Comparison of a natural sampling and random PWM control strategy for reducing acoustic annoyances

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Abstract

This paper compares the vibratory responses of a well-known mechanical free response stator with two PWM strategies (natural sampling and random) implemented on a TMS320F240 DSP. The presented results are discussed as well as on vibratory response and computing DSP time, for similar THD current, for the two PWM controls in load and no load conditions.

1. Introduction

Reducing noise of electric machines was already a problem before the generalisation of electronic power supplies. LIWSCHITZ published an excellent paper [1] with an extended list of references on the subject in 1942. ALGER wrote one of the main publications on the subject in 1951 in the first edition of [2]. Acoustic noise generated by the association of an electric machine and its converter has now become of prime importance for choosing an electric drive. This problem has been studied since the generalisation of the electronic converters. One of the first references on the subject is due to P.L. TIMAR in 1977 [3] and some books [4] have included a synthesis on the problem.
Various strategies for reducing induction motor noise are classically used:

- High switching frequencies (above 15 kHz) is a very efficient method but imposes high stress of the switches.
- Spread spectrum strategies (for example random strategies [5], [6] and [7] reduce acoustic noises annoyances but may coincide with mechanical resonances).

The paper proposes to point out the advantages and drawbacks of natural sampling (sinus-triangle comparison) and random PWM (Pulse Width Modulation) control strategies for induction motor. The comparison takes into account vibratory response, harmonic distortion currents and computing time on a same hardware and a same range of switching frequencies.
Previous works in our laboratory permit to express the surface forces that are due to the converter as a superposition of revolving fields thanks to an analytical model [8] and [9]. Space and time harmonics are taken into account to define the source of mechanical excitation that causes acoustic noise. The mechanical structure of the studied machine is presented first. Next comes the method used to reduce acoustic noise, knowing that electromagnetic acoustic noise, which is the noise discussed in this paper, is the results of stator vibration. Then, the control strategies and implementation are presented before experimental results.

2. Mechanical structure response

As it will be described in the next part, electromagnetic noise is linked to the control strategy of the power converter. Nevertheless, a precise knowledge of the internal machine constitution is required to reach an efficient acoustic noise reduction.

2.1 Studied machine description

The machine used for experimentation was designed in Laboratoire d'Electromécanique de Compiègne (LEC). Therefore the geometric characteristics are perfectly known. It is a 3-phase induction machine supplied by a low voltage at a power of 700 W. This machine has P=2 pairs of poles (1500 rpm when supplied by a 50 Hz network). The stator has S=27 slots and the rotor is a R=21 slots squirrel cage rotor (Figure 1).

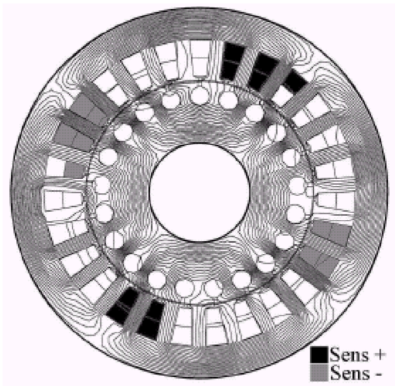


Fig. 1: Studied machine description.

2.2 Mechanical structure response

There are different kinds of vibration for the stator. They are classified in modal motion number as shown Figure 2. For *m*=0 we are generally speaking of a pure extensional mode because the strain is principally due to an extension rather than a bending. For *m*=1 in the plane of a sheet, it is so-called rigid body motion because there is motion without strain and finally for *m*≥2 we speak about bending modes.

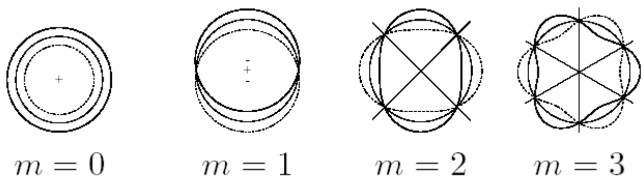


Fig. 2: Modal motion (mode shapes) for low frequencies in the plane of a sheet.

The mechanical structure response may be obtained by various ways. The table 1 shows that analytical method [13], FEM, shock method and sinus excitation methods give roughly the same results for the considered machine.

Mode number	Analytical Method (Hz)	Finite Element (Hz)	Shock Method (Hz)	Sinus Method (Hz)
0	14859	14656	O. R.	O. R.
1	0	0	1200	1273
2	2478	2364	2400	2423
3	6396	6473	6100	6210
4	12028	11898	11700	O. R.

Table I: Natural frequencies by 4 different methods (O. R.: Out of Range i.e. frequencies not in the range of the measured frequencies) in Hz

These five first modes have different influences on the acoustic behaviour.

- Mode 0 (extension mode) can be neglected because the corresponding frequency is superior to human hearing bandwidth.
- mode 1 would be excited by forces due to the rotor eccentricity, A high construction quality allows to minimize this forces and so the contribution of this mode will be neglected in our study.
- Mode 4 frequency is too high to have a significant contribution in the global noise. Its contribution will be covered by the mode 2 and 3.

