Damper winding for noise and vibration reduction of induction machine under sinusoidal conditions

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Abstract. The flux density harmonics in the air-gap of AC machines have many origins. They generate electromotive forces and current harmonics, Maxwell forces, noise and vibrations. The principle of the presented method is to use a new auxiliary stator winding, connected to capacitors. The induced current harmonics generate flux density components in opposition to the initial ones, creating a damping effect. The study presented in this paper concerns an induction machine and particularly focus on flux density harmonics generated by slotting effects. The method allows to reduce the sound pressure level main lines of about 15dBA. The vibrations are reduced too. Moreover the stator current harmonics are attenuated, and the power factor is significantly improved.

Keywords: Induction machine, magnetic noise, harmonics, auxiliary windings, capacitors, damper, sinusoidal.

1. Introduction

Magnetic noise and vibrations of AC rotating machines come from flux density harmonics in the air-gap of the machine. Often, machines are noisy when they are fed by a PWM inverter which generates a lot of harmonics, but a machine can be noisy even when fed by sine voltages. A lot of previous works explain how to design a silent machine or how to reduce noise and vibrations using active reduction methods [1]-[4]. This paper deals with a method to reduce flux density harmonics and noise using a damper circuit when the machine is fed by the electrical network. The main principle is to connect capacitors to a new three-phase auxiliary winding. In a first time, origins of flux density harmonics and magnetic noise in induction machines are reminded. Then the method will be presented, explaining how to design the damper circuit. Finally, some experimentations validate the procedure on an 11kW induction machine under sinusoidal conditions.

2. Origins of noise and vibrations

2.1. Origins of harmonics in AC machines

The rotating field in the air-gap of AC machines is never perfectly sine, indeed flux density harmonics can be generated by several sources such as spatial distribution of the coils in a finite number of slots (space harmonics), variable thickness of the air-gap [1], [5], [6] (permeance harmonics), eccentricity [7], magnetic saturation or voltages harmonics due to the power supply [8].

The expression of the radial component $b_h(\alpha,t)$ of a flux density harmonic characterized by its order h, its angular position in the air-gap α, its amplitude $\hat{B}_h$, its pulsation ω_h and its phase ψ_h, in the air-gap of a *2p* poles machine, is:

$$b_h(\alpha, t) = \hat{B}_h \cos(\omega_h t - hp\alpha - \psi_h) \tag{1}$$

$h = 1$ corresponds to the fundamental component which angular frequency is that of the network. The amplitude and frequency of harmonics are largely in relation to the number of stator and rotor slots [3], [4], [9].

There is an infinity of flux density harmonics in the air-gap. Each of them generates an induced electromotive force (e.m.f.) at stator and rotor frames, which induces current harmonics and generates other flux density harmonics. Fig. 1 shows the interaction between stator and rotor, and the generation of the flux density harmonics.
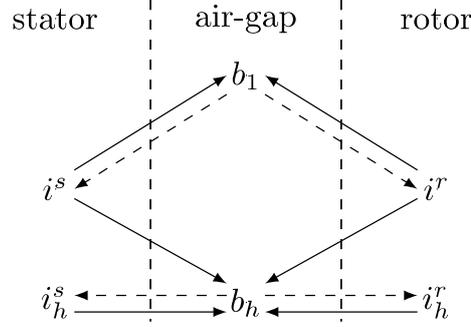

Fig. 1. Interactions between stator and rotor.

The stator current i^s, at the supply frequency, generates a lot of flux density components:
  – a b_1^1 fundamental component at the supply frequency with the *2p* pole number ($h = 1$),
  – several b_h harmonics at different ω_h angular frequencies and pole numbers ($h \neq 1$).
Each flux density component induces in each conductor an electromotive force and so a current. Some b_h flux density harmonics at ω_h angular frequency are generated by the fundamental current at ω angular frequency, so they can't influence it but they generate i_h^s and i_h^r current harmonics at stator and rotor coils. Those currents partially mitigate the b_h flux density harmonics which generated them.

