Some Ways for Three-phase Induction Motors Electromagnetic Noise Reduction

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Abstract : Increasing awareness of industrial noise pollution and emerging stricter standards have made noise an important topic of research in electric motors. The standard three-phase induction motors, see Fig. 1, (abbreviated further as TPIM) are mass-produced as being simple, robust and rather inexpensive, as opposed to other types of electric motors. Electric motors use over half of all electricity consumed in most countries. Typically motors consume 60~80 % of the electricity for those used in the industrial sector and about 20~35 % of the electricity for those used in the commercial sector. For that is important to know their participation to the noise pollution of the environment and the efficient ways of their noise reduction. Each step in determining the ways for TPIM electromagnetic noise reduction including the methods that highlight their efficiency, are presented and explained.

1. Electromagnetic Noise of TPIM Supplied by PWM Inverters

Nowadays, induction motors are in many cases driven by pulsewidth modulation (PWM) inverters. That is why we need to extend the classic known sources (aerodynamic, electromagnetic and mechanic) with the electronic one. Figure 2[1] presents main sources for these four noise categories, electromagnetic, mechanical, aerodynamic and electronic, for the case of TPIM supplied by PWM inverters.

By using solid-state inverter drive systems for induction motors supply we have a lot of harmonics at the electrical input of our TPIM.[2] The frequency of the harmonics are given by $f_\nu = f_1 = (1+6k)\ f_1$ where $k=0$, ±1, ±2, etc. The most important harmonics are the 5th, 7th and the 11th. If these frequencies are close enough to the natural frequencies of the stator, they can produce important noise by the resonance phenomena. Induction motors demonstrate considerably less noise if the torque ripple is minimized.

When a PWM inverter drives a TPIM, acoustic electromagnetic noise caused by flux time harmonics can be considered as a function of harmonic components of induction motor current. The acoustic electromagnetic noise versus harmonic current characteristic (NHCC)

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function is defined in[2] as a response of acoustic electromagnetic noise to a single harmonic current. The NHCC function can be obtained by experiment and supplied by the motor maker in the motor's specification manual.

Figure 3(a) shows the predicted, respectively measured electromagnetic noise for the case of a TPIM of 7.5 kW.[2] By using NHCC function electromagnetic noise was calculated as the response to whole harmonic components of the

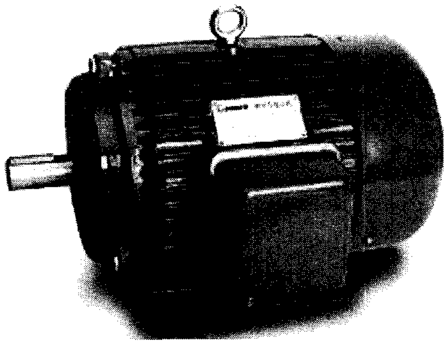


Fig. 1 The standard three-phase induction motor (TPIM)

