps (Y/YY). For the case of two separate windings, following situations were examined: 3 000/1 500, 1 500/750 and 1 500/1 000 r.p.m.

Within the air gap of the three-phase motor, the main magnetic field which produces the shaft torque is accompanied by several higher-order field harmonics [3]. The latter have a parasitic influence and considerably reduce machine performances with effects on additional losses, radial efforts, starting torque curve sagging [3]. High-order harmonics of magnetic fields in cage rotor induction motors are generated by the windings placed in slots, the presence of slots on both armatures, magnetic circuit saturation, various admitted or accidental asymmetries due to the manufacturing process (rotor eccentricity with respect to stator).

Magnetic noise produced in induction motors is the consequence of interaction between stator and rotor magnetic field high-order harmonics.

As a consequence of this interaction, magnetic forces will arise, producing mechanical oscillations of magnetic core plates, frame and rotor [6, 7]. These generate sonic pressures of the same frequency as the above-mentioned magnetic forces.

Two-speed motors produce different magnetic noise levels for each speed due to the higher-order harmonics of magnetic fields in cage rotor induction motors generated by:

- the presence of slots; the number of slots can be optimum for one speed but may not be optimum for the second speed;
- the windings placed in slots are different both for motors with separate windings and for motors with Dahlander winding.

By neglecting the magnetostrictive effect, we consider the contribution to magnetic noise of the compressing force at which the stator core plates (laminations) were assembled [7]. Due to harmonics (CEI 34-17) arising in frequency inverter supplied motors, the study of magnetic noise generation in such cases is more complex than in sinusoidal voltage supplied motors.

A higher mounting pressure applied during stator assembly [7] may result in global noise reduction by around 1 dB. The experiments carried out by the authors at assembly pressures of 10 bar, 20 bar, 35 bar and 65 bar have demonstrated this improvement. This represents a novel approach introduced by the authors in the analysis of noise generated by single-or two-speed, cage rotor, three-phase induction motors.

A number of four stators packed at different pressures of 10 bar, 20 bar, 35 bar and 65 bar were investigated. These were equipped with identical windings and pressed into identical frames. Next, two modified rotors were prepared: one rotor consisting of a pile of disk plates (slotless cylinder) and a second slotted, but cage less rotor. Except for the modifications, the motors were assembled in accordance with normal production-line standards and specifications (in terms of machine length, air-gap, diameter etc.). The prepared motor parts were mounted in different combinations and the resulting motor was supplied at nominal voltage and frequency.

The spectrograms were determined in the following cases:

1. The motor with stator assembled at 10 bar and slotless cylindrical rotor.
2. The motor with stator assembled at 20 bar and slotless cylindrical rotor.
3. The motor with stator assembled at 35 bar and slotless cylindrical rotor.

4. The motor with stator assembled at 65 bar and slotless cylindrical rotor.
5. The motor with stator assembled at 10 bar and slotted cylindrical rotor.
6. The motor with stator assembled at 20 bar and slotted cylindrical rotor.
7. The motor with stator assembled at 35 bar and slotted cylindrical rotor.
8. The motor with stator assembled at 65 bar and slotted cylindrical rotor.

Spectrogram analysis shows that when the stator is assembled at 10 bar; the total noise level is 3 dB above the noise level obtained when applying a 65 bar stator assembly pressure.

6. **NOISE REDUCTION METHODS**

6.1. AERODYNAMIC NOISE REDUCTION METHODS

In order to reduce aerodynamic noise in air-cooled machines, a first priority is to remove the sources of pure tone components. This can be achieved by ensuring sufficient clearance between fan blade tips (outer diameter) and the inner surface of the ventilation chamber and the fixed obstacles placed in the airflow. This free space should be at least 10÷15% of the outer diameter of the fan. Generally, this cannot be ensured in modern motors where pure tones can be substantially attenuated by providing a variable blade pitch and blades of unequal lengths [1]. *E.g.* a 7-blade fan with the following angles between its blades can be used: 40.7°; 68.3°; 52.5°; 37°; 54°; 67.4°; 40.1°. Tests employing fan blades of different lengths were not performed. The authors intend to perform these tests and to include them in a future paper.

In order to reduce broadband aerodynamic noise, the most effective way is to reduce the size of the rotational elements, especially of the fan. From (6) it can be noticed that the ventilation noise level strongly depends on the fan diameter D_v. Consequently, one of the ways of reducing ventilation noise is to reduce fan diameter. As was mentioned above, ventilation noise is dominant in the global noise of 2-pole motors, which confirms the idea of employing fans of smaller diameter than in 4- or 6-pole motors.

In conclusion, ventilation noise in 2-pole motors can be reduced by using fans with a smaller outer diameter D_v without affecting motor cooling.

6.2. MAGNETIC NOISE REDUCTION METHODS

Reduction of field harmonics plays an important role in magnetic noise reduction and can be achieved as follows:

- selecting the appropriate numbers of stator and rotor slots;
- skewed slots, usually in the rotor;
- increased the air gap.

In order to limit oscillations due to magnetic forces, a careful analysis of this phenomenon is required by determining the appropriate number of slots. The ratio of stator and rotor slot numbers has a major influence on the radial forces and thus on the noise level. In the case of two-speed motor, selecting the appropriate numbers of stator and rotor slots is a very difficult matter due to the above exposed reasons.