2.2. Maxwell forces, noise and vibrations

The flux density in the air-gap creates forces between stator and rotor. Three kinds of forces appear:
  – Tangential forces which create torque and rotor rotation.
  – Magnetostrictive forces, negligible for rotating machines.
  – Radial forces, expressed by the Maxwell relation. The radial component of the flux density *b* (T) in the air-gap of a magnetic circuit of surface *S* (m²), creates a force *f* (N) which tends to attract stator and rotor. Noting μ_0 the vacuum magnetic permeability (4π 10^{-7} H/m), the force can be expressed as:

$$f = \frac{b^2 S}{2\mu_0} \tag{2}$$

Because of the multiplicity of the flux density harmonics, many pressures waves occur and multiply the vibrations sources.

$$\sum \mathrm{f}(\alpha,t) = \frac{\left(\sum b_h(\alpha,t)\right)^2}{2\mu_0} = \frac{1}{2\mu_0}\left[\begin{array}{l}\sum_h \dfrac{\hat{\mathrm{B}}_h{}^2}{2}\left(1+\cos(2\omega_h t - 2hp\alpha - 2\psi_h)\right) + \\[2ex] \sum_h\sum_{h'} \hat{\mathrm{B}}_h\hat{\mathrm{B}}_{h'}\left[\begin{array}{l}\cos((\omega_h+\omega_{h'})t-(h+h')p\alpha-(\psi_h+\psi_{h'}))+ \\ \cos((\omega_h-\omega_{h'})t-(h-h')p\alpha-(\psi_h-\psi_{h'}))\end{array}\right]\end{array}\right] \tag{3}$$

So non-stationary pressure components are expressed by:

$$f(\alpha,t) = \hat{\mathrm{F}}\cos(\omega_f t - m\alpha - \psi_f) \tag{4}$$

Where m is the mode number, $\hat{F}$ the amplitude of the pressure in N/m², f_f the frequency ($\omega_f = 2\pi f_f$). m characterizes the number of maximal and minimal attraction points between the stator and the rotor. The pressure waves rotate at ω_f/m angular speed, they generate variable attractions between the stator and the rotor and then vibrations and magnetic noise.

3. Principle of the passive noise reduction method

3.1. Supplementary stator winding and capacitors

This method needs an auxiliary stator winding. In the ideal case, it can be wounded in the same slots as the initial one, creating secondary stator coils similar to the initial stator ones. For example, Fig. 2 shows a classical three-phase winding with one pole pair and 4 slots per pole and per phase. The principle consists in creating another similar stator winding superimposed to the initial one, star or delta connected, in short circuit via three capacitors as shown in Fig. 3. The current in this auxiliary winding is noted i_a. The rotor is in short circuit as usually for induction machines.
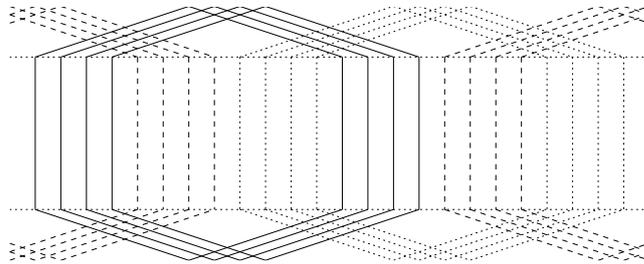

Fig. 2. Three-phase winding with one pole pair and 4 slots per pole and phase.
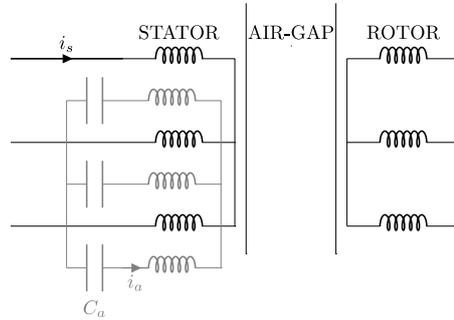

Fig. 3. Representation of the machine with auxiliary windings.

The flux density fundamental induces a current in the auxiliary windings at the same frequency than the stator. For this low frequency, the capacitors have a high impedance, so the induced currents are small and don't disturb the machine torque.

