Determination and Analysis of Causes of Induction Motor Magnetic Noise

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***Abstract* - This paper presents the causes of the acoustic noise magnetically generated by three-phase induction electric motors and some results of tests and calculation are discussed. The influence of the rotor slots skewing on the reduction of the magnetic noise is also analysed through calculated values. The paper gives a general view about how the magnetic noise in induction motors is generated and how much its prevision is important during the design stage.**

INTRODUCTION

Basically, the rotating electric machines have three noise sources:

a) due to the ventilating system;
b) due to the bearings;
c) magnetic origin.

The segregation of the noise in these three categories permits the evaluation of each source individually. So, it is possible to determine the higher intensity source which must be reduced.

The noise due to the ventilating system is particularly important in the 2 and 4 poles motors. In these motors it is the highest noise source. By the other hand, in the 6 and greater poles motors the main noise source is the electromagnetic circuit. There are two reasons for that: first, as the velocity of the fan decreases with the increase of the numbers of poles, the noise generated by it also decreases. Second, in opposition, if the number of poles is higher, the stator yoke height is smaller. So, as it is easier to deform a stator core with a thin yoke than with a thick one, the generated noise due to electromagnetic origins is higher.

The noise due to the bearings is not significant in comparison with the other causes when the bearings have no failures. Otherwise, if the bearings are damaged, the noise can be increased very much. In such case, the solution is to change those bearings.

Many researchers have investigated and written about magnetic noise in electric motors. Kako et alli [1] considered the magnetic noise only due to slot harmonics and they determined the noise emitted by a motor for a skewed and non-skewed rotor, but they did not mention how much the rotor was skewed. Brauer [2] described a digital computer program which predicts the total magnetic noise of induction motors. But, for pratical results, it is very important to make evident each cause of the magnetic noise in order to reduce the biggest one. This is the aim of this paper.

The references were selected taking into account the objective of the paper. We suppose to be more appropriate to consider pioneer but still current works about the basics of this subject [3, 4, 5, 6, 7], including doctorate dissertation [6, 7] in order to clarify some aspects about the generation of the magnetic noise. Nevertheless, other avaliable recent books and papers were also analysed just to give us more information and knowledge about magnetic noise, but they were not used as reference.

The originality of this paper is to present the causes of the magnetic noise separately for three-phase induction motors as well as the results calculated for 24 different motors from 1 hp to 550 hp for 2, 4, 6 and 8 poles. The influence of the rotor slots skewing is also analysed for several values of skewing.

MAGNETIC NOISE GENERATION

The noise of magnetic origin in electric machines is generated by the interaction of the induction waves (fundamental and harmonics) present in the airgap. These waves are variable in space and time and exist because of the winding distribution and variation of the airgap permeance due to the stator and rotor slots, saturation and eccentricity. These induction harmonics, combined themselves according to Maxwell´s tensor expression, generate periodic force waves in the airgap deforming the stator core and exciting the surrounding air. This way, the acoustic noise is generated. The Fig. 1 shows this situation.

The induction harmonic calculation as well as the determination method of magnetic noise were early presented by Jordan [3] in 1950. Nevertheless, the magnetic noise calculation requires thousands of combinations of the harmonics. Therefore, a reliable and fast determination of magnetic noise became possible only after the computers appearance.

It is not easy to determine accurately the magnetic noise. The accuracy of the results is reduced by the simplificative hypothesis which are necessary to eliminate some randomic influences of the motor manufacturing process. In fact, the magnetic noise determination is accurate in relation to the frequencies involved. Nevertheless, the results of the sound pressure level or sound power level do not have a good accuracy in all cases. In some cases they provide us only a good idea about the magnetic noise.

