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Univ. Artois, EA 4025, Laboratoire Systèmes Electrotechniques et Environnement (LSEE)
F-62400 Béthune, France, e-mail: gregory_bauw@ens.univ-artois.fr

Abstract

Purpose – The paper presents a design method for induction machines including a three-phase damper winding for noise and vibrations reduction.
Design/methodology/approach – In a first part, the principle of the damper winding is recalled. The second part presents the iterative design method which is applied on a 4kW PWM-fed induction machine in order to study the impact of the additional winding on the geometry. In a third part, the finite element method is used to validate the designed geometry and highlight the harmonic flux density reduction. Finally, some experimental results are given.
Findings – The study shows that the impact of the additional three-phase winding on the geometry and weight of the machine is low. Moreover, the proposed noise reduction method allows one to reduce the total noise level of a PWM-fed induction machine up to 8.5dBA.
Originality/value – The originality of the paper concerns the design and characterization of a three-phase damper winding for a noiseless induction machine. The principle of this proposed noise reduction method is new and has been patented.
Keywords – Design, Induction machine, Damper, Noise and vibrations reduction, PWM.
Paper type – Research paper

I. INTRODUCTION

Induction machine design has been studied for decades as a field in its own right, and the construction rules are nowadays well known (Boldea, 2009; Pyrhonen *et al.*, 2013; Toliyat and Kliman, 2004). The environmental context encourages manufacturers to design high efficiency electric motors in keeping with increasingly strong constraints. Thus, more recently, acoustic standards have added a new constraint on the design process. The main international acoustic standard (IEC 60034-9) (Rotating electrical machines – Part 9: Noise limits) specifies a total sound power level (SWL) limit depending on the speed of the machine.

When the machine is fed by sine voltage, magnetic noise can be predicted and anticipated in the design process by choosing an adequate number of stator/rotor slots or by skewing the rotor for example. If the machine is noisy despite the respect of the construction rules, it is possible to reduce noise and vibrations using active reduction methods (Ojeda *et al.*, 2009; Pellerey *et al.*, 2012). When the machine is fed by a PWM inverter, noise is often corrected after the manufacturing by using an anti-harmonic filter or by modifying the PWM strategy (Brudny *et al.*, 2015; Gabsi *et al.*, 1999; Zhang *et al.*, 2017).

In this context, we propose a method to include a passive noise reduction solution for PWM supply in the design process. Numerical applications concern a 4kW induction machine which targeted characteristics are: 1500rpm – 400V – 8.8A – 50Hz – 3 phases – power factor: 0.79.

II. PRINCIPLE OF THE DAMPER WINDING

The proposed noise reduction method is a three-phase damper winding (Cassoret and Romary, 2016) wound into the stator slots and superimposed to the initial winding as shown in Figure 1. This additional winding, following the same path and having the same number of turn than the stator winding, is connected to three capacitors of suitable values in order to create a resonance around the switching frequency of the PWM inverter. At these frequencies, the voltage harmonics are important. They are responsible of flux density harmonics, and consequently at the origin of magnetic noise. The main principle is similar to that of a classical LC filter but in our case the inductance is integrated to the machine. Previous work (Bauw *et al.*, 2017) shows that the capacitors mainly resonate with the leakage inductances of the machine. Experimentations on a PWM-fed 4kW prototype including damper windings allowed to reduce the overall sound pressure level (SPL) by more than 8.5dBA in some cases. Vibrations were also considerably reduced.

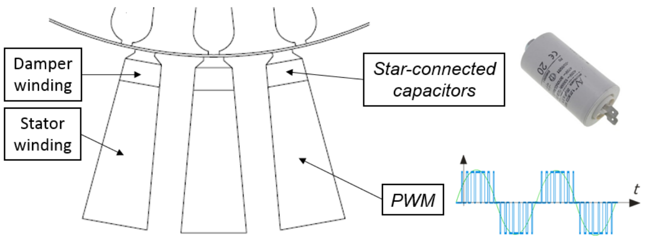

Fig.1. Induction machine with damper windings.

III. DESIGN METHOD

A. *Context*

The proposed study is based on a classical iterative design method of induction machine (Boldea, 2009) which has to be adapted to take into account the space required by the damper winding in the stator slots. The difficulty is that this additional space is linked to the value of the current in the damper, itself linked to the impedance of the machine and the chosen capacitors.