The equivalent single-phase diagram relative to the fundamental variables is presented in Fig. 4 where r_s, l_s, r_a', l_a', r_r' and l_r' are the resistance and leakage inductance respectively of the stator, auxiliary and rotor windings. Z_μ is the classical magnetizing impedance, and s is the slip.
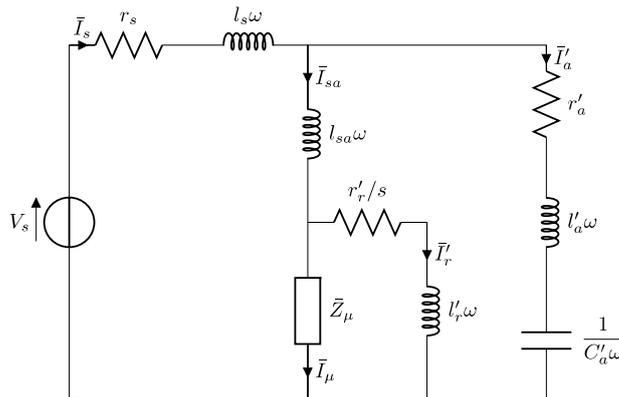

Fig. 4. Equivalent single-phase diagram.

The symbol $'$ means that the considered values are brought back to the stator, depending on the number of turns.

Compared to the classical equivalent diagram of an induction machine, a new auxiliary branch appears with the capacitor C_a', and a new inductance l_{sa} which represents the flux in common between stator and auxiliary windings [10,11].

3.2. Principle of harmonic reduction

The flux density components induce current harmonics in the auxiliary windings. For the high frequency harmonics, these induced currents can easily circulate and generate flux density components in opposition to those which create them, according to the Lenz law. However, the created components must have the same polarity than the original ones. Fig. 5 illustrates the phenomena.
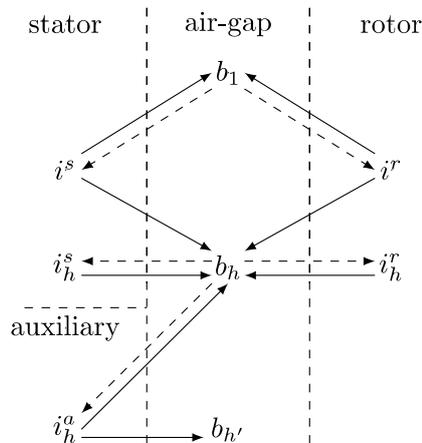

Fig. 5. Interactions between stator, rotor and auxiliary windings.

The b_h flux density component which generates i_h^a has a different frequency from the supplying current. So a fictitious current can be considered: i_h^{fict} is the current at ω_h angular frequency which would generate b_h. For the harmonics, it can be assumed that the network is a short circuit and the slip is equal to 1. According to these hypothesis, the equivalent single phase diagram for the harmonics given in Fig. 6 can be used.
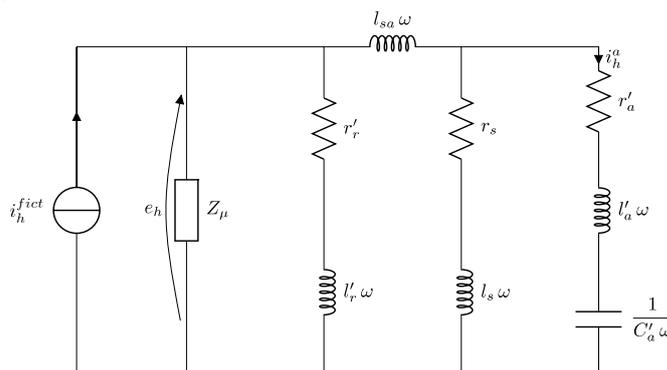

Fig. 6. Equivalent single-phase diagram for the harmonics.

The auxiliary branch creates an important damping effect because the value of C_a' can be chosen so that a resonance exists with the inductances at a given frequency. In those conditions, the voltage e_h is minimized. The latter is proportional to the flux density harmonic that we want to reduce.