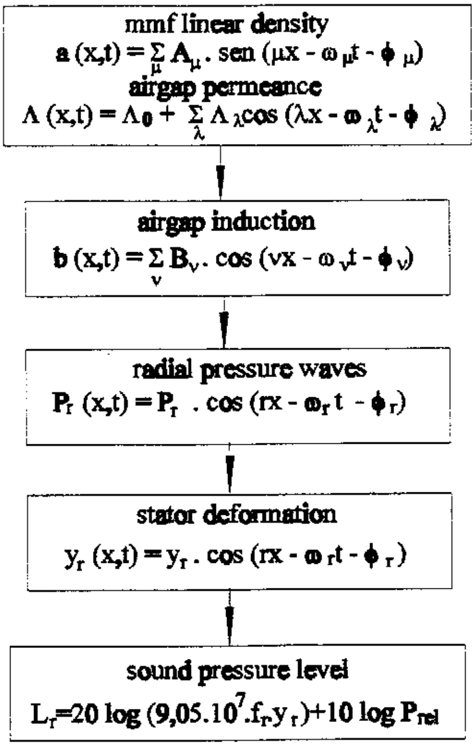

Fig. 1: Magnetic noise generation scheme

In Fig.1, Prel is a correction in sound pressure level that considers the cylindrical surface of the motor and fr is the frequency of the force wave.

RADIAL FORCE WAVES

On the stator surface in contact with the airgap, i. e., in the boundary between two regions with different permeabilities - in this case iron and air - radial forces act. Such forces are proportional to the squared airgap induction b(x,t). The Maxwell's tensor expression gives the magnetic pressure P(x,t) [4,5,6]:

$$P(x,t) = \frac{b(x,t)^2}{2\mu_0} \qquad (1)$$

Where μ_0 is the air permeability.

The airgap induction b(x,t) is, actually, the sum of the fundamental induction wave with all harmonics due to winding distribution, stator and rotor slots, saturation and eccentricity [3]. Generally, b(x,t) is expressed by [4,5]:

$$b(x,t) = \sum_{n=1}^{p} B_n \cos(\nu_n x - \omega_n t - \varphi_n) \qquad (2)$$

Where:

B_n = amplitude of the induction harmonic
ν_n = pair of poles of the induction harmonic
x = space coordinate
ω_n = angular frequency of the induction harmonic
ϕ_n = phase angle of the induction harmonic
p = integer number as high as possible to consider the most of the induction harmonics.

So, developing the equation (1), it results:

$$P(x,t) = \frac{1}{2\mu_0} \sum_{n=1}^{p} \frac{Bn^2}{2} \left[1 + \cos\left(2\nu_n x - 2\omega_n t - 2\varphi_n\right)\right] +$$

$$+ \frac{1}{2\mu_0} \sum_{n=1}^{p-1} \sum_{m=n+1}^{p} B_n . B_m \, .$$

$$.\cos\left[\left(\nu_n \pm \nu_m\right)x - \left(\omega_n \pm \omega_m\right)t - \left(\varphi_n \pm \varphi_m\right)\right] \qquad (3)$$

It can be noted that the magnetic pressure is formed by a constant term, a double frequency term and one third term where induction harmonic frequency and pair of poles are given by adding and subtracting each individual component.

The waves of the induction harmonics are given according to [4] by:

$$b(x,t) = \mu_0 R \Lambda(x,t) . \sum_{\nu=1}^{n} \frac{A\nu}{\nu} . \cos\ (\nu x - \omega \nu . t - \varphi_\nu) -$$

$$- \frac{1}{2\pi\Lambda_0} \sum_{\nu=1}^{n} \sum_{\lambda=1}^{n} \frac{A_\nu . \Lambda_\lambda}{2\nu} \int_0^{2\pi} f(x,t) dx \qquad (4)$$

Where f(x,t) is given by:

$$f(x,t) = \left[\cos (\nu \pm \lambda) x - (\omega_\nu \pm \omega_\lambda) t - (\varphi_\nu \pm \varphi_\lambda)\right] \qquad (5)$$

The permeance $\Lambda(x,t)$ is given by a constant permeance of the airgap $\Lambda_0(t)$ and a sum of periodic permeances due to slots, saturation and eccentricity generically shown as follows:

$$\Lambda(x,t) = \Lambda_0(t) + \sum_{\lambda=1}^{n} \Lambda x . \cos\ (\lambda x - \omega_\lambda . t - \varphi_\lambda) \qquad (6)$$

and the mmf linear density a(x,t) is given by:

$$a(x,t) = \sum_{\nu=1}^{n} A_\nu sen (\nu x - \omega_\nu t - \varphi_\nu) \qquad (7)$$

The equations to calculate the permeances and mmf linear density are not shown in this paper. They are easily found in the literature [4].

