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## MAGNETIC NOISE IN INDUCTION MOTORS

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### ABSTRACT

Noise in large high voltage induction motors (500Hp - 18000Hp) may be airborne or magnetic in nature. Usually, large high voltage induction motors are custom built and tailored to meet customer's demand. Since every motor is unique in its design, it is imperative to predict accurately the magnetic noise generation during design phase, this way avoiding expensive rework cost and not losing the customer confidence. Stator – rotor mechanical design, along with careful electrical coil design, can significantly cut down magnetic noise in an induction motor. This paper discusses the various causes and control of magnetic noise in large induction motors. Theoretical noise predictions in large induction motors, along with measured experimental noise data, are presented.

### INTRODUCTION

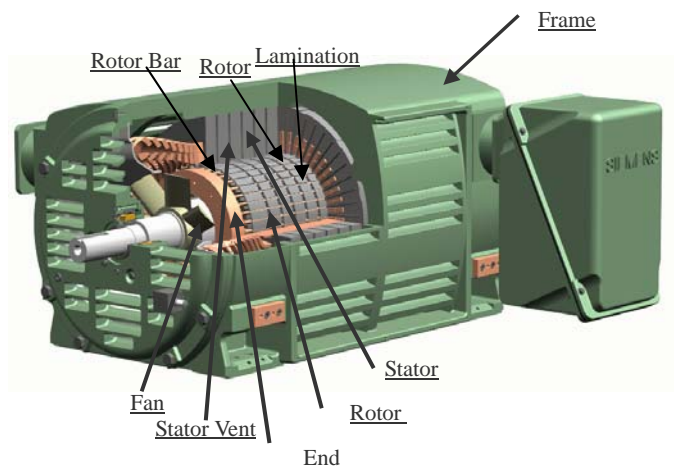
Large induction motors form the backbone of cement, mining, chemical, power, oil and gas industries driving fans, kiln, compressors, pumps and other critical applications in manufacturing processes. Unlike small induction motors, most of the large induction motors are usually custom engineered to meet special application demands of torque, starting time, inrush current, acceleration time and efficiency. Besides the electrical specifications, the motor manufacturer is also required to meet stringent temperature, vibration and noise requirements. Large induction motors, if not designed appropriately for noise, could be very detrimental to environment and human ears. Motor manufacturer has to meet stringent noise requirements during testing and operation of motor.

In order to effectively reduce the overall noise level around an induction motor, it is first necessary to understand the causes producing the noise. The two main sources of noise in induction machines are windage noise and magnetic noise. Windage noise, as the name suggests, is generated by the interaction of moving parts, such as rotor, fans, with

ventilating air inside the motor. Noise is also generated by the interaction of the moving air with stationary parts of the motor. Windage noise is airborne, and unlike magnetically generated noise does not manifest itself as a structural vibration of the motor.

Magnetic noise is usually generated by the interaction of electromagnetic flux waves with the resonant frequencies of stator core or teeth. Electromagnetic field is not uniform in the air gap and consists of various harmonics which may arise due to several reasons as discussed by Hildebrand [1], Alger [2]. Out of various causes which induce harmonics in the air gap, the field effects of stator-rotor slot combinations are the common causes for high magnetic noise in induction motors [3], [4], [5]. Finley [4] discussed various techniques to decrease the magnetic noise in electric motors. A good literature review on this topic could be found in [7].

This paper presents a theoretical model for the prediction of magnetic noise in induction motors. Numerical results are shown for the various stator-rotor slot combinations and slot geometries. Theoretical predictions are compared with measured data.



**Figure 1. Schematic of induction motor**

## NOMENCLATURE

$f$ -	line frequency [Hz]
$N$ -	speed [rot/min]
$p$ -	number of pairs of poles
$P$ -	number of poles
$S$ -	number of stator slots
$R$ -	number of rotor slots
$Z$ -	patterns per circumference
$s$ -	slip [per unit]
$m$ -	modes of vibration
$k_s$ -	saturation factor for the zig-zag flux path
$k_{s2}$ -	second harmonic for $k_s$
$k_{s4}$ -	fourth harmonic for $k_s$
$B_{g1}$ -	peak value of the fundamental flux density in air gap
$B_{g3}$ -	peak value of the third harmonic of $B_{g1}$
$H$ -	order of harmonic
$B_{zH}$ -	peak value of the zig-zag air gap flux density produced by the $H$ -th harmonic
$D$ -	stator outer diameter [inches]
$h$ -	depth of stator core behind slot [inches]
$G$ -	ratio between the weight of core plus the teeth weight and weight of core
$Y_C$ -	peak amplitude of radial core vibration
$Y_T$ -	peak amplitude of tangential tooth vibration
$n_C$ -	noise level at the stator core surface [dB]
$n_T$ -	noise level for tangential vibration at tooth tip [dB]

