STATIC ECCENTRICITY AS A CAUSE FOR AUDIBLE NOISE OF INDUCTION MOTORS

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Abstract

Static eccentricity of the rotor with respect to the stator bore of electrical machines with small airgaps leads to additional harmonics in the magnetic flux density field, the so-called *eccentricity fields*. This way rotor eccentricity, in most cases due to machining and production tolerances, gives rise to magnetic forces which can produce a considerable amount of audible noise, when the frequencies of these forces are close to the structural stator eigenfrequencies. This paper presents a way to calculate these eccentricity fields, force components and their characteristics.

1. Introduction

In designing and manufacturing induction motors, it is necessary to allow dimensional tolerances on every part, e.g. on stator and rotor stampings, stator frame, rotor assembly, bearings and endshields. Generally speaking, the larger the machining tolerance, the lower the manufacturing cost [1]. On the other hand, these tolerances are often related to the performance of the machine, since an increase in tolerance causes a deterioration of the performance; e.g. lower efficiency, torsional vibrations, radial oscillations, shorter lifetime due to increased overall temperature or hot spots.

In several papers (e.g. [2,3,4]) it has been reported that audible noise data vary considerably between nominally identical small machines, and this variation is most likely to be caused by the variations of the dimensions of parts between the tolerance limits in mass production.

For electric machines with small airgaps, such slight variations in the dimensions of the stator, rotor, endshields and bearings may lead to a considerable variation of the airgap length at different angular positions between stator and rotor.

In operation, this non-uniform airgap gives rise to unbalanced magnetic pull. The unbalanced magnetic pull due to a static eccentricity (incorrect positioning of the rotor with respect to the stator bore) is a static force, in most cases not causing any problem. However, in two-pole motors, and to a minor extent also in more pole machines, vibrating components at double supply frequency are present that may cause detrimental effects [5]. In a dynamically eccentric machine, i.e. a machine with a bent shaft due to mechanical unbalance, the unbalanced magnetic pull leads to a decrease in the critical speed of the machine [6]. In two-pole machines with dynamic eccentricities, again a force component at double slip frequency will occur.

2. Eccentricity fields-undamped

When the rotor is eccentrically positioned with respect to the stator bore, the airgap length δ is a function of space and time (Figure 1):

$$\delta(\alpha,t)=\delta''\left\{1-\varepsilon\cos\left(\alpha-\omega_\varepsilon t-\varphi_\varepsilon\right)\right\} \tag{1}$$

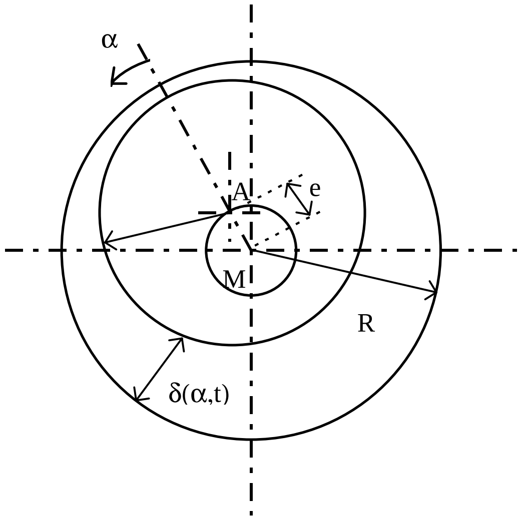

Fig.1 Eccentric rotor position and variable airgap length δ

with

$$\omega_\varepsilon=\begin{cases}0 & \text{for a static eccentricity}\\ (1-s)\dfrac{\omega}{p} & \text{for a dynamic eccentricity}\end{cases} \tag{2}$$