The best value of the capacitors depends on the inductances values. A large range of capacitors values is suitable: if the resonance frequency is slightly below the unwanted frequencies, the impedance of the auxiliary branch will be small for a large frequency range.

4. Experimental results

4.1. Used machine

The used induction machine has the following characteristics: 11kW – 50Hz – 380/660V – 23/13A – p = 2 pole pairs – $N_t^s = 48$ stator slots – $N_t^r = 32$ rotor slots.

The theoretical analysis [1], [3] shows that flux density harmonics exist at the frequency $50(1 + k\frac{N_t^r(1-s)}{p})$ where k is an integer ($k = 0; \pm1; \pm2; \pm3\ldots$). Neglecting the slip s, the frequencies of the important flux density harmonics are 750Hz, 850Hz, 1550Hz, 1650Hz, 2350Hz, 2450Hz, etc. Consequently, current harmonics circulate at those frequencies in the stator windings.

The magnetic noise and vibrations, due to the Maxwell forces, are essentially due to the combination of those harmonics with components at the supply frequency. So, according to equation (3), magnetic noise and vibrations exist at frequencies near to 700Hz, 800Hz, 900Hz, 1500Hz, 1600Hz, 1700Hz, 2300Hz, 2400Hz, 2500Hz, etc. The acoustic spectrum shows important noise components at 800 and 900Hz, in accordance to the theory; this is shown in Fig. 7 where the acoustic pressure is measured with a microphone at 1 meter. The global level is 74.8dBA at no-load. There is no auxiliary winding in this machine but all the windings connections are accessible outside the machine. As there are 4 slots per pole and per phase, it was decided to use an half of the windings (2 slots per pole and per phase) to supply the machine by the network, and the other half as auxiliary windings.
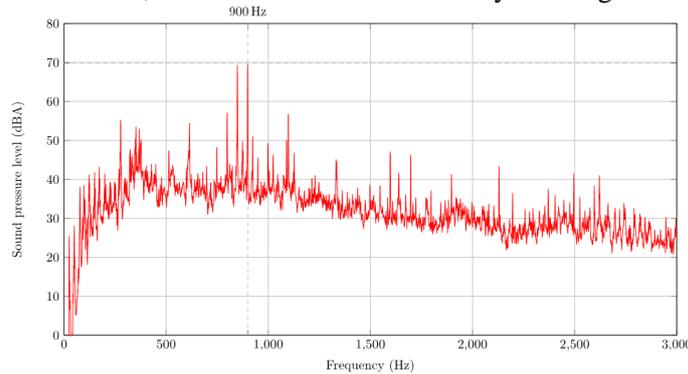

Fig. 7. Acoustic pressure level of the no-load machine at 1 meter.

4.2. Experimental noise and vibrations reduction

As only half of the windings is connected to the supply (star), the 50Hz phase to phase voltage U is reduced to 325V in order to have a current value (15A) similar to the no-load fundamental current with a classical power supply. At no-load, the rotating speed is 1496rpm. In a first time, there is no impedance connected to the three auxiliary windings, allowing us to measure the induced e.m.f. spectrum. Those e.m.f. harmonics are in relation to the flux density harmonics in the air-gap. It can be seen in Fig. 8 that induced e.m.f. harmonics appear at 750Hz, 850Hz, 1550Hz and 1650Hz as shown in theory; other harmonics exist because only an half of the windings are used.
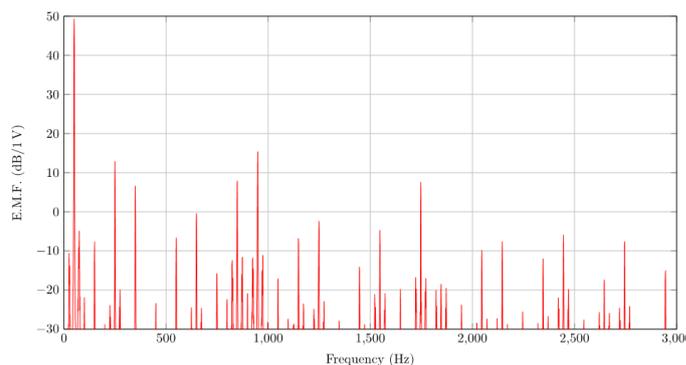

Fig. 8. Induced e.m.f. at the free winding (2 slots per pole and phase).