The first step is to design a reference machine without damper windings to provide a comparison point. The computations using the characteristics defined in the introduction lead to a stator outside diameter D_{out} of 185.4mm and a stack length L of 129mm. The stator has 36 trapezoidal slots and the squirrel-cage of the rotor has 28 bars. The current density in the stator winding is chosen at 4.5A/mm² as recommended by (Boldea, 2009). Parameters of the classical single-phase equivalent diagram of the machine have been calculated analytically and are given in Table I.

TABLE I
PARAMETERS OF THE SINGLE-PHASE EQUIVALENT DIAGRAM OF THE REFERENCE MACHINE

r_s (Ω)	**0.56**
l_s (mH)	**9.3**
L_μ (mH)	**221.5**
r_r' (Ω)	**0.986**
l_r' (mH)	**10.1**

The goal of the design method is to minimize the increase of the diameter D_{out} of the machine with damper windings while keeping the same flux density in the yoke and the same performances. We assume that the damper does not impact the stator inner diameter and the rotor geometry.

B. *Design of the machine with damper windings*

Empirically, the maximum current value in the damper windings is first set to 20% of the rated stator current, which corresponds to 1.76A for the studied machine. Experience and experimentations on existing prototypes have shown that this value is coherent. The current density in the damper windings is the same to that of the stator. The design process has to be done again increasing the stator slot depth and so the outside diameter. The slot depth is increased while keeping the tooth width constant. Consequently, the outside diameter D_{out} is increased to 192mm.

C. *Single-phase equivalent diagram*

Since the geometry is now fully designed, analytical calculations of resistances and leakage inductances of the machine (Lipo, 2017) allow one to establish the parameters of the equivalent diagram of Figure 2. l_s is the leakage inductance of the stator winding; l'_{az} is a mutual inductance relative to the common flux between the stator and the auxiliary which does not link the rotor winding (Bauw *et al.*, 2018a; Bauw et al., 2018b). l'_{ac} corresponds to the leakage flux of the auxiliary which does not link any other winding, this flux is essentially composed of coil-end leakage.

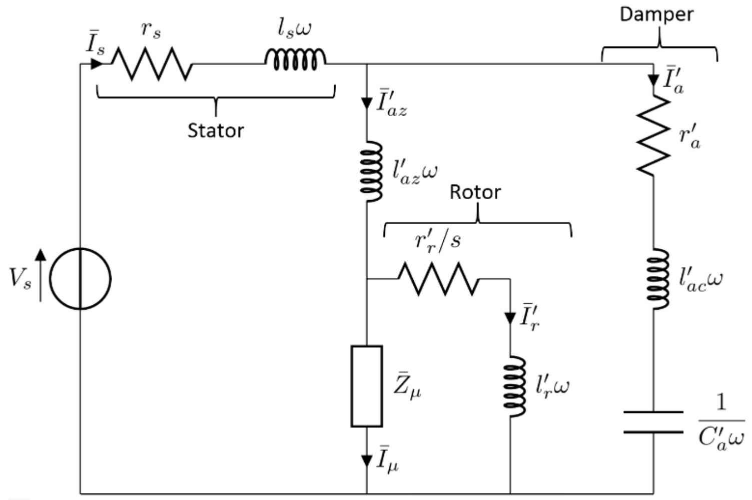

Fig.2. Single-phase equivalent diagram of the machine with damper windings.

Analytical values of these parameters are given in Table II. One can notice that the sum of l_s and l'_{az} gives a close approximation of the value of l_s given in Table I. Indeed, when the damper windings is not connected, the auxiliary branch of the equivalent diagram is open and the inductances l_s and l'_{az} are then in series to give the classical induction machine diagram.

