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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 electrical 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 created current harmonics generate flux density components in opposition to the initial ones, creating a damping effect. Experimentations were done on an induction machine. The presented method allows to reduce the mainly lines from about 10dB, with or without load. 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.

I. INTRODUCTION

Magnetic noise and vibrations of AC rotating machines can disturb. They 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 process on an 11kW induction machine under sinusoidal conditions.

II. ORIGINS OF NOISE AND VIBRATIONS

A. 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:

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

$h=1$ 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.

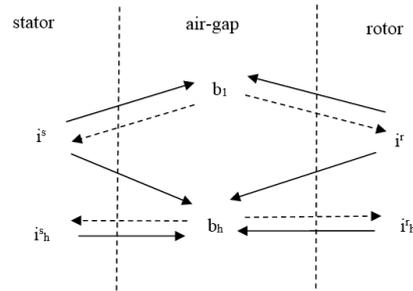


Fig. 1. Interactions between stator and rotor

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^s_h and i^r_h current harmonics at stator and rotor coils. Those currents partially mitigate the b_h flux density harmonics which generated them.

B. 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 permeability ($4\pi \cdot 10^{-7}$ H/m), the force can be expressed as:

$$f = \frac{b^2 S}{2\mu_0} \quad (2)$$

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

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

So non-stationary pressure components are expressed by:

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

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.

III. PRINCIPLE OF THE PASSIVE NOISE REDUCTION METHOD

A. Supplementary stator winding and capacitors

This method needs an auxiliary stator winding. In the ideal case, it can be wound 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 to create 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 usual for induction machines.

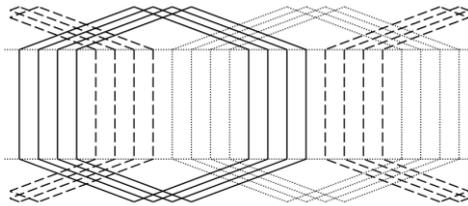


Fig. 2. Three-phase winding with one pole pair and 4 slots per pole and phase.

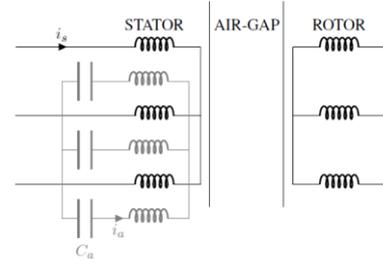


Fig. 3. Representation of the machine with auxiliary windings.

The flux density fundamental induces a current in the auxiliary windings at the same frequency than the stator. For this low frequency, the capacitors form a high impedance so the induced currents are small and don't disturb the machine torque. The equivalent single-phase diagram 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. The symbol ' means that the considered values are "seen" from 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].

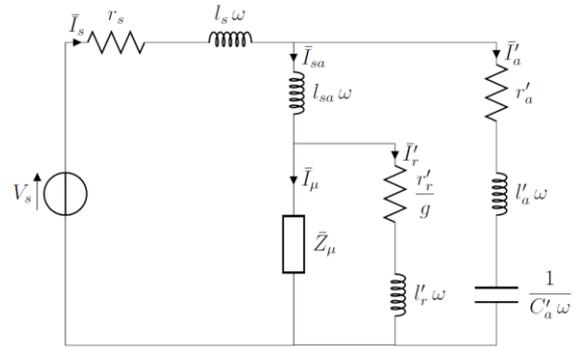


Fig. 4. Equivalent single-phase diagram.

B. 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. Fig. 5 illustrates the phenomena.

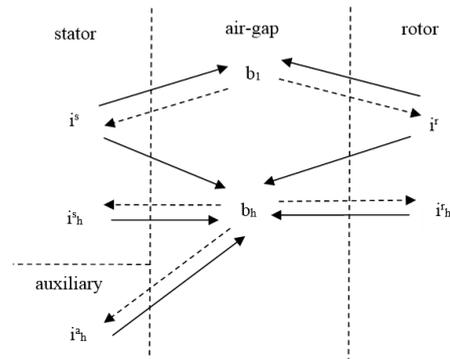


Fig. 5. Interactions between stator, rotor and auxiliary windings.

