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Comparison of two passive solutions for noise reduction of PWM-fed induction machines

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Abstract—In this paper, two passive solutions for noise reduction of PWM-fed induction machines are compared: the use of LC filter connected between the PWM inverter and the machine, and a three-phase damper wound inside the machine and connected to three capacitors. Firstly, the principle, advantages and disadvantages of each solution are recalled. The equivalent electrical circuits used for the study are also explained. Then, the effectiveness of both solutions in terms of voltage harmonic reduction and harmonic flux density reduction is discussed. The weight and size criteria are also studied. Results are given for two different power ranges of induction machines: 4 kW and 55 kW, and for two different switching frequencies of the PWM inverter: 3 kHz and 8 kHz.

Index Terms—Induction machine, PWM, passive, LC filter, damper, harmonics, noise

I. INTRODUCTION

Pulse-Width Modulation (PWM) inverters are commonly used to feed and vary speed of induction machines (IM). The output voltage of such inverters can be complex and has a rich harmonic content. As the switching frequencies of most PWM drives are within the human hearing range, the magnetic noise produced by the machine can be annoying for the user. Moreover, pulses generated by the inverter can cause deterioration of the insulation and electromagnetic interference (EMI) problems. To prevent these problems, different techniques can be used:

- Some authors suggest to modify the PWM strategy by increasing the switching frequency beyond the audible range, or by using spread spectrum technique [1]. However, first solution has the disadvantage of affecting the losses and heating of the electronic components of the drive. The second solution does not actually reduce the noise produced by the machine since the overall sound level often remains the same, but the noise spectrum is spread over the audible range which makes it more bearable;
- LC filter is an effective and common technique used to reduce the harmonics of an inverter output voltage [2]–[9], and so, reduce magnetic noise of IMs. This method has the advantage of being passive but often requires a lot of space. Moreover, the iron and copper of such filters make it heavy, and its inductances are likely to be noisy;
- Previous works [10] suggest to use an additional three-phase winding, called damper winding, wound into the

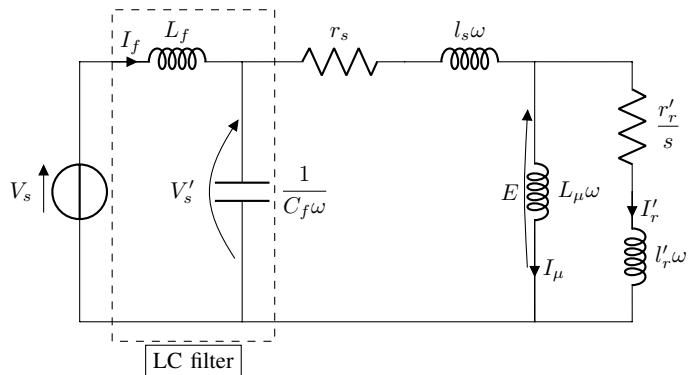


Fig. 1. Equivalent electrical circuit of the machine with a LC filter

stator slots and connected to capacitors. This method is passive and does not require any electronic regulation system. Consequently, the damper can be likened to an integrated filter which requires more space into the stator slots but can be particularly interesting for embedded applications.

This paper is a comparative study of the two previous solutions: LC filter and damper winding. Both techniques are first presented in more details. The study is then done on two IMs of different power range, allowing the comparison of the chosen noise reduction methods in terms of effectiveness, size, weight and cost.

II. PRESENTATION OF THE STUDIED SOLUTIONS

A. LC Filter

When a LC filter is connected between an IM and its PWM inverter, the voltage distortion of the drive is drastically reduced so that the supply voltages become nearly perfectly sine. Despite the effectiveness of that method, the drawbacks are real. For example, a filter often needs its own electrical cabinet which can be a problem when the space is limited [11]. Moreover, the inductances of the filter can become a source of magnetic noise, so the noise of the machine is not truly removed but moved to the filter instead.

In the case of a classical LC filter placed upstream of the machine, the equivalent electrical circuit used is that

of Fig. 1. V_s is a frequency-dependent PWM voltage, L_f and C_f are respectively the inductance and capacitor of the filter, r_s and r_r'/s the resistances of the stator and rotor windings respectively, l_s and l_r' are the stator and rotor leakage inductances, and L_μ the magnetizing inductance.

