Magnetic noise from on-board electric motor

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Abstract: Maxwell pressure is the cause of stator deflection at the origin of acoustic noise radiated by stator. That is why precise determination of air-gap radial flux density \(B_g\) is of prime importance. It could be obtained by finite element method, semi numerical or totally analytic method with computation of magneto motive force and permeance. Slot number, pole pair number and PWM affecting acoustic behavior must be included in flux density computation. The vibratory and acoustic behaviour of a variable-speed induction machine due to Maxwell forces is detailed and validated by experimental results on several motors.

Keywords: vibration, harmonics, flux density, PWM

1. Introduction

Acoustic comfort is an increasingly important factor at the design stage of electric motors [1-3]. Many studies were realized in the past [4,5] and these recent years on several motor types, especially: Switched Reluctance Motor [6,7] and Induction Motor [8-11,15]. The acoustic noise generated by electric motors can come from aerodynamic noise (fans, windage noise, …), mechanical noise (bearings, …) and magnetic noise which is caused by magnetic forces acting on the active materials of the machine. In some cases (generally: starting phases), the global sound pressure level (SPL) is dominated by the magnetic noise radiated by the motor and this noise can be quickly annoying as its spectrum contains high tonalities. This study focuses on Induction Motor usually chosen for low cost and high reliability qualities, as example, it is the more used traction motor in railway domain. Thanks to dedicated models, the method detailed with this motor can be extended to other kind of electric motors (available for electric or hybrid vehicles).

The Maxwell pressure simplified expression (1), is the cause of stator deflection at the origin of acoustic noise radiated by stator. That is why precise determination of air-gap radial flux density \(B_g\) is of prime importance. It could be obtained by numerical method like Finite Element Method (FEM), semi numerical method with help of permeance network or totally analytic method with analytic computation of magneto motive force and permeance. The analytic computation of air-gap permeance is detailed in this article. It is shown that rotor and stator slot numbers, must be included in permeance computation to take into account their influence on acoustic behavior. Then, a mechanical and acoustic model of electric motor is quickly described and finally experimental results using these models are shown.

\[P_M = B_g(t, \alpha)^2 / (2\mu_0)\]  

2. Flux density computation

Finite Element Method (FEM) is the best method to compute precisely mechanical behavior of machine and electromagnetic forces taking into account saturation, but it is also the most time consuming [12]. Semi numerical methods, with help of permeance network, have almost the same advantages and drawbacks for flux density computation [13-14]. However, a small network does not allow local saturation computation and a big one become time consuming too. Furthermore, permeance network is not useful for geometry modifications. If local saturation is not a main problem, analytic method is suitable to compute electromagnetic forces depending on flux density [15]. This method is the less time consuming and can be precise enough for prediction of acoustic noise tendencies (Fig. 1). The air-gap radial flux density \(B_g\) computation is a function of air-gap permeance per unit area and magneto motive force from stator and rotor as shown equation (2). \(\Lambda\) is the permeance per unit area, given by (3), where \(\mu_0\) is
the air magnetic permeability and \( g_f \) is the mean flux density line length of the non constant air-gap taking into account rotor and stator slotting.

\[
B_g(t, \alpha_s) = \Lambda(t, \alpha_s)(f_{\text{ms}}^+(t, \alpha_s) + f_{\text{ms}}^-(t, \alpha_s)) \quad [2]
\]

\[
\Lambda(t, \alpha_s) = \frac{\mu_0}{g_f(t, \alpha_s)} \quad [3]
\]

3. Computation of airgap permeance including slot numbers

As shown equation (3), \( g_f \) is the mean flux density line length, approximated as a piecewise constant function which takes four different values according to the rotor and stator slot relative position. By this way, the permeance function includes slotting effect especially important for spatial order and frequency of excitation forces acting on stator. Table 1 presents some slotting forces expressions with \( f_s \) the supply frequency, \( s \) the rotor slip, \( p \) the number of pole pairs, \( Z_r \) and \( Z_s \) the numbers of rotor and stator slots and \( k_r, k_s \) the harmonic factors. A spatial waveform and spectrum of permeance is presented Fig. 2, harmonics are function of parameters shown in table 1.

Table 1. Spatial order and frequency of main slotting forces expressions

<table>
<thead>
<tr>
<th>Function</th>
<th>Frequency ( f )</th>
<th>Spatial order ( m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{\text{slot}}^- )</td>
<td>( f_s(k_rZ_r(1-s)/p - 2) )</td>
<td>( k_rZ_r - k_sZ_s - 2p )</td>
</tr>
<tr>
<td>( f_{\text{slot}}^0 )</td>
<td>( f_s(k_rZ_r(1-s)/p) )</td>
<td>( k_rZ_r - k_sZ_s )</td>
</tr>
<tr>
<td>( f_{\text{slot}}^+ )</td>
<td>( f_s(k_rZ_r(1-s)/p + 2) )</td>
<td>( k_rZ_r - k_sZ_s + 2p )</td>
</tr>
</tbody>
</table>

4. Exciting force and mechanical model

4.1 Exciting force

As shown Fig. 4, the force distribution (Maxwell pressure) is developed into a 2D Fourier series where major lines are detailed according to table 1. This simulation has been done with sinus mmf hypothesis, at no load (neglecting the slip) and fundamental frequency (50Hz). Pressure \( P_{mw} \) is composed of spatial order \( m \) and frequency \( f \) (respectively pulsation \( w \)) in Figure 4 and 5.