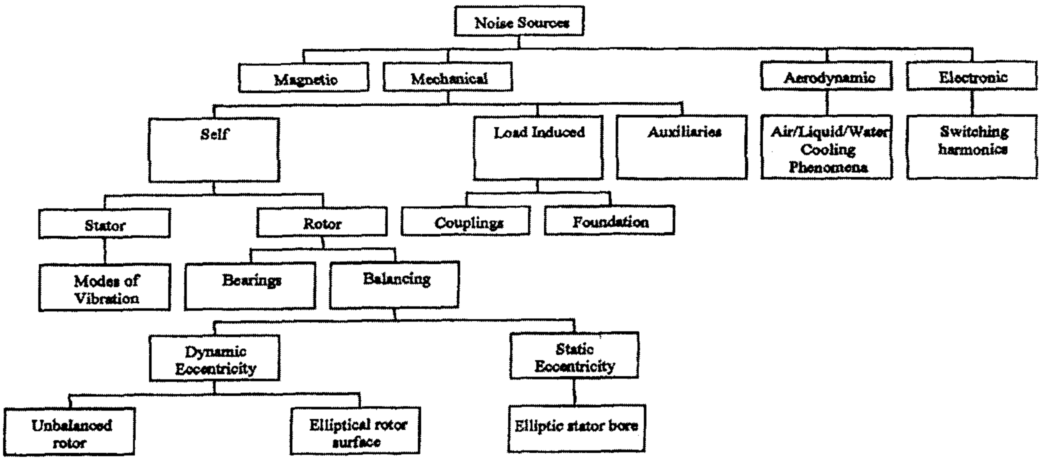
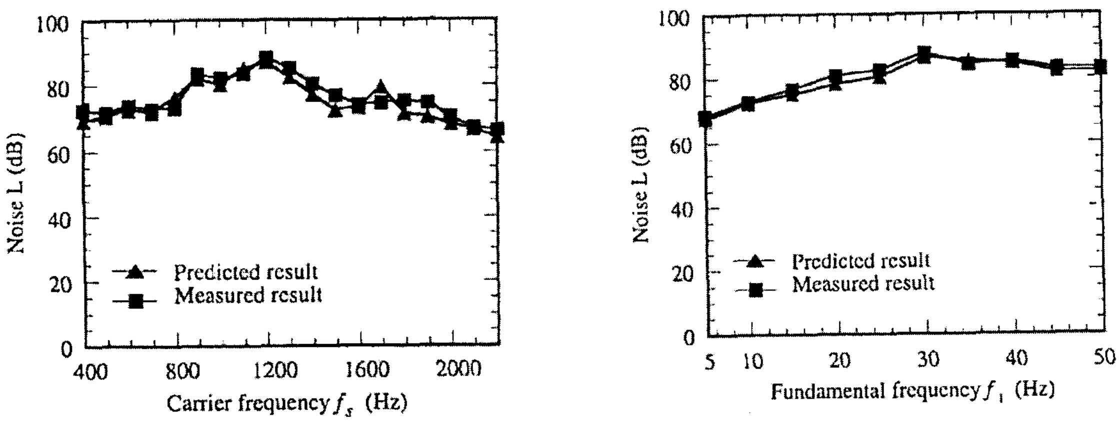


Fig. 2 Sources of noise of electric machines



(a) Motor is running in rating state

(b) Motor is running in VVVF state

Fig. 3 Prediction of acoustic electromagnetic noise induction motor current. The motor is running in rated state, and on the x-axis is the carrier frequency f_s. Figure 3(b) presents the result when the induction motor is running in variable-voltage variable-frequency (VVVF) state with PWM carrier frequency $f_s = 1\,\text{kHz}$, where the x-axis is the fundamental frequency of the inverter output or induction motor input. The predicted and measured results are in good agreement.

Acoustic electromagnetic noise caused by flux time harmonics is computed with equation (1) where i_j are the harmonic components in induction motor current and j is the frequency of harmonic current.

$$L = 10\log \cdot \left(\sum_{j>1}^{\infty} 10^{\frac{L_{0j}}{10}} \times \left(\frac{i_j}{I_{0j}} \right)^2 \right) \quad (1)$$

In equation (1) L_{0j} is the acoustic electromagnetic noise generated by a single-frequency harmonic current I_{0j}. The flow chart of predicting acoustic electromagnetic noise, presented in Fig. 4, contains the equation (1).

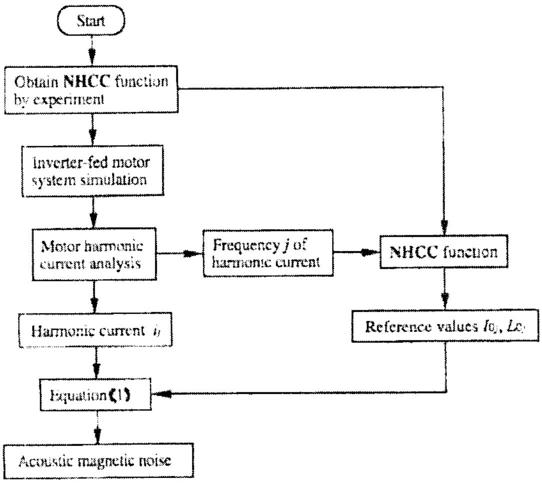


Fig. 4 Flow chart of predicting acoustic electromagnetic noise

2. Electromagnetic Noise of Constant Voltage Supplied TPIM

2.1 Vibrations Modes and Frequencies

For these induction motors we must consider three main noise components:

- Aerodynamical noise A, exclusively caused by the air-flow;
- Fundamental noise F, caused by the no-load running at full voltage, the fan being removed. (F roughly represents the logarithmic sum between electromagnetic noise, E, and the mechanical noise, M);
- Load noise L, which occurs during operation at rated load.

Depending on the base speed the three components have different contribution, as it is shown in Table 1 for the case of ABB's range of TPIM.[3] For the higher speed motors (2-pole motors) the aerodynamical noise, A, is the most important. The load noise is also important and its participation in the total noise

Table 1 TPIM noise components contribution

Pole pairs	Noise component		
	A %	F %	L %
2	70	20	10
4	50	25	25
8	10	30	60

is growing with the number of poles. The fundamental noise F (the electromagnetic noise combined with the mechanical which can not be separated for the practical measurements), exhibits an important contribution of 20 to 30 %, also, function of the poles motor's number.

Simulation software is available in order to give to the designers the best configuration to minimize electromagnetic noise and vibration. The main source of electromagnetic noise in induction machines is created by the interaction of induction waves (fundamental and harmonics) developed in the air gap. These waves are generated due to winding distribution and variation of the air gap permeance imposed by the stator and rotor slots, saturation and eccentricity. The most useful techniques for electromagnetic noise diminishing are a proper design witch checks the saturation be kept inside the electromagnetic circuit below the prescribed values for the ferromagnetic material, the correct choice of stator and rotor number of slots, the skewing of the rotor slots, the appropriate opening of the slots as the use of sinusoidal winding.

The challenging facts from the technological point of view of manufacturing low-noise TPIM are a minimum eccentricity due to a good project implementation as to a rotor right balance of the rotor. The eccentricity based electromagnetic noise can be reduced by using parallel path in stator winding.[4]

Jordan was the first who calculated the electromagnetic noise starting from the induction harmonic setting.[5]

Basically a computing noise program starts with the establishing of radial forces generated by interaction of the induction harmonics, the deformation of the stator surface, the excitation frequency of this force, the natural frequency of stator being calculated for each vibration mode. Vibration mode r plays an important role in the electromagnetic noise generation. It results from the combination of the induction harmonic pole pairs and can be considered important until, at maximum, $r=4$ for small machines and till $r=20$, for larger TPIM.[6] As an example, E harmonics for a 7.5 kW, 4 poles TPIM, having computed radial modes r according to relation (1) for the frequencies f_r, determined with relation (2) are presented in Table 2. The most dangerous modes are for $r=0$ to 4. For these modes were computed the acoustic pressure levels in dB(A) by the computing program. For $r=0$, the force has a

Table 2 E harmonics for a TPIM of 7.5 kW, 4 poles

	f, Hz	E harmonics in dB(A)				
		-2	-3	4	-9	12
-1	697	44.0				
		$r=4$				
	597	40.8				
1	697		57.9			
			$r=4$			
	796		60.6			
-2	1393			38.5		
				$r=4$		
	1294			37.6		
-4	2786				40.7	
					$r=4$	
	2687				40.5	
5	3483					52.1
						$r=4$
	3582					52.2

uniform distribution along stator bore, varying in time. We have a rotating radial force over the stator or rotor for $r=1$. For $r=2$ or more, there are rotating radial forces applied on $2r$ points of stator which deform it periodically in time and space. We get the most critical case for deformation and noise generation when $r=2$. This is the easiest way to deform the motor frame. Figure 5 presents radial vibration modes for $r=1$ to $r=5$.