TABLE II
PARAMETERS OF THE SINGLE-PHASE EQUIVALENT DIAGRAM OF THE MACHINE WITH DAMPER ($I_a = 0.2\, I_s$)

r_s (Ω)	**0.56**
l_s (mH)	**4.9**
l'_{az} (mH)	**5.7**
L_μ (mH)	**215.4**
r'_r (Ω)	**0.986**
l'_r (mH)	**10.1**
r'_a (Ω)	**5.61**
l'_{ac} (mH)	**2.6**

D. *Capacitor value and auxiliary current*

We assume that the machine is fed by a PWM inverter which minimum and maximum switching frequencies are respectively 3kHz and 8kHz. For each switching frequency, the harmonic voltage content can be experimentally measured. In our case, the main voltage harmonics are respectively 3100 and 8100Hz and their amplitudes are both 49V. Figure 3 shows the peak flux density $\hat{B}$ in the air-gap at these frequencies as a function of the capacitor value, calculated from (1) where L_μ is the magnetizing inductance, I_μ the magnetizing current for the considered harmonic, p the number of pole pairs, n the number of turns per phase, D_{is} the stator inner diameter and L the stack length. The value $C'_a = 0$ corresponds to the amplitude of the flux density harmonic when the damper has no influence.

$$\hat{B} = \frac{\sqrt{2}\, L_\mu\, I_\mu\, p}{n\, D_{is}\, L} \tag{1}$$

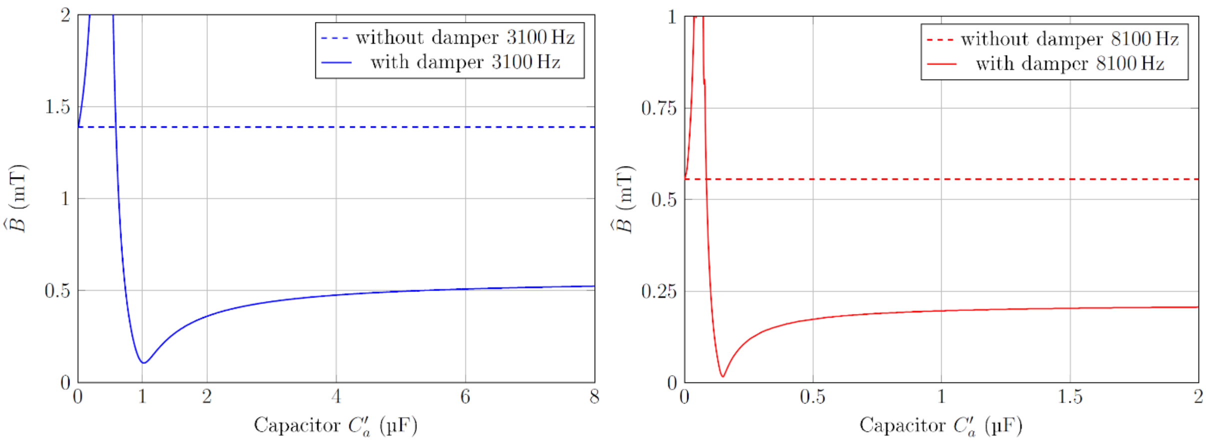

Fig.3. Peak flux density in the air-gap with (solid line) and without (dashed line) damper windings as a function of the capacitor C'_a for f = 3100Hz and 8100Hz.

An optimal capacitor value for both operating point would be of 1µF, but taking into account the accuracy of leakage inductances estimation, there is a risk of amplification of the harmonic flux density. Therefore, we will choose the value of 2µF. For this particular capacitor value, considering every harmonic components of the 3kHz PWM voltage supply, the computed RMS current in the damper windings is 0.75A. The current value for higher switching frequency is lower because the nature of the damper winding's impedance is mainly inductive.

E. *Optimization of the geometry*

Since the calculated current value in the damper windings is lower than the estimated value of section III.B, the design can be optimized. By choosing a maximum current of 1A in the damper, the outside diameter of the machine can be reduce from 192 to 189mm. D_{out} is thus increased by less than 2% compared to the reference machine without damper windings as shown in Figure 4. The design process has been finally done again in order to verify that the current value in the damper and the optimum value of capacitor of the optimized machine are not changed.

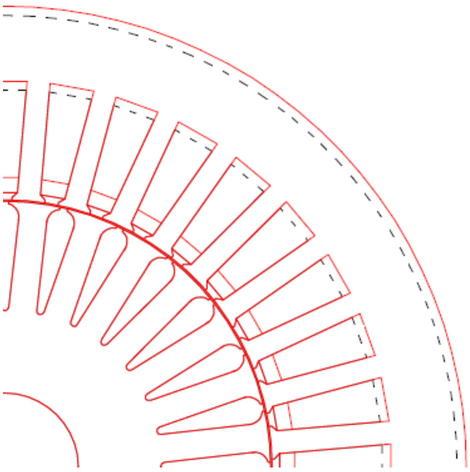

Fig.4. Comparison of the geometries: reference machine (dashed line) / optimized machine with damper windings (solid line).