Fig. 3 shows computed evolution (different scales) of permeance, MMF and Maxwell pressure in the air gap.

Fig. 4. Example of 2D Fourier transform of simulated radial Maxwell pressure (no load case, sinusoidal mmf, \( f_s = 50 \text{ Hz}, \ s = 0 \)) in [500 Hz,3000 Hz] range
4.2 Mechanical model

Then, stator must be modeled, and its static deflections $Y_{mw}$ (equation 4) under the sinusoidal loads $P_{mw}$ can be computed. Classical finite element models are not detailed here. They can be used for precise results but they are usually too much time consuming for optimization method needing a big amount of computations because of multiple loops. Therefore, a simplified analytical model (vibratory and acoustic) of the stator as a 2D ring is presented here. It can give very quickly good tendencies even if precise results are out of its scope.

$$Y_{mw}^s = 12R_a R_m^3 P_{mw} / (Eh^3(m^2 - 1)^2)$$  [4]

where $h$ is the thickness of the stator back core (yoke), $R_m$ is the mean stator radius (computed without considering the teeth), $E$ is the stator’s Young modulus in radial direction and $R_a$ is the stator bore radius. Then, dynamic displacements $Y_{mw}^d$ are computed through a second order transfer function:

$$Y_{mw}^d = Y_{mw}^s \left[ (1 - f_m^2 / f_m^2)^2 + 4\zeta_m^2 f_m^2 / f_m^2 \right]^{-1/2}$$  [5]

where $\zeta_m$ is the damping coefficient, and $f_m$ is the $m$-th stator circumferential mode natural frequency. $\zeta_m$ lie between 1% and 4%, it is computed using the experimental established by Yang [3]. The natural frequencies are computed modeling the stator sheet as a 2D ring, they are detailed in [1]. The natural frequencies computation was validated by FEM and tests [10,11], with some operational or experimental modal analysis (Fig. 6).

4.3 Acoustic analytic model

The velocity vibration waves $v_{mw} = w Y_{mw}$ and the associated radiated power $W_m$ are then computed as

$$W_m(f) = \rho_0 c S \sigma_m(f) |v_{mw}|^2 / 2$$  [6]

where $\sigma_m$ is the radiation factor, $\rho_0$ the air density, $c$ the speed of sound and $S$ the stator outer surface including frame. The radiation factor computation is analytically computed using the model of a pulsating sphere [2]. The total sound power $W(f)$ is the sum of the sound power radiated by each mode. The total sound power level associated to a given frequency is then:

$$L_n(f) = 10 \log_{10}(W(f)/W_0), \; W_0 = 10^{-12} W$$  [7]

5. Experimental results

5.1 Sinus fed motor

In Fig. 7 which represents vibration for sinus fed motor, the peak around 625 Hz corresponds to the excitation mode 2 which is not dangerous in this case because it is far from the mode 2 resonance frequency (2400 Hz) of the induction motor. We can also see the resonance mode number 1 at 1200 Hz.

5.2 PWM fed motor

The use of PWM to feed the induction machine implies increasing the exciting force harmonics content. The peaks coming from the fundamental of current and machine design still remain, like the peak at 625 Hz. But a lot of harmonics coming from PWM are susceptible to excite the mechanical resonances around 1200 Hz and 2400 Hz for instance. Figure 8 shows a vibration spectrum for...
natural PWM with 1800 Hz switching frequency. We can see 625 Hz and 1200 Hz peaks but the most important peak is the 2400 Hz one because an important exciting force of mode number 2 is generated at 2400 Hz (mode 2 mechanical resonance) by the PWM.

Fig. 8. Vibration spectrum (PWM 50Hz/1800Hz)

6. Conclusion

The Maxwell pressure is the cause of stator deflection at the origin of acoustic noise radiated by stator. That is why precise determination of air-gap radial flux density $B_g$ is of prime importance. Analytic computation of magneto motive force and permeance gives flux density. This article shows that slotting effect can be efficiently included in permeance computation. Moreover, the influence of PWM harmonics must often be taken into account. Simulated acoustic results using electromagnetic and mechanical models show good accuracy with experimental results. This method is now used to improve acoustic behavior of induction motors at design and control stage.

7. References