(p: number of polepairs; s: slip; ω: supply pulsation). δ'' is the airgap length, increased for the slotting and saturation. The relative eccentricity ε is (e: absolute eccentricity)

$$\varepsilon=\frac{e}{\delta''}<1 \tag{3}$$

The airgap permeance λ is proportional to the inverse of the airgap length δ:

$$\lambda(\alpha,t)=\sum_{\lambda=0}^{\infty}\Lambda_\lambda\cos\left[\lambda\left(\alpha-\omega_\varepsilon t-\varphi_\varepsilon\right)\right] \tag{4}$$

with

$$\Lambda_\lambda=\begin{cases}=\dfrac{\mu_0}{\delta''}\dfrac{1}{\sqrt{1-\varepsilon^2}} & (\lambda=0)\\ =2\,\dfrac{\mu_0}{\delta''}\dfrac{1}{\sqrt{1-\varepsilon^2}}\left(\dfrac{1-\sqrt{1-\varepsilon^2}}{\varepsilon^2}\right)^\lambda & (\lambda>0)\end{cases} \tag{5}$$

For a small relative eccentricity (ε<<1) we have:

$$\lambda(\alpha,t)\approx\frac{\mu_0}{\delta''}\left\{1+\varepsilon\cos\left(\alpha-\omega_\varepsilon t-\varphi\right)\right\} \tag{6}$$

During transients, insufficient time is available to allow for energy build-up and generate the large vibration amplitudes required for increased and sustained audible noise. Therefore, with regard to audible noise, the steady state condition is important and in this case the slip is small $\left(0\le s\le s_{rated}\right)$. If damping caused by rotor currents is neglected, the resulting airgap flux density is

$$b(\alpha,t)=B_p\cos(p\alpha-\omega t-\varphi_m)$$
$$+\frac{\varepsilon}{2}B_p\left\{\cos\left[(p+1)\alpha-(\omega+\omega_\varepsilon)t-(\varphi_m+\varphi_\varepsilon)\right]\right. \quad (7)$$
$$\left.+\cos\left[(p-1)\alpha-(\omega-\omega_\varepsilon)t-(\varphi_m-\varphi_\varepsilon)\right]\right\}$$

with B_p the almost constant, undamped amplitude of the fundamental field in the machine. The undamped amplitudes of the eccentricity fields are

$$B_{\varepsilon,p\pm1}=\frac{\varepsilon}{2}B_p \quad (8)$$

with number of polepairs, pulsations and phase angles:

$$\nu_{\varepsilon,p\pm1}=p\pm1 \quad (9)$$
$$\omega_{\varepsilon,p\pm1}=\omega\pm\omega_\varepsilon \quad (10)$$
$$\varphi_{\varepsilon,p\pm1}=\varphi_m\pm\varphi_\varepsilon \quad (11)$$

The eccentricity fields are the more important when the machine is supplied directly from the grid, where a constant voltage is applied. When the induction motor is supplied from a frequency inverter, field weakening is applied in the high speed range (above base speed given by the motor's rated voltage and frequency, and the inverter's dc link voltage). This clearly indicates that the electromagnetically generated audible noise components get less pronounced at high speed. Furthermore, at high speed the airborne audible noise dominates.

These supplementary eccentricity components are the basis of the extra forces and audible noise that are observed in practice [7-10].

3. Influence of damping

The eccentricity fields are damped by currents in the rotor bars, both in amplitude and in phase. The phase shift is not considered here, as it does not influence the force components to a major extent. Therefore, the imaginary part of the damping factor is neglected and its amplitude is [11]:

$$\alpha_{p\pm1}=1-\frac{s_{p\pm1}^2}{\beta_{p\pm1}^2+s_{p\pm1}^2}\frac{k^2\xi_{p\pm1}^{*''2}}{1+\sigma_{gRp\pm1}^{''}} \quad (12)$$

with the slip of the eccentricity fields

$$s_{p\pm1}=\begin{cases} s\mp\dfrac{1-s}{p} & \text{static eccentricity}\\ s & \text{dynamic eccentricity}\end{cases} \quad (13)$$