In the computing program[7] the modes r were computed according to relation (2) and the corresponding frequencies were given by relation (3):

$$r = p \cdot (6 \cdot k_1 + 1) \pm (k_2 \cdot Z_2 + p) \quad (2)$$

$$f_r = f_1 \cdot \left[\frac{k_2 Z_2}{p} \cdot (1-s) \ {}^{+2}_{0} \right] \quad (3)$$

Where $k_2 = 0, \pm1, \pm2, \pm3$

Z_2 = number of rotor slots

s = slip

p = pairs of poles

f = supply frequency

In this case electromagnetic noise components are joined by vibration mode at calculated

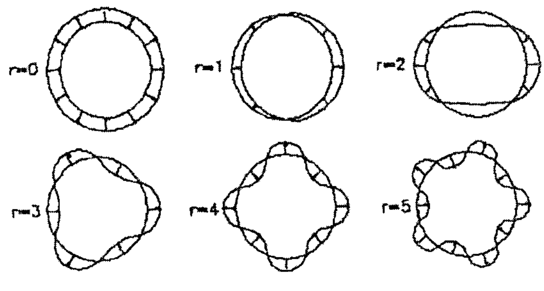


Fig. 5 Vibration modes from $r=0$ to $r=5$

frequencies for the first two causes presented in Table 3.[6] Table 3 synthesized the vibration modes and their frequencies for saturation and eccentricity harmonics, also. We assigned ν for the stator field harmonics, μ for the rotor field harmonics, Z_1 and Z_2 being the stator, respectively the rotor slots number.

The full comparison between computed and measured acoustic levels for the case of five TPIM, having a Y stator winding connection and being supplied at 220 V and 50 Hz is presented in Table 4.[7] Main characteristics of the analyzed TPIM are shown in Table 5 and Table 6 presents main tested parameters for TPIM with different rotor's skewing.

The load noise was not computed nor tested for this motor, its value being not requested for usual measurements according to the

Table 3 Causes of electromagnetic noise

Origin	Vibration mode	Frequency
Stator harmonics with themselves	$r=\nu_1+\nu_2$	$f_r=2f$
Stator harmonics with rotor harmonics	$r=\mu_1+\nu$	$f_r=f_\mu \pm f_\nu$
Stator harmonics with rotor harmonics induced by saturation harmonics	$r=\mu_s+\nu$	$f_r=f_{\mu s} \pm f_\nu$
Stator harmonics with rotor harmonics induced by eccentricity harmonics	$r=\mu_s+\nu$	$f_r=f_{\mu\varepsilon} \pm f_\nu$
Rotor harmonics with stator saturation harmonics	$r=\nu_s+\mu$	$f_r=f_{\nu\varepsilon} \pm f_\mu$
Rotor harmonics with stator eccentricity harmonics	$r=\nu_\varepsilon+\mu$	$f_r=f_{\nu\varepsilon} \pm f_\mu$

international standard.[8] However, the standard stipulates the opportunity of load noise acoustic levels declaration, as a special customers request, agreed formerly by a mutual contract with the manufacturer.

One method to measure acoustic noise of loaded machines is to construct a noise testing enclosure. But a very efficient method to obtain the acoustic power level of loaded TPIM or other equipment is to use Sound Intensity measurements.[9]

2.3 Effect of Slot Combination

The vibration of the stator core depends strongly on the number of slots, that is the combination between the number of the stator and rotor slots. The aim of the rotor slots skewing is to reduce the influence of the slots harmonics. An unsuitable slots combination causes a large vibration and acoustic noise. In (10), the authors concluded that the level of acoustic noise order is dependent on the first space harmonic order. They expressed the lower harmonic order h_l with relations (4) and (5).

