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ANALYSIS OF THE EFFECTS OF TIME HARMONICS ON THE RADIATED SOUND POWER OF VARIABLE SPEED INDUCTION MOTORS

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1. INTRODUCTION

There has been an increasing demand for variable speed drives in industries because some technological applications require variable speed operations and/or because significant energy savings can be achieved. However, the use of frequency converters in driving induction motors has resulted in significant increase in both acoustic and vibration levels. Such increase has been mainly attributed to the time harmonics introduced by the inverters. As a result, most studies have been concentrated on designing inverters which eliminate undesirable harmonics ([1]-[8]). However, there is generally a lack of understanding of the vibro-acoustic behaviour of inverter-fed induction motors and the electrical design of these drives is usually far more advanced than the understanding of their acoustical performance. As noted by Belmans & Geysen [1], the electromagnetic excitation and the mechanical response of the motor structure are inter-related and even a purely sinusoidal supply can produce unacceptable noise and vibration levels. Subsequently, Timar & Lai [9] presented an algorithm for establishing the lowest limit of acoustic noise radiation in the absence of time harmonics (i.e., for an ideal frequency converter). The objective of this paper is to consider the effect of time harmonics on the radiated sound power level of inverter-fed induction motors.

2. RADIAL TENSILE STRESS WAVES

In the derivations presented here, the following assumptions are made:

- the induction motor is a linear magnetic circuit and the time harmonics do not cause any saturation in the iron core;
- the change in speed due to the change in supply frequency is a quasi-stationary process.

The radiated sound power W (see, for example, [10], [11]) is given by

$$W = \rho c S_{rad} \sum_r \sigma_r v_{fr}^2 \qquad (1)$$

where ρ is the air density, c is the speed of sound in air, S_{rad} is the machine surface area, σ_r is the radiation factor for vibration mode number r and frequency f_r. The rms value of the vibration velocity v_{fr} can be calculated from the tensile stress wave $p_{sr} = P_r \cos(rx - 2\pi f_r t)$ as $v_{fr} = \sqrt{2}\pi f_r \sum_j H_j P_r$; where x is the space coordinate along the centreline of the air gap; H_j , the system function of the motor as a vibrating system, can be determined experimentally. The radial tensile stress wave p_s can be determined according to Maxwell's law from

$$p_s = b^2 / 2\mu_o \qquad (2)$$

where μ_o is the magnetic permeability. The total air gap flux density b may be decomposed into:

$$b = b_{\mu=1,\nu} + b_{\mu,\nu} + b_{\lambda,\nu} + b_{\lambda e,\nu} \qquad (3)$$

where $b_{\mu=1,\nu}, b_{\mu,\nu}, b_{\lambda\nu}$ and $b_{\lambda e,\nu}$ are the flux density due to the space fundamental (μ=1) of all time harmonics; the flux density due to the time fundamental and the space harmonics of the time harmonics; the rotor flux density space harmonics and the rotor eccentricity harmonics due to time harmonics in the supply respectively. These can be expressed as:

$$b_{\mu=1,\nu} = \sum_\nu B_{\mu=1,\nu} \cos(px - \nu\omega_1 t)$$

$$b_{\mu,\nu} = \sum_\mu \sum_\nu B_{\mu=1,\nu} \cos(\mu px - \nu\omega_1 t) \qquad (g = \pm 1, \pm 2, ...) \qquad (4)$$

$$b_{\lambda\nu} = \sum_\lambda \sum_\nu B_{\lambda,\nu} \cos(\lambda px - \omega_{\lambda\nu} t) \qquad b_{\lambda e,\nu} = \sum_{\lambda e} \sum_\nu B_{\lambda e,\nu} \cos(\lambda_e px - \omega_{\lambda e,\nu} t)$$

where p is the pole pair number; μ =2mg+1 is the order of stator flux density space harmonics; m is the no. of phases; ω_1 is the fundamental angular velocity; ν =6k+1(k=0,±1,±2,...) is the order of time harmonics; $\omega_{\lambda,\nu}$ is the angular frequency of the rotor space harmonics and $\omega_{\lambda e,\nu}$ is the angular frequency of the rotor eccentricity space harmonics.

By substituting equations (3) and (4) into equation (2), a complete collection of the mode numbers and frequencies of all the force wave groups can be obtained and listed in Table 1. It is immediately obvious that the time harmonics in the supply do not generate force waves with new mode numbers. However, new force wave components with new frequencies are generated, thus increasing the potential coincidences with the mechanical resonance frequencies of the motor and leading to increased noise and vibration levels.

3. EFFECT OF TIME HARMONICS ON SOUND POWER

In the absence of local resonance (Fig. 1), the electromagnetic sound power due to purely sinusoidal supply is expected to increase with speed in the constant flux speed domain because the exciting force frequency increases; it reaches a maximum value at f_{mains}, then it starts to decrease with increasing speed due to flux weakening. In the low speed domain, the increase in electromagnetic sound power due to time harmonics is larger than in the higher speed domain because it is more difficult to reduce the time harmonics when the fundamental frequency is low. When local resonance is present (for example, 3 resonances in Fig. 2), the effect of time harmonics in the supply on the total sound power will be more prominent in the low speed range and its effect will gradually decrease with increasing speed as the aerodynamical and mechanical noise becomes more dominant than electromagnetic noise at high speeds.