Three 120μF capacitors have been connected on the three free windings (2 slots per pole and phase). This value of capacitor, determined experimentally, corresponds to the optimum for noise and vibrations reduction. The sound pressure level at 900Hz decreases from 70 to 52dBA as illustrated in Fig. 9 which can be compared to Fig. 7. Moreover, the global acoustic pressure level decreases from 74.8 to 69.9dBA.
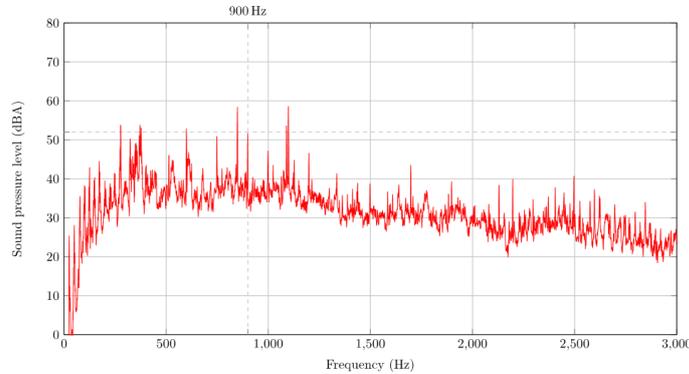

Fig. 9. Acoustic pressure level of the no-load machine at 1 meter, with three 120μF capacitors star connected.

The vibrations are measured too with an accelerometer placed on the stator, which confirm the acoustic measures: the vibrations at 800 and 900Hz decrease respectively from 0.104 and 0.965m.s^{-2} to 0.070 and 0.213m.s^{-2}. The current harmonics flowing in the stator windings are reduced too.

4.3. Other advantages

4.3.1. Influence on the power factor
Without capacitors, the machine requires a reactive power Q. With auxiliary windings and capacitors, at the supplying frequency, a small current circulates in the capacitors. It produces some reactive power Q_c that the network has not to provide. Its value can easily be estimated by relation (5), taking into account the winding turn ratio.

$$Q_c = \left(\frac{z^a}{z^s}U\right)^2 C\omega \tag{5}$$

In order to minimize the stator current and to maximize the power factor of the studied machine where $z^s = z^a$, the capacitor should produce $Q_c = Q = 3800$VAR. As $U = 325$V and the frequency is 50Hz, the value of the capacitor should be 115μF. In this case, it appears that the capacitor value is almost the same that the one used to minimize noise and vibrations. With the used 120μF capacitors, the auxiliary current at 50Hz is 7.6A, $Q_c = 3982$VAR, so the stator fundamental current at no-load decreases from 14.8 to 9.1A and the power factor at no-load increases from 0.2 to 0.3.

4.3.2. Influence on the stator current and torque harmonics
As the flux density harmonics are mitigated by the auxiliary windings and the capacitors, the induced e.m.f. and the stator current harmonics are mitigated too; except for the line at 250Hz. This is illustrated by Fig. 10 which shows the supply current spectrum without and with capacitors. As the torque harmonics are in relation to the flux density harmonics, they can be reduced too.