Solving the equation (4), the fundamental and the induction harmonics waves are determined. In this survey, each induction harmonic component is separated in groups according to its origin as follows :

1. **Fundamental induction wave.** It is determined by multiplying the fundamental magnet-motive force (mmf) by the constant permeance of the airgap.

2. **Harmonics due to stator and rotor windings.** These harmonics exist due to the variation of the mmf caused by the winding distribution combined with the constant permeance of the airgap.

3. **Harmonics due to stator and rotor slots.** They occur due to the combination of stator and rotor slots permeance with the mmf.

4. **Harmonics due to the interaction between stator and rotor slots.** They occur due to the mutual permeance between stator and rotor slots combined with the mmf.

5. **Fundamental saturation wave.** It is determined from the fundamental mmf combined with the saturation permeance waves.

6. **Harmonics due to stator and rotor slots saturation.** These harmonics are caused by the mutual permeance due to the saturation and stator and rotor slots combined with the mmf.

7. **Harmonics due to stator and rotor winding saturation.** These harmonics are caused by the saturation mmf waves combined with the constant permeance of the airgap.

8. **Fundamental eccentricity wave.** It is determined from the fundamental mmf combined with the eccentricity permeance waves.

9. **Harmonics due to stator and rotor slots eccentricity.** These harmonics are caused by the mutual permeance due to the eccentricity and stator and rotor slots combined with the mmf.

10. **Harmonics due to stator and rotor winding eccentricity.** These harmonics are caused by the eccentricity mmf waves combined with the constant permeance of the airgap.

These induction harmonics, combined according to (1) give as result force density waves which deform the stator core periodically in time and space, generating the noise. Nevertheless, only few combinations can provide a high level of sound power [5]. In order to limit the number of possible combinations of the induction harmonics, it is enough to consider the following combinations:

- **stator harmonics with themselves**

$$r = \nu_1 + \nu_2 \qquad (8)$$

$$f_r = 2\, f_\nu \qquad (9)$$

- **stator harmonics with rotor harmonics**

$$r = \lambda \pm \nu \qquad (10)$$

$$f_r = f_\lambda \pm f_\nu \qquad (11)$$

- **stator harmonics with rotor saturation harmonics**

$r = \lambda_s \pm \nu$ (12)

$fr = f_{\lambda s} \pm f_\nu$ (13)

- **stator harmonics with rotor eccentricity harmonics**

$r = \lambda_\varepsilon \pm \nu$ (14)

$fr = f_{\lambda\varepsilon} \pm f_\nu$ (15)

- **rotor harmonics with stator saturation harmonics**

$r = \nu_s \pm \lambda$ (16)

$fr = f_{\nu s} \pm f_\lambda$ (17)

- **rotor harmonics with stator eccentricity harmonics.**

$r = \nu_\varepsilon \pm \lambda$ (18)

$fr = f_{\nu\varepsilon} \pm f_\lambda$ (19)

The parameters used to determine the vibration modes r and the noise frequencies fr are listed below for three phase squirrel cage induction motors:

$\nu = p\,(1 + 6g_1)$ $g_1 = 0, \pm 1, \pm 2, \pm 3, \ldots$
$\lambda = \nu + g_2 N_2$ $g_2 = \pm 1, \pm 2, \pm 3, \ldots$
$\nu_s = 3\,p + g_s N_1$ $g_s = 0, \pm 1, \pm 2, \pm 3, \ldots$
$\lambda_s = \nu_s + g_s N_2$
$\nu_\varepsilon = p \pm 1 + g_\varepsilon N_1$ $g_\varepsilon = 0, \pm 1, \pm 2, \pm 3, \ldots$
$\lambda_\varepsilon = \nu_\varepsilon + g_\varepsilon N_2$
$f_\nu = f$

$$f_\lambda = f + \frac{g_2\ N_2}{p}(1-s)\,f$$

$f_{\nu s} = 3f$

$$f_{\lambda s} = 3f + \frac{g_2\ N_2}{p}(1-s)\,f$$

$f_{\nu\varepsilon} = f$

$$f_{\lambda\varepsilon} = f + \frac{g_\epsilon\ N_2}{p}(1\text{-}s)\,f \qquad \text{for static eccentricity}$$

$$f_{\lambda\varepsilon} = f + \frac{g_\epsilon\ N_2 \pm 1}{p}(1\text{-}s)\,f \qquad \text{for dynamic eccentricity}$$