$$h_l = (Z_1 - Z_2)/p \pm 2 \tag{4}$$

$$h_l = (Z_1 - Z_2)/p \tag{5}$$

Table 4 Comparison between computed and measured noise components for five TPIM

TPIM No.	1		2		3		4		5	
L_p	Comp	Meas.	Comp	Meas.	Comp	Meas.	Comp	Meas.	Comp	Meas.
L_F[dB(A)]	65.2	68.2	58.8	57.7	52.5	55.3	60.9	61.2	63.7	63.6
L_A[dB(A)]	63.1	63.6	54.6	54	47.6	48	40.7	42	45	49.5
L_{Unload}[dB(A)]	67.3	69.5	60.2	59.2	53.8	56	61	61.3	63.8	63.8

Table 5 Main characteristics of the analyzed TPIM

TPIM No.	1	2	3	4	5
Power in kW	7.5	3	3	1.1	3
Pole number	4	4	6	6	8
Stator slots, Z_1	36	36	36	36	36
Rotor slots, Z_2	28	28	39	39	39

Table 7 Lower space harmonics of force, h_l

Rotor slots number, Z_2	38	40	42
$(Z_1 - Z_2)/p$	5	4	3
$(Z_1 - Z_2)/p+2$	7	6	5
$(Z_1 - Z_2)/p-2$	3	2	1

Table 6 Main tested parameters for TPIM with different rotor's skewing

Parameter	I_0	I_R	η	$\cos\varphi$	T_S/T_R	T_M/T_R	I_S/I_R	L_W
Skew,% t_1	[A]	[A]	%	-	p.u.	p.u.	p.u.	dB(A)
6.4	5.87	15.85	83.83	0.858	2.09	2.56	5.96	73.9
20.5	5.96	15.95	83.27	0.858	2.18	2.51	5.78	73.2
52.7	5.63	16.03	83.55	0.851	2.34	2.53	5.18	73.2
72.6	5.97	16.05	84.13	0.844	2.31	2.31	5.20	68.5
93.7	5.83	16.60	81.86	0.839	2.47	2.07	5.26	63.6

For the case of three TPIM with $p=2$, having $Z_1=48$ and $Z_2=38$, 40 and 42, the lower space harmonics of electromagnetic force is presented in Table 7. For $Z_2=42$ it was detected a first space harmonic order.

Simulation results presented in Table 7 showed that the TPIM with 42 rotor slots had $h_l=1$ and l = -23 for the harmonic order of the electromagnetic force.

By checking the variation of acoustic noise with current frequency it was found a dangerous frequency at 83.3 Hz, and multiplying it with the harmonic order -23 the resonant frequency was established for 1917 Hz. Spectrum analysis presented in Fig. 6(acoustic noise in dB function of frequency in kHz) for this TPIM certifies the assumption that the level of acoustic noise order is dependent on the first space harmonic order.

2.4 Slot Skewing Optimization

The aim of the rotor slots skewing is to reduce the influence of the slots harmonics. Slot skewing is appropriate for small TPIM, but it is not advisable for large motors having hundreds of kW. For the latter were reported large axial forces and torsion resonance.[11]

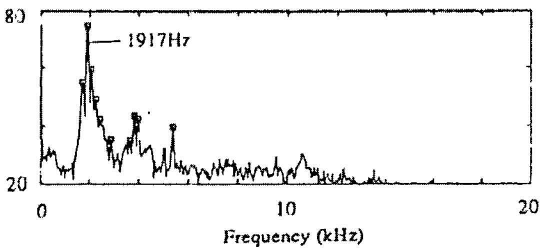


Fig. 6 Acoustic noise spectrum for $Z_2 = 42$

Starting from the magnet forces per unit volume F_m, we can obtain the deformation of the magnetic core of the electrical motor, proportional to the square of the electromagnetic flux density and then one can compute the average F_{rm} radial force over the l length of the magnetic core.