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, the network is a short circuit and the slip is equal to 1. That explains the equivalent single-phase diagram for the harmonics given in Fig. 6.

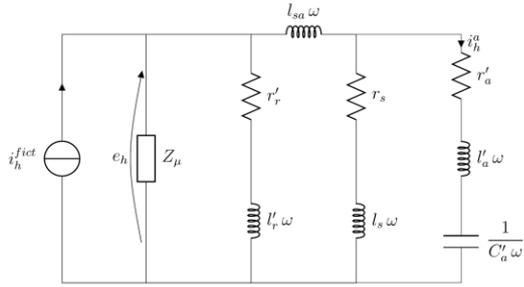


Fig. 6. Equivalent single-phase diagram for the harmonics.

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. 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 value. 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 range of frequencies.

IV. EXPERIMENTATION

A. Used Machine

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

The theoretical analysis [1], [3] shows that flux density harmonics exist at the frequency $50(1+k N_r^r (1-s)/p)$ where k is an integer ($k=0; \pm 1; \pm 2; \pm 3\dots$). 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 magnetic noise and vibrations exist at frequencies near to 700Hz, 800Hz, 900Hz, 1500Hz, 1600Hz, 1700Hz, 2300Hz, 2400Hz, 2500Hz, etc. The acoustic spectrum shows an important noise component at 800Hz, in accordance to the theory; this is shown in Fig. 7 where the acoustic pressure was measured with a microphone at 1 meter. The global level is 75dB 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.

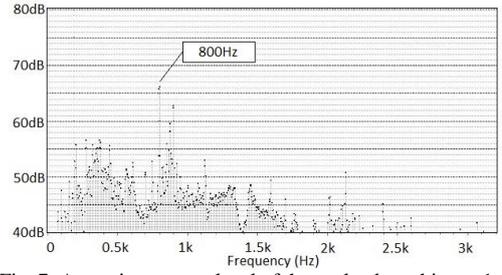


Fig. 7. Acoustic pressure level of the no-load machine at 1 meter.

B. Experimental Noise and Vibrations Reduction

1) At no load

As only an half of the windings were connected to the supply (star), the 50Hz phase to phase voltage U was reduced to 250V in order to have the same no-load fundamental current (9A) than with a classical power supply. At no-load, the speed was 1496rpm. In a first time there was no impedance connected to the three auxiliary windings, allowing us to measure the induced e.m.f. spectrum. It can be seen in Fig. 8 that induced e.m.f. harmonics exist at 750Hz, 850Hz, 1550Hz and 1650Hz as in theory.

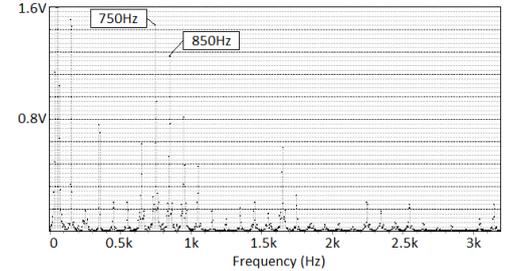


Fig. 8. Induced e.m.f. at the free winding (2 slots per pole and phase)

Three $107\mu\text{F}$ capacitors were connected on the three free windings (2 slots per pole and phase), the global acoustic pressure level decreases from 75 to 73dB. The level at 800Hz decreases from 67 to 56 dB as illustrated in Fig. 9 which can be compared to Fig. 7.