Where:

ν/f_ν: pairs of poles/frequency of stator harmonics
λ/f_λ: pair of poles/frequency of rotor harmonics
$\nu_s/f_{\nu s}$: pair of poles/frequency of stator saturation harmonics
$\lambda_s/f_{\lambda s}$: pair of poles/frequency of rotor saturation harmonics
$\nu_\varepsilon/f_{\nu\varepsilon}$: pair of poles/frequency of stator eccentricity harmonics
$\lambda_\varepsilon/f_{\lambda\varepsilon}$: pair of poles/frequency of rotor eccentricity harmonics

Actually, the most important source of magnetic noise in induction motors is the combination of the stator induction harmonics with the rotor induction harmonics. Sometimes the fundamental induction wave combined with itself can also produce a high level of noise and vibration with double line frequency.

NOISE DETERMINATION

For each force wave generated by interaction of the induction harmonics, it is calculated the deformation y_r on the stator surface, the vibration mode r, the excitation frequency of this force f_r and the natural frequency of stator f_n for each vibration mode [3]. The expressions used to calculate the vibration mode r and the excitation frequency fr are given in the equations (8) to (19). The expressions for deformation Yr and natural stator frequency fs are well known from literature [4, 6]. The rotor deformation can be neglected, because it is very much easier to deform the stator than the rotor.

After that, the sound pressure level in dB or dB(A) on the stator surface is determined, considering it as a vibrating free body. In the determination of magnetic noise are considered only the radial forces acting in the motor airgap. The proximity between natural frequencies and excitation frequency are considered through a ressonance factor [5] that can increase significantly the noise. In practice, it is not easy to find good results for this factor, because the algebric expressions do not take into account the influence of the frame. So, as suggestion, perhaps better results would be acquired through the use of an finite element method to determine the natural frequencies of the motor.

Vibration Mode

The vibration mode r, that results from the combination of the induction harmonic pole pairs is important until, at maximum, r=20 for large machines. Normally, it is enough to consider r=12. The natural frequency of the stator is determined for each vibration mode. The force waves deform the stator according to the vibration mode. Fig. 2 shows these deformations. For r = 0, the force has a uniform distribution along stator bore, varying in time. For r = 1, there is a rotating radial force over the stator or rotor. The stator deformations are not considered, only the rotor bending. For r=2 or more there are rotating radial forces applied on 2r points of stator that deform it periodically in time and space. The most critical case for deformation and consequently noise generation is when r=2 because, in this case, the stator is eliptically deformed. This is the easiest way to deform it.

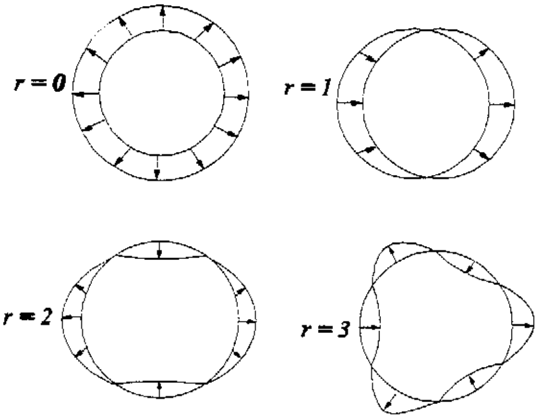

Fig. 2: Vibration modes

Results

The results of the magnetic noise calculation on the stator surface are shown in the Table 1 for several motors on load from 1 hp (0.75 kW) to 550 hp (400 kW) for 2, 4, 6 and 8 poles. These results were obtained using a software developed for FORTRAN 77 (Microsoft FORTRAN Powerstation 32 bits) with the presentation of the results for WINDOWS. This software calculates and shows the noise separated by causes and it runs together with WEG's motor design and calculation softwares in order to give to our engineers a fast analysis tool. In the Table 1 are shown only the most significant values for each vibration mode and cause. There are three separated columns, according to the causes of the magnetic noise: **winding/slots, saturation and eccentricity based on 10%.** For each column there are still two other columns indicating what combinations of flux density harmonics were considered according to equations (8) to (19).