The skew factor for the μ rotor harmonic is defined as

$$f_{s\mu} = \frac{\sin\left(\mu \cdot \frac{\alpha_s}{2}\right)}{\mu \cdot \frac{\alpha_s}{2}} \tag{6}$$

For the rotor skew cage experimental study it was used a TPIM of 7.5 kW, having 4 poles, Y connected in stator, at 220 V and 50 Hz.[12] The considered motor had a stator/rotor slot number combination of 36/28, and was provided with five different skewed rotors, the skewing being expressed as a percentage of the stator slot pitch, t_1.

Experimental results presented in Table 6 have shown an important decrease of the total noise with the slots skewing. The general rule of one stator slot pitch skewing for the rotor slots is considered efficient and sufficient for the case of this type of 4-pole TPIM. Also, in Table 6, one can see the variation of other parameters as the unload current, I_0, the rated current, I_R, the efficiency and power factor and the relative values of starting and the maximum torque against the rated one, the starting current ratio to the rated current and the sound power levels L_W for different rotor slot skews.

2.5 Carter's Factor Optimization

Flux density in the air gap of the TPIM has harmonics as result of the slot inserting of the windings. So-called slots harmonics have the order k $Z_{1,2}/p \pm 1$ and are superposing over the fundamental of the flux density in the air gap. The Carter factor is dependent of the stator slot pitch, the air-gap length between the stator and rotor and the opening of the stator slot. The experiment checked the influence of Carter's factor and of this one combined with the rotor skew upon the electromagnetic noise of TPIM.

The results are presented in Table 8 and it is clear that Carter's factor contribution is a function of the skew of the rotor slots, also. While we have a noise reduction of electromagnetic noise of 4.5 dB for the case of unskewed slots, this difference diminishes to only 1.5 dB for the case of skewed slots.

2.6 Sinusoidal Winding Implementation

Here is a good question: It is possible to diminish electromagnetic noise by using sinusoidal winding? The answer is 'Yes', as it was proved by other researches in the field.[13, 14]

(a) Equal coils, two layers, 4-slots pitch, $w_1' = w_2' = w_3'$.

(b) Concentric coils, pitch 3/4/5 slots, two layers, $w_1' = w_2' = w_3'$.

Table 8 Carter's factor and rotor slots skew contribution to the electromagnetic noise, dB(A)

Carter factor	1.226	1.598
For skew = 0.060 t_1	64.5	69
For skew = 0.726 t_1	57	58.5

(c) Unequal coils, one/two layers, $w_1' = 0.667$; $w_2' = 0.333$

(d) Concentric coils, sinusoidal winding, two layers, $w_1' = 0.5321, w_2' = 0.3473$, $w_3' = 0.1206$

Here was used a method for spatial harmonics harmonics analysis. The actual winding is replaced by a fictitious one with diametric pitch and a single coil with w_1 turns, preserving the total winding flux and also the electromotive-motive force. Starting from the equivalent winding made by concentric coils, the relation for ν order spatial harmonic mmf is developed for the general case of different turn numbers per coil.

We can see in Fig. 7(a) the usual winding used in common manufacturing. The winding represented in Fig. 7(b) is the same from all points of view with the first one but it has concentric coils instead of equal coils. Now one can see that the big coil (coil μ, 5 slots pitch) can be replaced without any change in the air gap mmf with the medium coil (coil μ, 4 slots pitch) as in Fig. 7(c). In this case, the performance is the same but the copper weight was about 5 % lower and also the manufacturing time was reduced.

A compromise was made in case of sinusoidal winding presented in Fig. 7(d). For this case the fundamental winding factor of the last winding is 0.9023 instead of 0.9452, the initial one, but the harmonic 2 to 8 are absent.

The described windings have been experimented on a 1.5 kW, 8 poles TPIM and the noise for the sinusoidal winding from Fig. 7(d), were with 3 dB(A) lower (from 65 to 62 dB(A)). Also, for this motor the measured starting torque was 20 % bigger than the one measured for cases 7(a) to 7(c) windings.