The acoustic behavior of the motor significantly depends on the constructional characteristics of the stator yoke, frame and machine dimensions. The highest noise level is registered at the resonance of a specific radial electromagnetic force with one of the fundamental frequencies of the stator yoke-frame system.

The adequate slot numbers recommendable in two-speed three-phase motors resulting after studies carried out by the authors are presented in Table 1.

Table 1

Optimum slot numbers

$2p$	Z_1	Z_2
2/4	24 36	16,18, 20, 22, 28, 30 22, 28
4/6	24 36	22 26, 28,44,46
4/8	24 36 48	22, 30 26, 28, 44,46 44
2/8	24 36	30 28
6/8	36	44
6/12	36	46
8/16	48	36

As was mentioned above, the noise is influenced by the stator packing pressure. Consequently, applying greater pressure during stator assembly will reduce noise. The experimental results obtained after a series of tests, are summarized in the graph of Fig. 3.

The acoustic power level L_v is represented on the ordinate in dB, whereas the stator assembling pressure P in bar appears on the abscissa.

Above a certain stator core packing pressure (90 bar) no further reduction of noise level can be observed.

The stator packing pressure is the pressure exerted on the surface of the core plates during the stator packing process. This is an original element of the paper and it demonstrates that stator fabrication process can contribute to motor noise increase.

As was shown before, magnetic noise can be reduced by eliminating the high-order harmonics in the magnetomotive force, which can be obtained by providing shorted pitch windings or skewed rotor slots. Adequate skew angles as well as shorted pitch windings can reduce or eliminate some of these harmonics.

Skewed slots, usually provided in the rotor, is a frequently applied technique with good results in magnetic noise reduction.

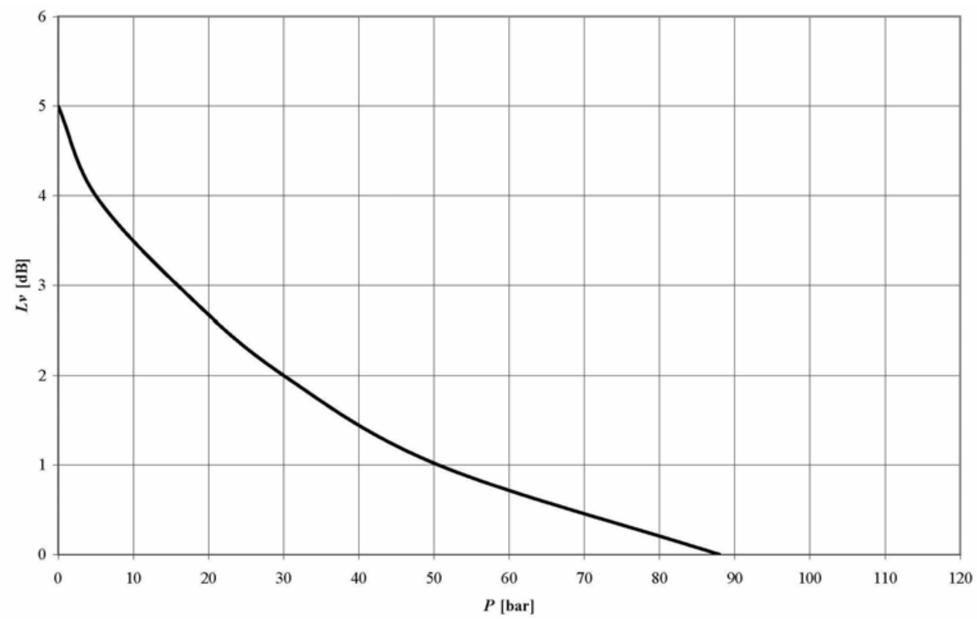

Fig. 3 – Stator packing pressure as a function of acoustic power level.

The teeth harmonics which are caused by unevenly distributed windings are of the same order as the slotting harmonics, the former occurring whatever the slot configuration, whereas the latter are encountered only in open slots.

Slotting harmonics can be much more important than teeth harmonics the latter being of rather low amplitude due to their higher order. Unlike slotting harmonics which have the same amplitude throughout the entire load range, teeth harmonics depend on the load current through the windings.

In single-and two-speed three-phase machines with stator slots wider than rotor slots, teeth and slotting harmonics are attenuated by skewing of the rotor cage bars. This is an effective way of reducing noise and parasitic torques frequently presented in technical literature.

7. **CONCLUSIONS**

The paper presents the results of three-phase two-speed motor noise analysis based on experimentally obtained spectrograms. Among many noise reduction methods, some have been analyzed and selected, based on experimental investigations. The authors have demonstrated the significant effects of the stator core packing pressure on noise generation.

The paper proposes:

- An improved formula for the calculation of the acoustic ventilation power level (6), developed by the authors on an experimental basis. This novel expression can be applied to ventilation noise calculation in two-speed three-phase motors, of enclosed construction, with finned aluminium or cast-iron frame, self-ventilated, with the fan mounted on the rotor shaft and protected by a fan hood.
- A novel calculation method (9) for the acoustic power level, of mechanical nature.

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