In order to condense the results presentation, the frequency and the vibration mode are shown only for the higher sound pressure level calculated. In the Table 1 the sound pressure level Lr is shown for 1 meter far from the motor surface and it is given in dB(A). N1 is the number of stator slots and N2 is the number of rotor slots. The sound pressure levels below zero are not shown in the Table 1.

Some values of sound pressure level are higher than those obtained from the tests. This indicates that it is important to consider the influence of the motor frame in the stator natural frequencies. In this simulation the influence of the motor frame was neglected. If the resonance factor is too high when only the stator dimensions are considered in the natural frequency determination, the simulation results are higher than those obtained from the tests. Otherwise, if the resonance factor is low, the calculation can indicate a low value and the tests can indicate a high one.

INFLUENCE OF THE ROTOR SLOTS SKEWING ON THE MAGNETIC NOISE

Rotor slots skewing is a very useful way to reduce the rotor slot harmonics. As the rotor slots harmonics are an important cause in the generation of the magnetic noise, their reduction or elimination can decrease the magnetic noise as a whole. The magnetic noise for a 1 hp, 6 poles motor with rated load is shown in the fig. 3 in relation to rotor slots skewing. The rotor slots skewing is indicated in relation to the stator slot pitch.

This graphic shows the dependence of the noise with respect to the rotor slots skewing. The curve shown can be significantly different from one motor to another. It is important to perceive, however, the great dependence of the noise with respect to the rotor slot skewing.