B. Three-phase Damper Winding

1) *Main Principle:* The damper or auxiliary winding consists in adding a second three-phase winding which is superimposed to the initial stator winding and sharing the same slots [10]. The damper is wound at the top of the stator slot, close to the air-gap, as shown in Fig. 2. The two sets of windings are electrically independent: the stator can be fed directly by the network or, like in our case, fed by a PWM inverter.

The damper winding is simply connected to three capacitors. Therefore, the flux density harmonics due to the PWM naturally induce harmonic currents in the damper which generates opposed flux density waves with convenient capacitors.

2) *Equivalent Circuit:* The equivalent electrical circuit of an induction machine with damper winding [10] is given in Fig. 3. Most elements are common with that of Fig. 1. This circuit is derived from Kron's theory about equivalent circuits in electric machinery [12]. The branch on the right of the circuit represents the damper winding with r_a' , l_{ac}' and C_a' being respectively the resistance, the coil-end leakage inductance of the winding and the capacitor connected to the damper. l_{az}' is the slot leakage inductance of the damper winding and represents the coupling between the two sets of three-phase windings. The capacitor C_a' has to be chosen so that it mainly resonates with l_{ac}' around the switching frequency. The aim of this resonance is to minimize the harmonic electromotive force E that is directly proportional to the harmonic flux density at the origin of magnetic noise. The knowledge of the numerical parameters of the equivalent circuit of the machine is therefore essential for the choice of the capacitor. These parameters can be calculated analytically or numerically, they are given in I.

3) *Machine Design Including Damper Winding:* This additional winding can be included in the design process of an induction machine. Its cross section is small as it only carries

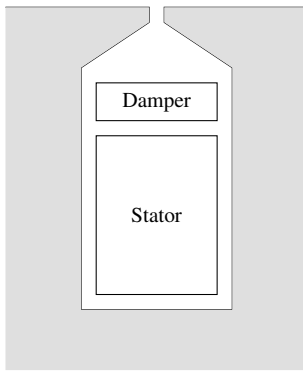


Fig. 2. Arrangement of the windings into the stator slots

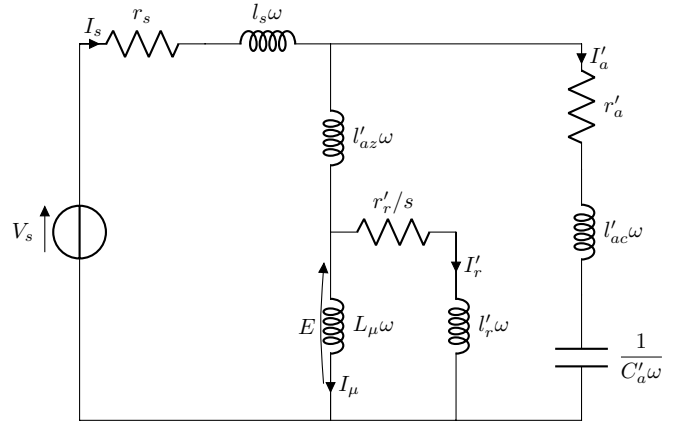


Fig. 3. Equivalent electrical circuit of the machine with damper winding

TABLE I
PARAMETERS OF THE EQUIVALENT CIRCUIT OF IM WITH DAMPER WINDING

	IM 4 kW	IM 55 kW
r_s (Ω)	0.56	0.061
l_s (mH)	4.7	0.563
l_{az}' (mH)	5.4	0.395
L_μ (mH)	218	21.7
r_r' (Ω)	0.986	0.036
l_r' (mH)	10.1	0.73
r_a' (Ω)	9.88	0.775
l_{ac}' (mH)	2.6	0.279
C_a' (μ F)	2	20

harmonic currents, unlike the LC filter which also carries the fundamental current. Examples of 4 kW and 55 kW IMs design including damper windings have shown an increase of the outside diameter of 2% and 1.4% respectively, compared to a traditional design. Further details on the design process of induction machines including damper are given in [13]. This design process is based on the conventional method [14] used to design IM but taking into account a larger space into the stator slots for the damper winding. The cross section of the damper is initially estimated to 20% of that of the stator winding. Then, this cross section is optimized in an iterative process using the equivalent circuit of the machine given in Fig. 3.