3. High-efficiency Motors and Their Noise

The Energy Policy and Conservation Act, signed into law in 1992, imposed high-efficiency motors (HEM) in the USA. Since then they were developed new series of electric motors, (TPIM as representative part of them) as high and premium efficiency motors. Premium efficiency motors offer improved efficiencies of 2 to 8 % over standard motors. The benefits of using high-efficiency motors (HEM) are wide-ranging.

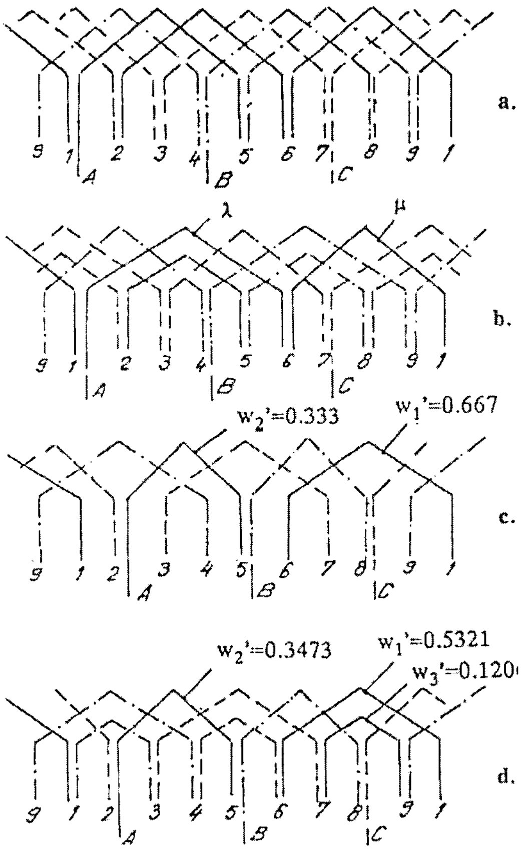


Fig. 7 Three-phase windings with 1.5 slot/pole and phase

Among advantages of use of these types of motors we have to enumerate an excellent power saving, extension of coil winding life through low temperature rise, the low maintenance cost as a low noise level. The last advantage is interesting from the point of view of environment acoustic protection, and the spreading of these types of motors must be welcomed everywhere. The analyzing of noise reduction implemented by these motors was presented in some papers[13, 14] and the results can be seen as very positive.

As a characteristic, high-efficiency motors use more materials inside them (for example, increased copper up to 60 %) and that is why their mechanical impedance is bigger and consequently, their vibration and electromagnetic noise lower. But, HEM also has an improved fan and mechanical part that was improved. That's why the electromagnetic noise and total noise of these motors is much lower than the standard ones. They have to be considered as belonging to the class of low-noise electric motors.

For the electromagnetic noise calculus we can roughly use next relations that take into account the mechanical impedance of the stator starting from geometrical sizes

Table 9 Electromagnetic noise L_E decreasing with h_{js}/D_j variation

h_{js}/D_{js}	1.05	1.1	1.2	1.3	1.4
L_E, dB	-1.27	-2.48	-4.75	-6.48	-8.8

$$L_m \sim 20\lg\left(\frac{D_{js}\cdot D}{h_{js}}\right) \quad for\ r=0 \tag{7}$$

$$L_m \sim 20\lg\left(\frac{D_{js}\cdot D}{h_{js}}\right)^3 \quad for\ r\geq 2 \tag{8}$$

Where

D_{js} is the middle diarr ter of the stator joke

D is the internal diameter of the stator core

h_{js} is the thickness of the joke

In a first step we can evaluate the electromagnetic noise diminishing considering the worst harmonic components for $r\geq 2$ by improved ratio of h_{js}/D_{js} as it is presented in Table 9.

This effect is consolidated by the saturation harmonics decreasing as a result of a larger amount of incorporated magnetic material.

4. Conclusions

There have been presented some specific ways developed on the length of previous years for TPIM electromagnetic noise mitigation.

Low noise electrical motors represent a challenging goal that deserves our need for an unpolluted environment.

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