At synchronous speed (s = 0), the static eccentricity fields are damped while the dynamic eccentricity fields remain undamped (α=1). The damped amplitudes of the eccentricity fields are

$$B_{\varepsilon,p\pm1}=\frac{\varepsilon}{2}B_p\alpha_{p\pm1} \quad (14)$$

When calculating the unbalanced magnetic pull, the damped amplitudes (14) have to be used. For radial forces other than generated by eccentricity, the damping may be neglected, as these forces concern mostly high pole fields yielding $\alpha_\nu\approx1$. The amplitudes of the components are the product of the stator harmonics, damped by the rotor and accounting for the addition using the appropriate phase angles for the slot and slotting harmonics. When an eccentricity is present, the eccentricity harmonics have to be taken into consideration. The undamped eccentricity harmonics with amplitude $\frac{\varepsilon}{2}B_{pu}$ induce at rated speed in the rotor bars current having the r.m.s.-value:

$$\underline{I}''_{R,\varepsilon,p\pm1} = -\frac{js_{\varepsilon,p\pm1}}{\left(\beta_{p\pm1} + js_{\varepsilon p\pm1}\right)} \frac{k\xi^*_{p\pm1}}{\left(1+\sigma''_{g,R,p\pm1}\right)} \cdot \frac{\delta'' \frac{\varepsilon}{2} B_{pu}}{\mu_0 \sqrt{2}} \tag{15}$$

with pulsation

$$\omega_{\varepsilon,p\pm1} = \omega\left[1 - \frac{(p\pm1)(1-s)}{p}\right] \tag{16}$$

These currents generate rotor harmonics, having the amplitudes:

$$\begin{aligned} B_{\varepsilon,p\pm1} &= \frac{\mu_0}{\delta''} k\xi^*_{\lambda,p\pm1} \underline{I}_{R,\varepsilon,p\pm1}\sqrt{2} \\ &= \frac{s_{\varepsilon,p\pm1}}{\sqrt{\beta^2_{p\pm1} + s^2_{\varepsilon,p\pm1}}} k^2 \frac{\xi''_{\lambda,p\pm1}\xi_{p\pm1}}{1+\sigma''_{g,R,p\pm1}} \left(\frac{\varepsilon}{2} B_{pu}\right) \end{aligned} \tag{17}$$

with the number of polepairs

$$\lambda_{p\pm1} = g'' N_2 + (p\pm1) \tag{18}$$

and with the pulsation as seen by a stator observer:

$$\omega_{\varepsilon,p\pm1} = \left(\omega + \omega_\varepsilon\right) + \frac{g'' N_2 \omega (1-s)}{p} \tag{19}$$

It has to be pointed out that when the teeth and the yoke are highly saturated, the amplitudes $B_{\varepsilon,p\pm1}$ may differ a lot from the results as shown here using an overall correction to the airgap δ''.

Due to saturation, an extra reluctance λ_{sat} can be introduced, being high where the flux density is high [12]:

$$\lambda_{sat}(\alpha,t) = \lambda_{average}\left[1 - \Delta\lambda_{saturation} \cos\left(2p\alpha - 2\omega_m t - 2\varphi_m\right)\right] \tag{20}$$

However, in the machine discussed further on, saturation is not critical.

4. Stator flux density

In a three phase machine with q slots per pole and per phase, the flux density is composed of a number of waves (eccentricity and saturation neglected):

$$b(\alpha,t) = \sum_\nu B_\nu \cos\left(\nu\alpha - \omega t - \varphi\nu\right) \tag{21}$$

with

$$\nu = 6gp + 1 \quad \text{with } g = 0 \tag{22}$$

In general the slot and slotting harmonics are sufficient. The slot harmonics are given by

$$B'_n = \left(K'_c - 1\right)\xi'_n B_{pu} \tag{23}$$

and the slotting harmonics by

$$B'_{Wn} = \frac{p}{\nu}\frac{\xi'_n}{\xi'_p} B_{pu} \frac{I'}{I_m} \alpha_n \tag{24}$$