III. PWM VOLTAGE HARMONIC REDUCTION

The use of a LC filter allows one to drastically reduce the harmonic content of a PWM voltage supply. The main advantage of such reduction, besides the acoustic aspect, is to prevent a premature aging of the windings. A damper winding can not prevent this aging as it is electrically independent of the stator.

Filters parameters L_f and C_f for each machine are given in Table II and are taken from the technical documentation [15]. The considered voltage source of the circuit presented in Fig. 1 is a PWM supply which voltage spectrum has been

TABLE II
FILTERS PARAMETERS

	L_f (mH)	C_f (μ F)	f_c (Hz)
IM 4 kW	5.2	6.8	846
IM 55 kW	0.5	20	1591

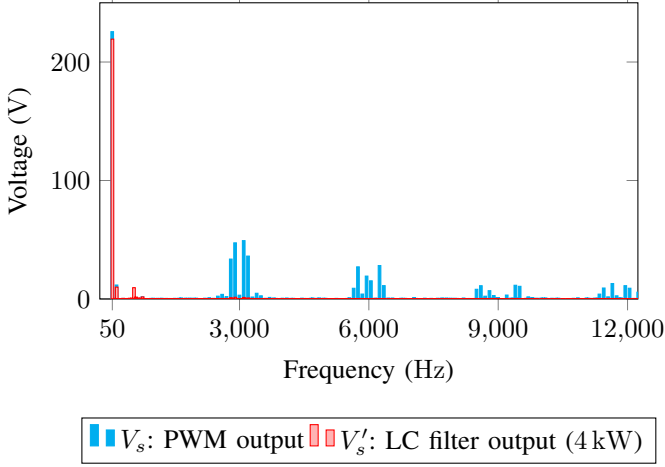


Fig. 4. PWM and LC filter output voltage of 4 kW IM for $f_{PWM} = 3$ kHz

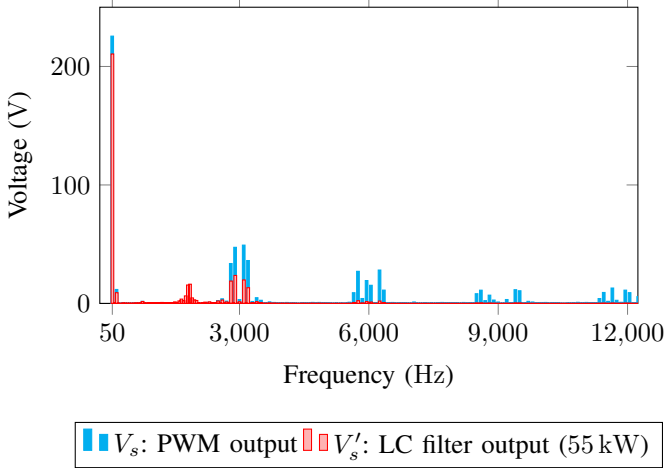


Fig. 5. PWM and LC filter output voltage of 55 kW IM for $f_{PWM} = 3$ kHz

experimentally measured on an industrial PWM inverter. Fig. 4 and Fig. 5 compare the PWM and LC filter voltage output for $f_{PWM} = 3$ kHz on a 4 kW and 55 kW IM respectively. For both machines, most of the PWM voltage harmonics are mitigated, particularly around the switching frequency and its multiples. However, new voltage harmonics appear around the cut-off frequency f_c of the filter. These harmonics can cause vibrations of the mechanical structure of the machine if they coincide with resonance frequencies. Another disadvantage shown by these figures is the small reduction of the fundamental voltage component. The impact on the fundamental