A great part of the global noise will be generated by the mode 2 (2478 Hz) and 3 (6396 Hz).

These two frequencies are sufficiently spaced to avoid to be simultaneously excited by forces due to PWM harmonics. On the other hand, low order modes are more awkward from an acoustic point of view. [13]
As a conclusion, this paper will be focused on the mode 2 even if the global noise is generated by the contribution the modes 2, 3 and 4. The experimental results will confirm this choice.

3. Proposed method to reduce magnetic acoustic noise

Stator vibrations due to radial forces are the principal source of the magnetic acoustic noise. Some previous works [9] [11] [12] have shown that to have an important noise, a frequency coincidence between the forces and the mechanical resonance of the structure is not sufficient but it must also have a similitude into the spatial force distribution and the mode shape of this mechanical resonance (we speak about spatial coincidence). Then, an efficient way of reducing noise is to move away the frequency of forces only when there is a spatial coincidence or a strong similitude into these two spatial distributions. In these cases, we easily use the modal superposition method. It consists to express the response of the structure on the modal shapes of the mechanical structure. It permits a decoupling of each new coordinate (orthogonality between the mode shapes). Because of the orthogonality between modes of different ranks, there is only one term different from zero, when the mode and the force have the same *m* rank. After the projection on the modal basis, it will lead to a second order Ordinary Differential Equation with modal excitation instead of Partial Differential Equation.
This conclusion is very interesting to limit the investigations of coincidence of excitation frequency and natural resonance frequency when there is a modal coincidence too. In our case, the most important natural resonance frequency is at about 2400Hz (mode 2), then we could limit our task on excitation forces with the same mode number m=2.

There is many means to compute excitation radial forces (numerical or analytical methods) and works in our laboratory permit the development of an analytical model well adapted for the coupling to a vibrational model. This modelisation uses Fourier Transform in two dimensions (space and time) and we obtain a radial force density function of a temporal variable and the angular position. The forces applied on the structure result of the Maxwell force density that is a quadratic form of the magnetic field (equation 1).

$$f_{radial} \approx \frac{B^2}{2\mu o} \tag{1}$$

Due to the form of B and its squaring, radial forces frequencies are not the frequencies present in current and voltage spectra. The interactions with the machine design must be considered.

The electromagnetic forces are defined with a vibratory mode and a frequency, the conclusions of previous works bring to say that generalised forces will be the projection of these forces on each mode. For the previously described machine, As seen in [2], B is expressed by the following relation, for a single time harmonic nω, where s is the rotor slip.

$$\begin{aligned} B = B_0.\cos(P\theta - n\omega t) + B_1.\cos((S-P)\theta + n\omega t) + B_2.\cos((S-P)\theta - n\omega t) \\ + B_3.\cos((R-P)\theta - n\omega t.(1-\frac{R.(1-s)}{P})) + B_4.\cos((R+P)\theta + n\omega t.(1-\frac{R.(1-s)}{P})) \end{aligned} \tag{2}$$

To introduce the behaviour of a machine fed by converter, this last equation must be generalised to two time harmonics where $n_1\omega$ is issued from the switching frequency and $n_2\omega$ from the fundamental. Since we are especially interested by the mode m=2 we present only the corresponding term, where (S-R-2P) gives the spatial mode m=2 with the values of our machine, in the expression of B^2.

$$B^2 = [... + B_1B_4.\cos((S-R-2P)\theta + n_1\omega t - n_2\omega t.(1-\frac{R.(1-s)}{P})) + ...] \tag{3}$$

The relation $n_1\omega t - n_2\omega t.(1-\frac{R.(1-s)}{P}))$ brings to the excitation frequency.

4. Control strategies used and implementation

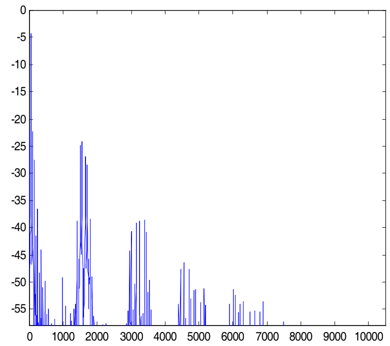
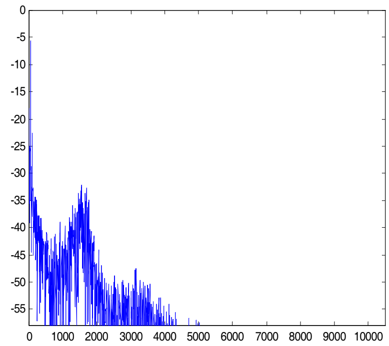
	Natural sampling	Random
F= 1600		

Fig. 3: Current (dB) versus frequency (Hz).