F. Weight criterion

Let D_{out} and D'_{out} respectively be the outside diameters of the reference and optimized machine with damper windings, L the stack length of both machines and ρ_{iron} the density of the iron. The added iron weight due to the increase of the outside diameter can be easily calculated from:

$$m_{iron} = \rho_{iron} \pi L \left[\left(\frac{D'_{out}}{2} \right)^2 - \left(\frac{D_{out}}{2} \right)^2 \right] \tag{2}$$

Considering a density of the iron equal to 7860kg/m^3, the weight of the magnetic core should be increased by only 1kg.

The copper weight of the damper winding can be calculated considering ρ_{iron} the density of the copper, l_c the coil-end length, S the cross section of the wire, N the number of turns per phase of the winding and q the number of phases:

$$m_{copper} = 2\, \rho_{iron}\, (L + l_c)\, S\, N\, q \tag{3}$$

In our case, the damper winding represents a weight of 1.512kg. The total weight due to the addition of the damper winding is then 2.512kg, which is small as an induction machine of this size usually weighs about 40kg. This aspect can be particularly attractive for embedded applications giving the size and weight of a traditional anti-harmonic filter.

IV. FINITE ELEMENT METHOD VALIDATION

A. Used geometry and coupling circuit

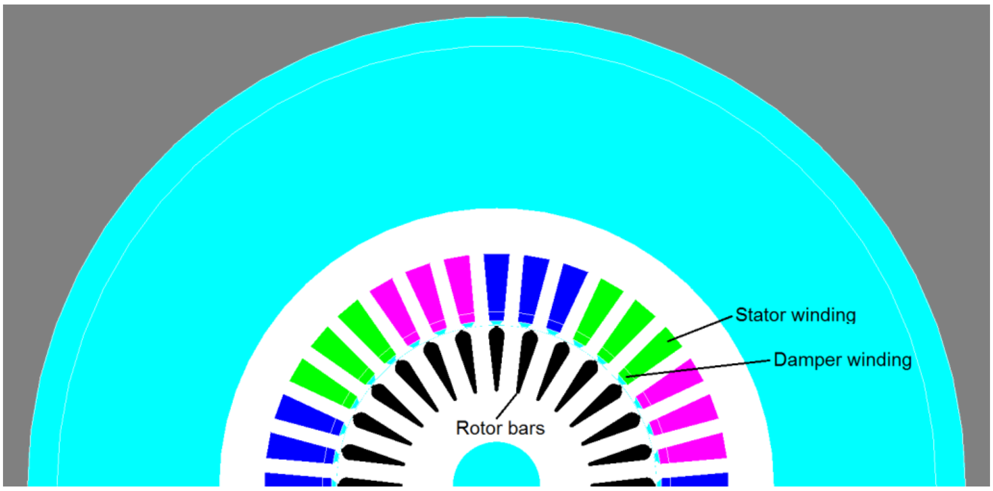

Fig.5. Used geometry of the 4kW induction machine with damper windings for FEM simulation (Flux2D).

The optimized geometry of the machine with damper windings obtained from the analytical design has been simulated on the FEM software Flux2D as shown in Figure 5. The coupling circuit in Figure 6 allows us to integrate the two three-phase windings, their resistances and coil-end inductances are calculated analytically. The stator winding is fed by a balanced system of voltage harmonics which amplitudes are frequency dependant. The damper windings are short-circuited via three 2µF capacitors. The rotor is a squirrel-cage rotor which ring impedances are calculated analytically.