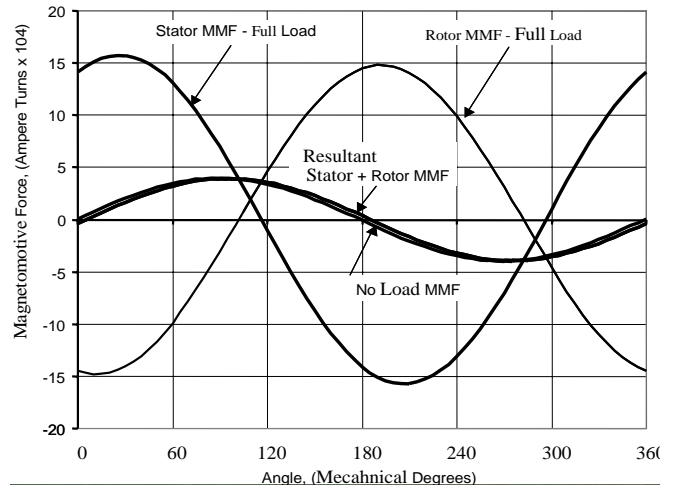
## THEORETICAL FORMULATION

The distribution of the magnetic flux in the air gap is not uniform along the circumference as shown in Fig.2. The fundamental flux is always superimposed by harmonics fields. Hence, the air gap field could be represented as a series of rotating field harmonics. The zig-zag leakage permeance pattern reveals these field harmonics. Mmf waves in air gap exert attractive radial forces and tangential forces on the stator core and stator tooth, respectively. The common causes of magnetic noise are the radial forces which result from the zig-zag leakage permeance and the load component of the fundamental mmf wave. The radial force is maximum at the point where the zig-zag leakage flux is the highest, and that occurs when a rotor slot opposes a stator tooth. Under load, the induced rotor current creates a stronger magnetic field, as shown in Fig.2, which also leads to significant tangential forces applied on the stator teeth.

It is important to know the frequencies at which radial and tangential forces are produced. If any of these forcing frequencies approaches the magnitude of the stator core or stator tooth natural frequency, resonance will occur and magnetic noise will be amplified. At a particular stator tooth, the forcing frequencies of magnetic forces are  $f_{force}$  plus side bands  $f_{force} \pm 2f$  where

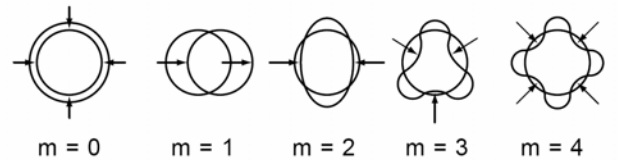
$$f_{force} = f \frac{n}{p} R (1 - s) \quad (1)$$

The space distribution of this force wave harmonic due to stator-rotor slot combination could be expressed in terms of patterns per circumference as shown in Fig. 3.



**Figure 2. Full load and no-load magneto-motive force for 2-pole machine**

$$Z = S - R \quad (2)$$



**Figure 3. Modes of stator core vibration**

The odds of resonance produced by lower modes of vibration, due to difference in stator and rotor slots, are much higher than the other higher modes. Modes of stator core vibration  $m$  can be computed as [4]

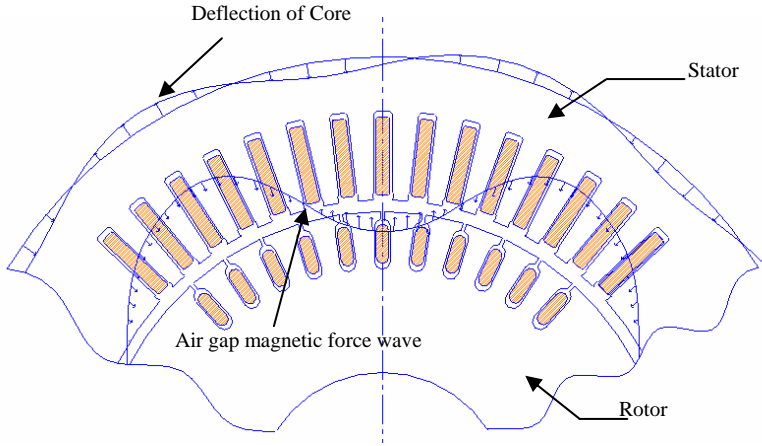
$$m = Z \pm kP \quad (3)$$

where  $k$  takes integer values 0,1,2,3, etc.