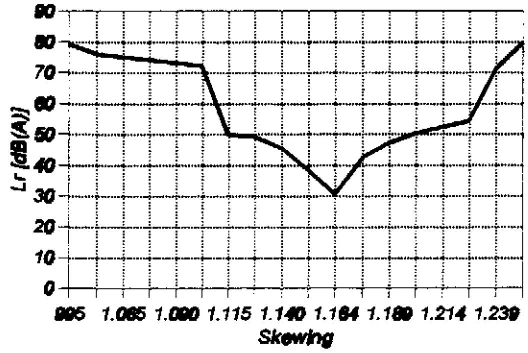

Fig. 3: Influency of the rotor slots skewing on the magnetic noise

TABLE 1 - RESULTS OF MAGNETIC NOISE CALCULATION SEPARATED BY CAUSES FOR ON LOAD (RATED) THREE-PHASE MOTORS

MOTOR / IDENTIFICATION f= 60Hz			WINDING / SLOTS (HARM.)						SATURATION (HARM.)						ECCENTRICITY / 10% (HARM.)					
			STATOR WITH STATOR			STATOR WITH ROTOR			STATOR WITH ROTOR SATURATION			ROTOR WITH STATOR SATURATION			STATOR WITH ROTOR ECCENTRICITY			ROTOR WITH STATOR ECCENTRICITY		
Power [hp]	Poles	N_1/N_2	r	f_r [Hz]	L_r [dB(A)]	r	f_r [Hz]	L_r [dB(A)]	r	f_r [Hz]	L_r [dB(A)]	r	f_r [Hz]	L_r [dB(A)]	r	f_r [Hz]	L_r [dB(A)]	r	f_r [Hz]	L_r [dB(A)]
1	2	24/18	2	120	29.5	2	2046.3	64.8	2	2826.3	43.9	2	2826.3	28.8	3	2946.3	14.4	3	2889.5	20.2
10	2	36/28	2	100	32.8	2	1345.3	65.9	2	1545.3	5.2	4	1545.3	3.7	3	4183.8	-	9	3887.7	14.7
50	2	36/28	2	120	51.3	6	8185.4	60.1	2	1541.1	-	4	1901.1	21.6	-	-	-	7	1720.4	22.2
100	2	48/40	2	120	50.2	8	11850.3	56.7	-	-	-	4	2610.1	10.2	3	2370.1	-	5	2549.3	19.5
200	2	48/40	2	120	55	0	2499.6	53.1	-	-	-	4	2019.6	14.5	-	-	-	5	2559.1	22.9
550	2	60/44	2	120	65	0	2500.1	62.1	14	7980.3	0.3	12	2860.1	24.3	13	7919.9	9.2	13	7919.9	35.5
1	4	36/44	4	120	9.6	4	6288.6	61.3	4	4013.2	9.7	0	1017.7	-	3	3653.2	17.7	3	1137.7	12.2
10	4	48/40	4	120	14.2	4	1271.1	60.5	0	1397.1	-	0	1397.1	16.3	3	1306.0	25.5	3	1306	31.9
50	4	48/54	4	120	26.0	2	1473.0	78.1	2	1353	15.5	2	1353	25.2	3	1473	42.6	3	1502.5	54.0
100	4	72/58	4	100	24.3	4	2757.2	61.3	-	-	-	6	1628.6	16.0	3	1528.6	29.4	9	1553.2	17.4
200	4	72/58	4	120	31.7	2	1841.9	56.3	-	-	-	6	1961.9	19.6	9	1871.6	1.8	9	1871.6	31.4
550	4	72/58	4	120	34.1	10	1839.8	51.7	6	1959.8	5.8	6	1959.8	24.5	9	1839.8	19.8	9	1859.5	35.3
1	6	36/44	6	120	-	2	708.2	61.9	2	708.2	13.3	2	708.2	12.3	3	723.0	9.3	3	727	8.1
10	6	36/28	2	120	1.1	2	1626.8	88.6	2	1866.8	30.9	4	1866.8	34.3	3	4702.2	51.9	5	1804.9	44.3
50	6	72/56	6	120	2.6	0	3186.5	76.2	4	1342.2	18.5	4	1342.2	32.4	3	1102.2	22.6	9	1241.9	22.1
100	6	72/58	6	120	18.1	4	1142.7	82.8	2	1382.7	-	2	1382.7	25.1	7	3327.8	14.8	7	1282.4	33.9
200	6	72/58	6	120	16.7	4	1142.0	71.2	2	1382.0	-	2	1382.0	19.4	7	1281.6	5.7	7	1281.6	36.8
550	6	72/58	6	120	24.5	4	1153.0	70.8	2	1393	20.5	2	1393.0	43.6	7	1292.9	9.3	7	1273.0	41.5
1	8	36/44	4	120	-	0	479.8	21.9	4	1439.5		-	-	-	3	1932.9	-	1	493.4	-
10	8	48/54	8	120	-	2	667.7	81.4	2	667.7	32.1	2	667.7	37.4	3	1455.3	30.9	3	653.1	25.0
50	8	72/56	8	120	5.6	0	3171.8	79.9	0	1062.9	5.4	0	1062.9	30.2	1	717.7	-	7	957.7	27.2
100	8	72/56	8	120	11.3	8	4157.2	77.6	0	1071.5	14.4	0	1071.5	42.9	7	966.3	-	7	966.3	34.4
200	8	72/82	8	120	1.5	2	1099.8	76.3	4	2199.6	21.0	4	2199.6	19.1	3	1114.7	40.0	3	1114.7	46.2
550	8	72/82	8	120	23.5	2	1100.3	78.9	4	2200.6	21.5	4	2200.6	20.2	3	1100.3	42.5	1	1085.4	52.2

CONCLUSION

As expected, from the Table 1, the highest magnetic noise level occurred several times for the vibration mode equal 2. Actually, when the vibration mode r=2 exists, the highest magnetic noise occurs likely for this mode, except when there is a strong ressonance in a frequency related to other vibration mode. It can be noted that the influence of the saturation and eccentricity is very small for an usual design of a motor. In this simulation, the eccentricity was limited in 10% of the airgap lenght.

According to the segregation of the magnetic noise causes it is possible to improve the performance of the electric motor. The calculation method provides very useful result to the magnetic noise evaluation of three-phase induction motors. The calculation of the force and deformation waves frequencies is accurate. If, through the calculation, the maximum noise occurs for a determined frequency, this situation certainly will happen during the test, but the measured value can be different in amplitude from the calculated value.

In relation to rotor slots skewing, the Fig. 3 shows clearly the dependence of the magnetic noise with respect to the rotor slots skewing. It can be noted for that specific case a minimum point, indicating that small skewing variations can produce large variations in the noise. This condition is critical because it is very difficult to assure a good precision in the rotor slots skewing during manufacturing process.

The determination of the magnetic origin sound noise is important during the motor design stage, when the characteristics of the motor can be changed with a relatively low cost. After the motor is assembled, there is nothing to do to reduce the noise level without a high cost. That is a reason for the electric motor manufacturers to use this calculation and analysis tool.

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