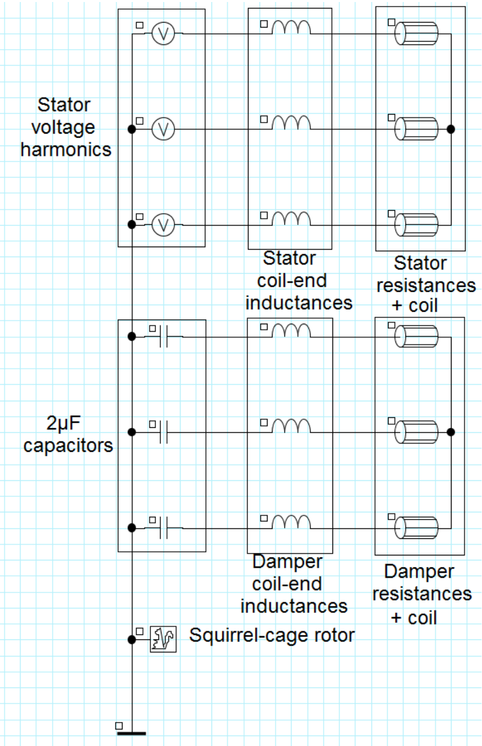

Fig.6. Coupling circuit of the 4kW induction machine with damper windings for FEM simulation (Flux2D).

B. Current value in the capacitors

Table III compares the current value in the capacitors calculated analytically from the equivalent diagram of Figure 2 and by finite element method for different harmonics. The chosen voltage harmonics have been obtained experimentally and correspond to the most significant ones of a PWM inverter when the switching frequency is set to 3kHz. Results show a good correlation between analytical and numerical models, which confirms that the analytical computation of the leakage inductances has been done accurately. Moreover, one can notice that the RMS value of the capacitor current calculated by FEM with the four studied harmonics is 0.69A, which is close to the value of 0.75A obtained from the equivalent diagram in section III.D. We can therefore neglect the contribution of the fundamental and other harmonics on the current value.

TABLE III
CURRENT VALUE IN THE CAPACITORS CALCULATED ANALYTICALLY AND BY FEM

Frequency	I_a (A) analytical	I_a (A) FEM	% error
2800 Hz	0.317	0.307	3.43
2900 Hz	0.421	0.407	3.44
3100 Hz	0.394	0.381	3.41
3200 Hz	0.276	0.267	3.37

C. Validation of the harmonic flux density reduction in the air-gap

Figure 7 shows the normal flux density in the air-gap without and with damper windings as a function of the position on a line plotted in the middle of the air-gap. The frequency is 3100Hz and corresponds, in our case, to the main voltage harmonic for a switching frequency of 3kHz. One can observe that the harmonic flux density at the origin of noise and vibrations is drastically reduced thanks to the damper windings. It also confirms that the capacitor value of 2µF is well chosen. A simulation has been done using three 4µF capacitors and give satisfactory results too but a slightly higher capacitor current value.

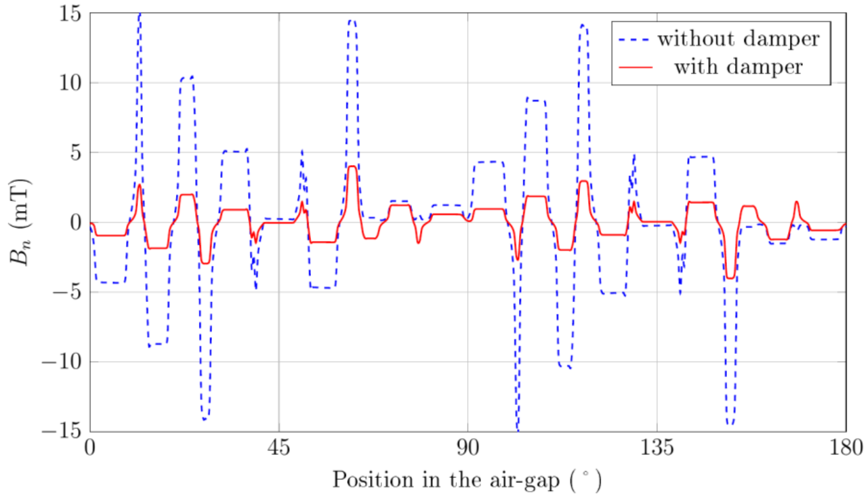

Fig.7. Normal flux density in the air-gap without (dashed line) and with (solid line) damper windings as a function of the position for f = 3100Hz and 2µF capacitors.