The core can be represented as a beam, supported on both ends and flexes due to forces applied on the beam as shown in

Fig. 4. The length of the beam is equal to the circumference length of the mean diameter of the stator for one-half the mode wave length. The core resonant frequency at a particular mode of vibration was derived from the elasticity theory for a flexural vibration of a ring [2].

$$f_0 = \frac{36700 m(m^2 - 1)h}{(D - h)^2 \sqrt{G(m^2 + 1)}} \quad (4)$$



**Figure 4. Deflection of stator core with magnetic forces**

The core natural frequencies for different mode shapes  $m$  are computed using equation (4). The amplification factors  $AF_{C,T}$  for core and tooth indicates how close the forcing frequency is to the resonant frequency of the core or tooth [4]

$$AF_{C,T} = \frac{1}{1 - \left( \frac{f}{f_{0C,T}} \right)^2} \quad (5)$$

The flux density in the air gap  $B$  is a function of time  $t$  and of circumferential coordinate  $\varphi$

$$B = B(t, \varphi) \quad (6)$$

The magnetic flux exerts a radial force (pull) at the air gap which is proportional to the square of the magnetic flux density

$$f_{radial} = \frac{B^2}{2\mu_0} \quad (7)$$

This radial force could be expressed in terms of the interaction between the stator and rotor harmonic force waves as [3]

$$F_{radial} = \left[ B_{g1} \cos(P\varphi - \omega t) - B_{g3} \cos 3(P\varphi - \omega t) \right] \left[ k_s - k_{s2} \cos(2P\varphi - 2\omega t) - k_{s4} \cos(4P\varphi - 4\omega t) \right] \left[ \cos\left(Z\varphi + \frac{R}{P}\omega t\right) \right] \sum_{H=1}^M B_{zH} \cos(HP\varphi \pm \omega t) \quad (8)$$

The saturation factors for the zig-zag flux path  $k_s$ ,  $k_{s2}$  and  $k_{s4}$  are specific for each machine, depending on several coil design characteristics such as coil pitch, number of phase belts, quantity of slots per pole per phase. By using the trigonometric identity

$$\cos A \cos B = \frac{1}{2} [\cos(A + B) + \cos(A - B)] \quad (9)$$

the force expression (8) can be expanded in the form

$$F_{radial} = E \left[ \cos(Z \pm MP)\varphi + \left( \frac{R}{P} \pm N \right) \omega t \right] \quad (10)$$

where

$$E = f(B_{g1}, B_{g3}) B_{zH}$$

and  $M$  and  $N$  represent values of opposite signs  $\pm 1, 3, 5, 7$ . Thus, the coefficient of  $\varphi$  from relation (8),  $(Z \pm MP)$  coincides with the number of wavelengths per circumference  $m$ , given in (3), while from (1) it can be seen that the  $\omega t$  coefficient  $\left( \frac{R}{P} \pm N \right)$  is equivalent with  $f_r = f_{force} \pm N f$  which represents the frequency of the load related magnetic force.

Once the values of radial and tangential forces are known, then core and tooth noise values can be computed [2],[3]

$$n_{C,T} = 20 \log_{10} (2.26 Y_{C,T} f_r 10^6) \quad [\text{dB}] \quad (11)$$

### Magnetic noise reduction

Load related magnetic noise requires considerable effort in order to be identified, due to the fact that a routine factory test is usually performed at no-load. Even if the factory includes a load test, the test stand equipment may have its own

noise levels which may be in excess of that of the motor and the magnetic noise generated by the motor under load will be difficult to quantify [1].

Magnetic noise levels can be reduced by adjusting various motor design parameters such as stator-rotor slot dimension and number. By modifying the stator slot size, the resonant frequencies of the core and tooth will change. For instance, a reduction in slot height will increase the stator tooth resonant frequency.

Another way is to vary the number of rotor slots, which will change the forcing frequencies as shown in equation (1) and the vibration modes of stator core. The force acting on the stator tooth is proportional to the square of the magnetic flux density in the air gap, therefore, by increasing the active magnetic core length or motor size one can reduce the magnitude of the flux density and consequently the magnetic forces. However, when the designers makes changes in regard to the slot combination, they should take into account not only the noise level, but other negative effects that these changes could impact, such as rotor standstill/ crawling during motor start-up [2],[8].