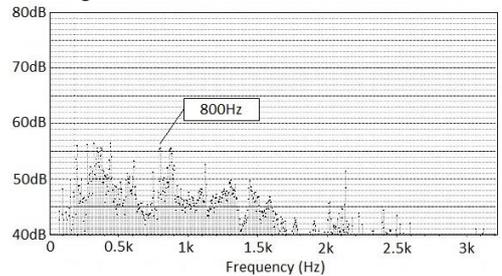


Fig. 9. Acoustic pressure level of the no-load machine at 1 meter, with three $107\mu\text{F}$ capacitors star connected.

The vibrations were measured too with an accelerometer placed on the stator, which confirm the acoustic measures: the vibrations at 800 and 900Hz decreased respectively from 277 and 237 m.s^{-2} to 88 and 173 m.s^{-2} . The current harmonics flowing in the stator windings are reduced too.

2) At load

The same experiments were done at load: the studied motor had to mechanically drive a 1kW load. The global noise without capacitors was 76dB as it can be seen in Fig. 10.

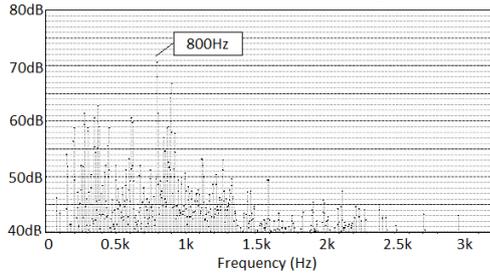


Fig. 10. Acoustic pressure level of the loaded machine at 1 meter, without capacitors.

Connecting the three 107μF capacitors, the global noise decreases to 74dB as it can be seen in Fig. 11. The important noise lines are reduced.

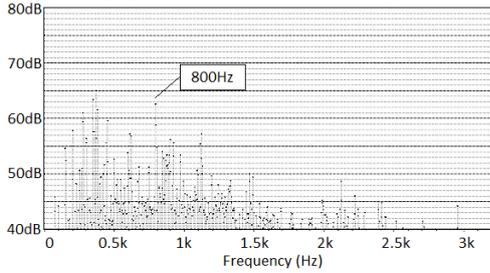


Fig. 11. Acoustic pressure level of the loaded machine at 1 meter, with three 107μF capacitors star connected.

C. Other advantages

1) Influence on the power factor

Without capacitors, the machine requires a reactive power Q_c . 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.

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

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 $Q_c = Q = 3800\text{VAR}$. As $U = 250\text{V}$ and the frequency is 50Hz, the value of the capacitor should be 193μF. This value is naturally different than the one used to minimize noise and vibrations but it is the same order. With the used 107μF capacitors, the auxiliary current at 50Hz is 4.85A, $Q_c = 2100\text{VAR}$, so the stator fundamental current at no-load decreases from 9 to 4.4A and the power factor at no-load increases from 0.22 to 0.45.

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 current harmonics into the stator are mitigated too. This is illustrated by Fig. 12 which shows the supplying current spectrum without and with capacitors. As the torque harmonics are in relation to the flux density harmonics, they can be naturally reduced.

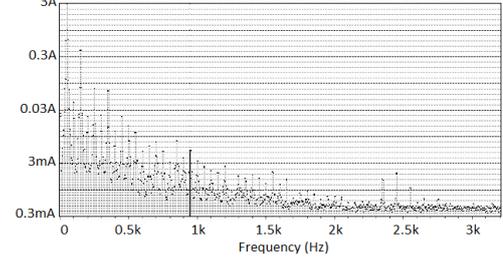
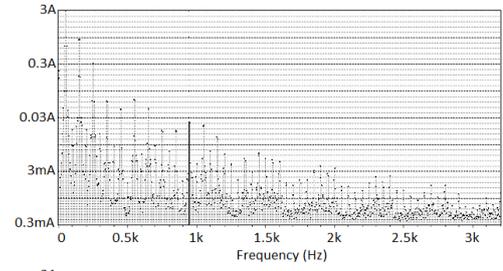


Fig. 12. Stator current spectrum without and with capacitors (scale in dB).

V. 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 wound 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 reduce noise and vibrations.

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.

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