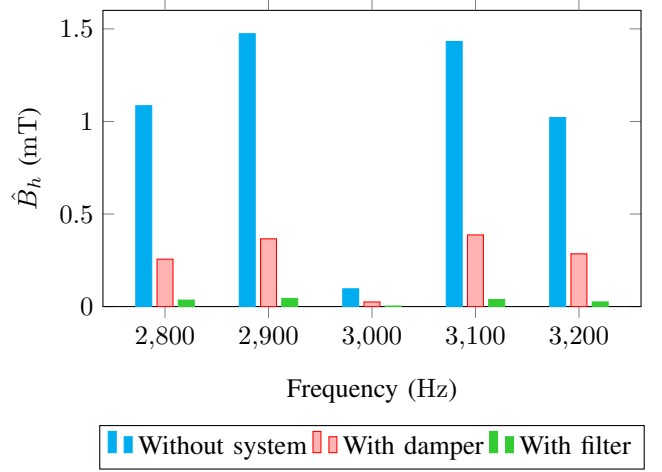


Fig. 6. Peak flux density in the air-gap of 4 kW IM for $f_{PWM} = 3$ kHz

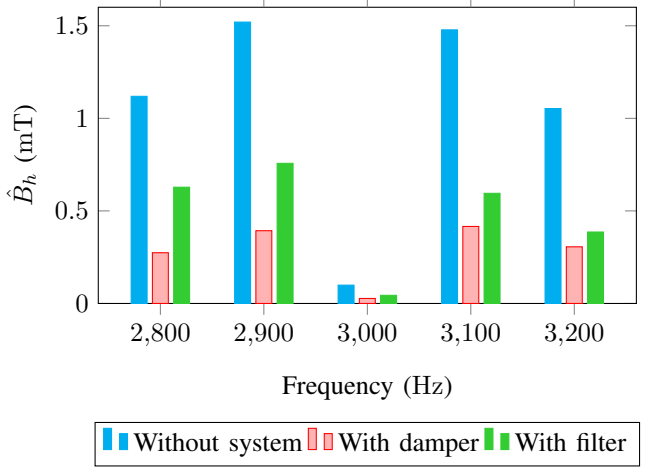


Fig. 7. Peak flux density in the air-gap of 55 kW IM for $f_{PWM} = 3$ kHz

flux density component will be quantified in the following section.

IV. HARMONIC FLUX DENSITY REDUCTION

In order to compare the two passive solutions in terms of noise reduction, the harmonic peak flux density in the air-gap of the machine is calculated analytically from the single-phase equivalent circuit. The three following cases are considered: the classical IM equivalent circuit, a LC filter upstream the classical circuit (Fig. 1), and the equivalent circuit of IM with damper windings (Fig. 3). For each case, the study will be done on the 4 kW and 55 kW IMs. The chosen capacitor values for each machine are respectively 2 and 20 μ F.

The peak flux density in the air-gap of an IM is given by:

$$\hat{B}_h = \frac{\sqrt{2} L_\mu I_\mu^h p}{N_s D_{is} L} \quad (1)$$

with L_μ the magnetizing inductance, I_μ the harmonic magnetizing current, p the pole pairs number, N_s the number