When slotting effect contributes substantially to the creation of rotating force wave, one can improve the noise level by using magnetic wedges in the stator slot, thus reducing the tangential forces acting on stator teeth.

## NUMERICAL RESULTS

The theoretical formulation described above has been implemented into a computer code.

First numerical example considered, is that of 6-pole induction motor of  $P=522$  kW, line voltage  $U=4$  kV, frequency  $f=60$  Hz, and 54 stator slots. Four different slot combinations were analyzed by varying the number of rotor slots. The computer program was run for each one of these slot combinations and the variation of magnetic noise with the number of rotor slots is shown in Fig.4.

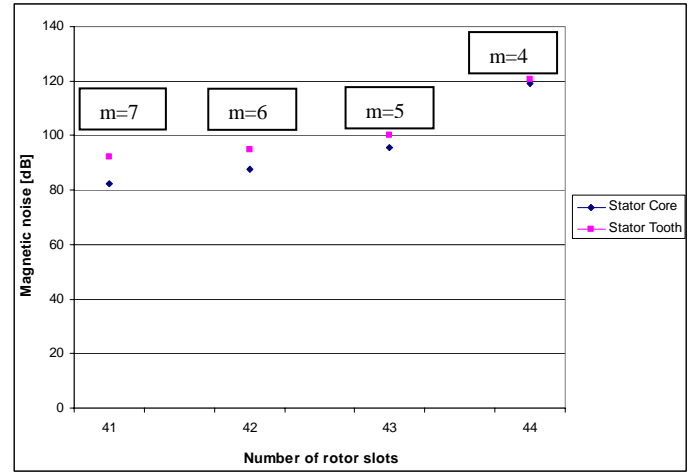
Rotor slots	f	m	Core [dB]	Tooth [dB]	$AF_C$	$AF_T$
41	934.1	7	82.5	92.3	1.072	1.064
42	954.1	6	87.8	95.0	1.153	1.067
43	974.3	5	95.6	100.2	1.424	1.071
44	994.1	4	119	120.7	5.266	1.074

**Table 1: Comparison between different slot combinations and corresponding noise levels.**

By increasing the number of rotor slots, one can notice from Table 1 that in each case considered, the forcing frequency in the +120 Hz ( $2 \times 60$  Hz) side band becomes closer to the core natural frequency which manifests itself as higher magnetic noise.

Table 2 shows the overall no-load test data from a factory routine test, for a motor built with 43 slots in the rotor. An +A weighted noise level was adopted per IEEE-85 standard, which

was recently withdrawn and replaced by NEMA MG1, part 9. It can be seen from Table 1, that the noise values are significant higher under load conditions than those resulted from the no-



**Figure 4. Magnetic noise levels vs. number of rotor slots for different modes of vibration.**

load test. In the same time, experience shows that for slower speed motors, such as the one analyzed here, most of the noise is load-related magnetic noise. This confirms also the statement that, in the case of six-pole and slower motors, a core load-related noise is usually predominant. The reason is that the stator back-iron has less depth and vibrates at a higher magnitude with smaller forces [4].

f [Hz]	Lp at 1m [dB]
63	44.43
125	57.43
250	66.13
500	69.23
1000	76.43
2000	69.43
4000	73.63
8000	63.23
Overall	79.59

**Table 2: Measured data per IEEE-85 standard, +A Weighting.**

A noise analysis is performed also for a 4-pole motor with a power  $P=8$  MW, voltage  $U=6.6$  kV at 60 Hz, and the stator tooth resonance calculated was 2090 Hz. For this particular design, one of the forcing frequencies has a very high value of 1973 Hz and the corresponding noise amplification factor  $AF_T = 8$  which is a critical value for the noise motor design. A slot height reduction by 5.7% yields a higher natural frequency of 2035 Hz and an acceptable  $AF_T = 3.74$ . Due to this change, a significant improvement in the noise level is achieved by avoiding resonance.

## SUMMARY AND CONCLUSIONS

Noise prediction is an important part of the induction motor design. While the motor designers would not be always able to predict the exact sound pressure level, most of the times, they can choose a suitable design in order to avoid critical rotating force waves.

In this paper, several techniques to control and reduce the magnetic noise are presented and validated through computer simulations. Numerical examples presented illustrate the major concern of stator tooth resonance on higher speeds, such as two

and four-pole machines which are built on smaller stator bore diameters and have deeper stator slots. Also, more common on slower speed motors, such as six-pole, stator core related noise could be avoided by choosing the appropriate design.

Performing noise measurements under load could be part of further investigations and comparison with the calculated data obtained.

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