5. Conclusion

It is usual to connect some capacitors in order to compensate the reactive power absorbed by induction machines. Another possibility is to connect capacitors on a new auxiliary three-phase winding which can be wounded into the same slots than the initial windings. By this way, the power factor of the machine is improved and the stator current harmonics are attenuated. Moreover, this damper circuit considerably mitigate flux density harmonics in the air-gap, reduce noise and vibrations, and can attenuate stator current harmonics.
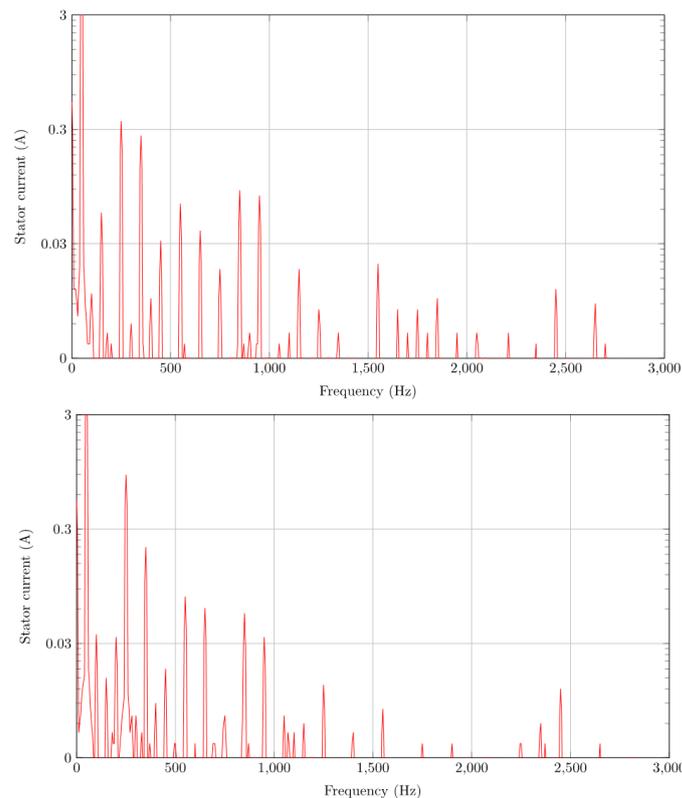
Fig. 10. Stator current spectrum without and with capacitors.

The drawback is to design the stator of the machine with supplementary windings, but those one can be small. No electronic is used and the damping effect is permanent.

Acknowledgements

References

[1] B. Cassoret, R. Corton, D. Roger et al: Magnetic noise reduction of induction machines, IEEE Transactions on power electronics, 2003, vol. 18, no 2, p. 570-579.
[2] B. Cassoret: Réduction active du bruit magnétique des machines asynchrones directement connectées au réseau, 1996, PhD Thesis, Université d'Artois.
[3] H. Jordan, *Geräuscharme elektromotoren,* W. Girardet, 1950.
[4] P.L. Timar, *Noise and vibration of electrical machines*, North Holland, 1989.
[5] M.H. Hesse: Air-gap permeance in doubly-slotted asynchronous machines, IEEE Transactions on Energy Conversion, 1992, vol. 7, no 3, p. 491-499.
[6] J. Le Besnerais, V. Lanfranchi, M. Hecquet et al: Prediction of audible magnetic noise radiated by adjustable-speed drive induction machines, IEEE Transactions on Industry Applications, 2010, vol. 46, no 4, p. 1367-1373.
[7] S. Ayari, M. Besbes, M. Lecrivain et al: Effects of the airgap eccentricity on the SRM vibrations, in: Electric Machines and Drives, 1999. International Conference IEMD'99. IEEE, 1999. p. 138-140.
[8] R.J.M. Belmans, D. Verdyck, W. Geysen et al: Electro-mechanical analysis of the audible noise of an inverter-fed squirrel-cage induction motor, IEEE Transactions on Industry Applications, 1991, vol. 27, no 3, p. 539-544.
[9] P.L. Alger, *The nature of induction machines*, Gordon and Breach, 1965.
[10] G. Kron, *Equivalent circuits of electric machinery*, J. Wiley & Sons, 1951.
[11] H. Kouki, M. B. Fredj, H. Reaoulia: Double star induction machine modelling: Impact of the stator mutual leakage inductance, International Journal of Applied Electromagnetics and Mechanics, 2017, vol. 53, no 1, p. 51-61.
[12] B. Cassoret, R. Romary: Moteur électrique à enroulement auxiliaire isolé, Dec. 29 2016, WO Patent App. PCT/EP2016/064,319.