with

$$n = p\left(6g'q' + 1\right) \text{ with } g' = \pm 1, \pm 2, \ldots \tag{25}$$

and

$$\alpha_n = 1 - \frac{k^2 \xi_n^{*"2}}{1 + \sigma''_{g,R,n}} \tag{26}$$

The resulting amplitudes B'_{rnu} of the undamped stator fields are:

$$B'_{rnu} = \sqrt{B_n^{'2} + B_{wn}^{'2} + 2B'_n B'_{wn} \sin\varphi'} \tag{27}$$

with $\sin\varphi' = \sqrt{1 - \cos^2\varphi'}$, $\cos\varphi'$ being the power factor.

5. Force calculation

The Maxwell stress due to the combined presence of eccentricity and slotting harmonics is:

$$\sigma_{\varepsilon,p\pm1} = \frac{B_{\varepsilon,p\pm1} B'_{rna}}{\mu_0} \tag{28}$$

These stress components have the number of polepairs:

$$r_{\varepsilon,p\pm1} = \lambda_{p\pm1} \pm n = g'' N_2 + (p \pm 1) + n = \left[\left(g'' N_2 + p\right) \pm n\right] \pm 1 = r \pm 1 \tag{29}$$

They differ from the normal one by ± 1. A silent machine can become loud due to the fact that the frequency of the forces generated by the eccentricity are close to the natural frequencies of the structure. The frequencies of the radial forces are

$$f_{r\pm1} = f_{supply}\left\{\frac{g'' N_2}{p}(1 - s) \pm \frac{\omega_\varepsilon}{\omega} + \begin{matrix}2\\0\end{matrix}\right\} \tag{30}$$

where 2 goes for r+1 and 0 for r–1. For the static eccentricity, $\omega_\varepsilon = 0$, yielding the frequencies

$$f_{r\pm1} = f_{supply}\left\{\frac{g'' N_2}{p}(1 - s) + \begin{matrix}2\\0\end{matrix}\right\} \tag{31}$$

6. Practical example

The following data are available from a practical motor that showed serious audible noise problems. Number of polepairs p=3. Number of stator slots N_1=54. Number of rotor slots N_2=68. Number of slots per pole and per phase in the stator q=3. Coil pitch in the stator w/τ_p=8/9. At rated speed, the slip is small compared to 1 (s<<1), leading to

$$f_{r\pm 1} = f_{supply}\left\{\frac{g"68}{3} + {}^{2}_{0}\right\}$$

The results of this analysis are shown in the following table for a supply frequency of 40 Hz.

g	1	-1	2	-2	3	-3	4	-4
2, r+1	987	827	1893	1733	2800	2640	3707	3547
0, r–1	907	907	1813	1813	2720	2720	3627	3627

When these results are compared to the values as found in the measured curves, the evidence is obvious. A main audible noise frequency was experimentally present at 3625 Hz with two side bands at ±80 Hz. This is exactly predicted by the theory (both main frequency and side bands). Also the measured 2800 Hz value is correctly predicted. Also the lower audible noise values around 1800 Hz probably coincide with the theoretical values, but cannot be assessed in great detail on the measured curves.

7. Conclusions

It is demonstrated how a static eccentricity can contribute to the generation of audible noise. The influence of the supply frequency and the number of rotor bars is analysed. When the frequency of the generated forces coincides with a natural frequency of the stator assembly, problems may be expected. As the static eccentricity is not checked in the manufacturing process, the possibility is clearly present. It should be stressed that choosing a different number of rotor bars will not help, as the same problem will occur at a different supply frequency. As the problem is due to the fundamental supply frequency, higher inverter switching frequencies will not influence the phenomenon. Only a reduction of the cause, i.e. the eccentricity will cure the problem.

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