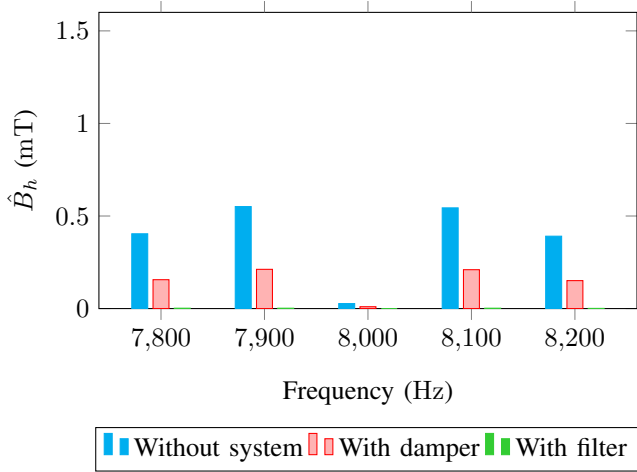


Fig. 8. Peak flux density in the air-gap of 4 kW IM for $f_{PWM} = 8$ kHz

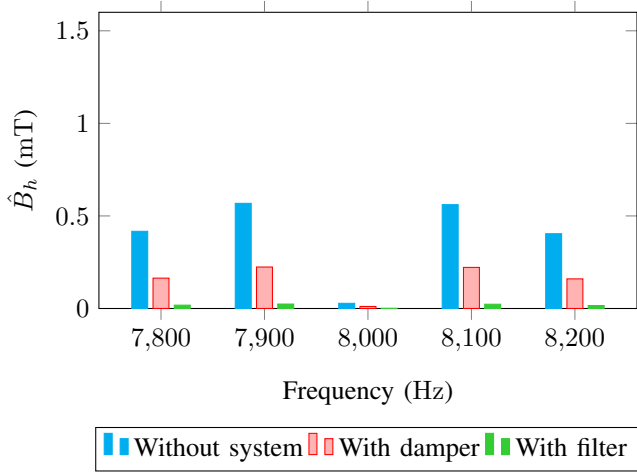


Fig. 9. Peak flux density in the air-gap of 55 kW IM for $f_{PWM} = 8$ kHz

of turns in series per phase, D_{is} the inner stator diameter and L the length of the iron core.

Figures 6 to 9 show the peak flux density of 4 kW and 55 kW IM respectively around f_{PWM} . Studied switching frequencies are 3 and 8 kHz. It appears that both damper and filter allow to significantly reduce harmonic effects due to PWM. The filter seems more adequate for most of the studied cases, with an exception for the 55 kW IM and 3 kHz switching frequency (Fig. 7). The effectiveness of the damper is less than that of the filter but seems not dependent on the switching frequency of the inverter nor the power of the machine. In fact, the value of the capacitor connected to the damper has been carefully chosen for a specific association of machine and its inverter. On the contrary, the filter is a more generic solution, supposed to work for any machine of a given power range and any PWM strategy.

Table III shows that the fundamental flux density at 50 Hz is more impacted with a filter which causes a voltage drop. This voltage drop is probably underestimated here because the resistance of the filter is not taken into account.

TABLE III
FUNDAMENTAL PEAK FLUX DENSITY AT RATED LOAD

\hat{B}_1 50 Hz (T)	Without system	With damper	With filter
IM 4 kW	0.733	0.730 (-0.4%)	0.713 (-2.7%)
IM 55 kW	0.813	0.807 (-0.7%)	0.759 (-6.6%)

V. SIZE, WEIGHT AND COST CRITERIA

Table IV shows that the LC filter solution is the heavier one, especially for the 55 kW IM. In this case, the weight of the filter is more than 10 times higher than the weight of iron and copper needed for the add of the damper. It also seems that the relative value of the weight of the damper decreases as the power range of the machine increases, the opposite applies for the filter. This is essentially due to the fact that the filter carries the fundamental current, unlike the damper which only carries harmonic currents.

Furthermore, the damper solution is very compact as it only requires space for the three capacitors outside the machine and an increase of the outside diameter of 1.4%. As a comparison point, the LC filter size for the 55 kW IM is $495 \times 305 \times 236$ mm [15].

In the case of a new IM design, the cost of adding a damper winding is simply due to the additional weight of copper and iron, as well as the three capacitors. This cost is clearly negligible compared to that of a LC filter. In the case of an existing IM, the add of a damper winding inevitably leads to a rewinding of the machine which can be more or less expensive than the cost of a LC filter, depending on the power range of the machine.

VI. CONCLUSION

The study has shown that the LC filter and damper winding are two effective solutions that allow reducing the harmonic flux density due to PWM supply, and so magnetic noise produced by induction machines. The LC filter appears to be globally more efficient than the damper winding in terms of harmonic flux density reduction, but this is a more generic solution that can be inadequate for a particular machine. On the contrary, in the case of the damper, the capacitor choice has to be done according the numerical values of the equivalent circuit parameters of a specific case of machine and its PWM inverter.

On the other hand, as a contrary of the filter which carries the fundamental current, the damper only carries harmonic currents and uses the iron of the machine. The additional weight of iron and copper required for the add of the damper is therefore very low in comparison to that of the filter. This

TABLE IV
WEIGHT OF SYSTEM WITH DAMPER OR FILTER

Weight (kg)	Initial machine	Damper	Filter
IM 4 kW	40	2.65 (6.6%)	6.1 (15.3%)
IM 55 kW	328	6.64 (2%)	68 (20.7%)

aspect can be particularly interesting in embedded applications for example.

As a conclusion, the damper winding is an interesting alternative noise reduction method in terms of size and weight, especially for medium and high power machines.

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