V. EXPERIMENTATIONS

In order to demonstrate the effectiveness of the proposed reduction method, experiments have been done on a 4kW prototype of induction machine with damper windings which characteristics are the same as the designed machine introduced previously. Nevertheless, the design method used by the manufacturer must be different than the one presented here so the geometry of the prototype is slightly different. Consequently, current value in the capacitors will not be compared to the theory. The machine is PWM-fed and the switching frequency is set to 4kHz. The noise level spectrum has been measured with a microphone at 1 meter of the machine in a semi-anechoic room. The A-weighting is used in order to take into account the sensibility of the human ear. Figure 8 shows the noise level spectrum of the machine without damper windings, the total noise level is 63.3dBA. With damper windings connected to three 4µF capacitors, the main lines around 8kHz are drastically reduced as shown in Figure 9. The total noise level of the machine with damper windings is 56.2dBA, so the reduction is about 7dBA in this case. Vibrations have been measured on the same machine using accelerometer and show significant reduction too.

CONCLUSION

In this paper, an iterative design method for induction machines including a passive noise reduction solution is proposed. It allows one to optimally design the geometry of a noiseless machine minimizing the impact of the damper windings in terms of size and weight of the magnetic core. Finite element method and experimental results validate the design process and the effectiveness of the proposed noise reduction method.

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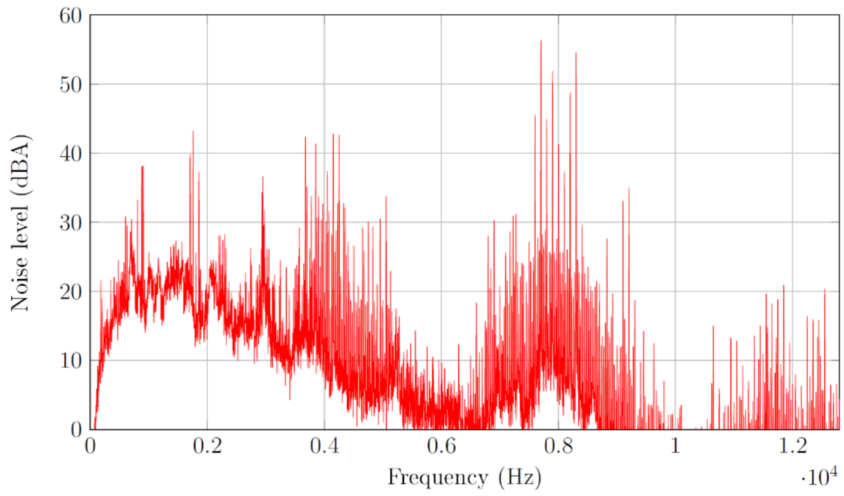

Fig.8. Noise level spectrum without damper windings for f_{PWM} = 4kHz.

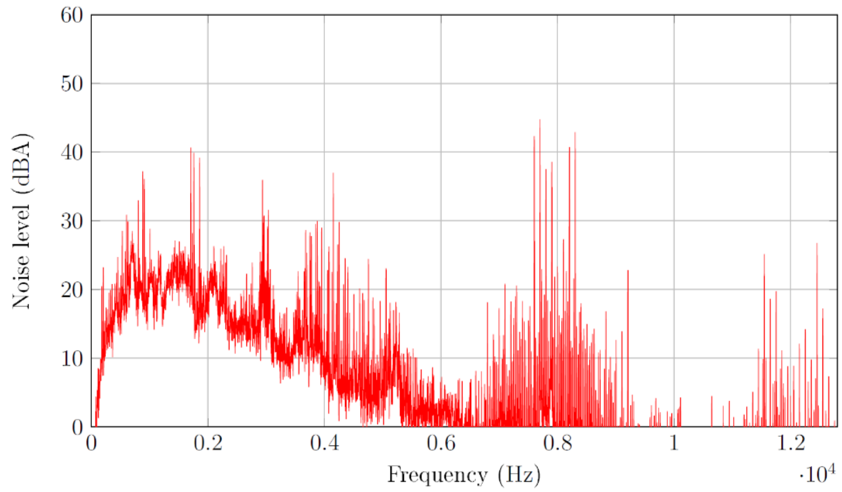

Fig.9. Noise level spectrum with damper windings for f_{PWM} = 4kHz and 4μF capacitors.

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