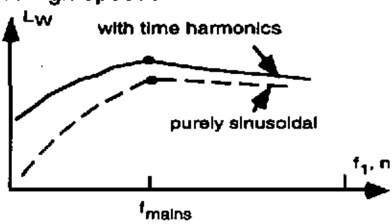

Fig.1 Electromagnetic sound power (without local resonance).

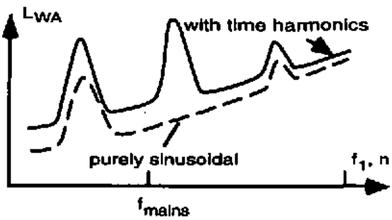

Fig. 2 Total sound power (with local resonance).

4. CONCLUSIONS

By assuming a quasi-stationary process for the change in speed and no iron saturation, it has been shown that the time harmonics in the supply do not produce new mode numbers for the force waves but produce new force wave components with new frequencies. The effects of the time harmonics on increasing electromagnetic and total sound power have been shown qualitatively to be decreasing with increasing speeds.

ACKNOWLEDGMENT

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Table 1 The mode numbers and frequencies of electromagnetic force wave components in inverter-fed induction motors

Origin of the force wave	Mode number $\lvert r \rvert$	Frequency $\lvert f_r \rvert$
$\sum_{v} b^2_{\mu=1,v}$	0 or 2p	0 or $2vf_1$
$\sum_{\mu}\sum_{v} b^2_{\mu,v}$	(0 or 4mgp) + 2p	0 or $2vf_1$
$\sum_{\mu}\sum_{v} b^2_{\lambda,v}$	(0 or $2g'S_2$) + 2p	0 or $2f_1[v + g'S_2(1 - s_1)/p]$
$\sum_{\lambda e}\sum_{v} b^2_{\lambda e,v}$	(0 or $2g''S_2$)+ 2p ± 2	0 or $2f_1[v+(g''S_2 \pm 1)(1-s_1)/p]$
$\sum_{v}\sum_{v} 2b_{\mu=1,v}b_{\mu=1,v}$	0 or 2p	$f_1[6(k \pm k') + (0 \text{ or } 2)]$
$\sum_{\mu}\sum_{v} 2b_{\mu,v}b_{\mu',v'}$	$2mp(g \pm g')$ + (0 or 2p)	$f_1[6(k \pm k') + (0 \text{ or } 2)]$
$\sum_{\lambda}\sum_{v} 2b_{\lambda,v}b_{\lambda',v'}$	$S_2(g' \pm g'')$ + (0 or 2p)	$f_{\lambda,v} \pm f_{\lambda',v'}$
$\sum_{\lambda e}\sum_{v} 2b_{\lambda e,v}b_{\lambda e'v'}$	$S_2(g'' \pm g''')$ + (0 or 2p)	$f_{\lambda,v} \pm f_{\lambda',v'}$
$\sum_{\lambda e}\sum_{v} 2b_{\lambda e,v}b_{\lambda e'v'}$	$S_2(g'' \pm g''')$+ (0 or 2p)+(0 or+2)	$f_{\lambda e,v} \pm f_{\lambda e',v'}$
$\sum_{\mu}\sum_{v} 2b_{\mu=1,v}b_{\mu,vv'}$	p[2mg + (0 or 2)]	$f_1[6(k \pm k') + (0 \text{ or } 2)]$
$\sum_{\mu}\sum_{v} 2b_{\mu=1,v}b_{\lambda,v}$	$g'S_2$+ [0 or 2p]	$f_1[g'S_2(1 - s_1)/p+(0 \text{ or } 2v)]$
$\sum_{\lambda e}\sum_{v} 2b_{\mu=1,v}b_{\lambda e,v}$	$g''S_2$+ [0 or (2p±1)]	$f_1[(g''S_2 \pm 1)(1 - s_1)/p+(0 \text{ or } 2v)]$
$\sum_{\mu}\sum_{\lambda}\sum_{v} 2b_{\mu,v}b_{\lambda,v}$	$g'S_2 \pm 2mgp$ + [0 or 2p]	$f_1[g'S_2(1-s_1)/p + (0 \text{ or } 2v)]$
$\sum_{\mu}\sum_{\lambda e}\sum_{v} 2b_{\mu,v}b_{\lambda e,v}$	$g''S_2 \pm 2mgp$ + [0 or (2p±1)]	$f_1[(g''S_2 \pm 1)(1-s_1)/p+(0 \text{ or } 2v)]$
$\sum_{\lambda}\sum_{\lambda e}\sum_{v} b_{l,v}b_{\lambda e,v}$	0 or $[S_2(g'+g'')+2p \pm 1]$	$f_1[S_2(1-s_2)(g' \pm g'')/p \pm (1-s_1)/p+(0 \text{ or } 2v)]$

Here S_2 is the rotor slot number; s_1 is the rotor slip referred to the fundamental.