This study wants to show that, in the same range of low switching frequencies, random PWM is not necessarily the best way to reduce noise. Figure 3 shows current spectra for natural and random sampling. Random PWM spreads the current spectrum to minimise excitation but increases the probability to meet a severe mechanical resonance by multiplying the number of harmonics. Then, a natural sampling PWM method could give good results if we take care to avoid resonance. Even if it is not especially dedicated to numerical implementation, natural sampling PWM is chosen as a comparison base because it is the more universal PWM strategy.

In order to compare experimentally these two methods, they have been implemented on a 20 MHz TMS320F240 Spectrum Digital DSP card with help of C Language as shown Figure 4. The studied machine is an induction motor mechanically connected to a load machine, a Bruël & Kjaer accelerometer sensor gives vibration measures through a Yokogawa 12 bits data acquisition system.

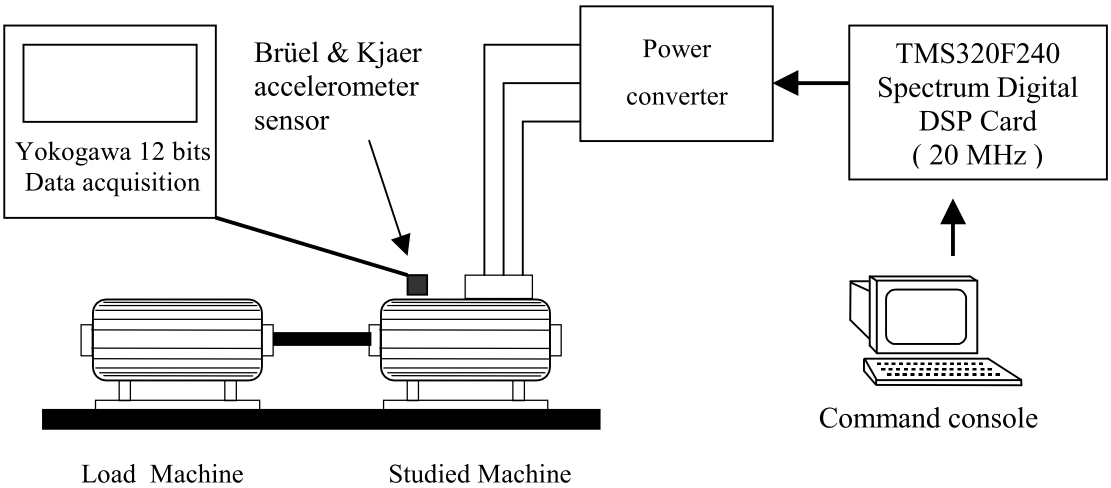


Fig. 4: Experimental implementation.

For the software implementation, the total C programming allows very easy changes in PWM control strategies to compare them. It is especially interesting for the random PWM implementation as shown below. Furthermore, we could reach satisfactory computing times for DSP systems.

```
if (aleat)
   {
   srand(t);                           /* random function initialisation */
   r=rand()%(plagmodaleat);            /* random number limited in modulation frequencies area */
   Fd=(fd-plagmodaleat/2)+r;           /* switching frequency definition */
   }
else Fd=fd=2000+df;
   period = (SYSCLK_FREQ/Fd)-1;        /* use of system clock frequency to define period */
   *T1PR = period;                     /* switching period register allocation*/
```

Fig. 5: C language code example for random PWM.

5. Experimental results

5.1 No load results

Experimental tests are performed with a 50Hz, 4.5 A RMS, fundamental current to control the induction motor. The experimental results summarised in Figure 6 show the spectra of the vibrations measured on the stator with an accelerator sensor. The first switching frequency (1800 Hz) is chosen to show the resonance case. In fact, a 1900 Hz current harmonic (two times the fundamental frequency added with the switching frequency) leads to an excitation frequency of 2375 Hz through the relation presented first in section 3 : $n_1\omega t - n_2\omega t.(1-\frac{R.(1-s)}{P}))$. This excitation frequency is very close to the mechanical resonance. The second switching frequency (1600 Hz) leads to excitation forces that avoid mechanical resonance, the worst one has a frequency of 2175 Hz. With the weak distance of these two switching frequencies, the current THD is similar for the two natural sampling cases.

Figure 6 shows computing time for the different PWM strategies too, 350 µs for the natural sampling and 450 µs for the random PWM. Because of time constants of the studied machine, a T=10 ms process sampling period is sufficient to control this machine. The DSP implementation allows providing a PWM signal as quickly as required. In fact, the ratio between the process sampling period and the time of PWM generation is about 29 for the natural sampling and 22 for the random sampling. This last ratio is particularly interesting because it allows envisaging easily the use of advanced PWM strategies to improve the converter-machine interactions.

In the F1 switching frequency case, the spectrum for natural sampling shows, as predicted by the mechanical response study, the higher vibration peak around 2400Hz with amplitude of –9dBV. A 1800 Hz switching frequency brings to an excitation force near the mechanical resonance, therefore the peak amplitude is so high. The corresponding spectrum with random PWM presents a significant improvement with the diminution of –11dBV of the higher peak amplitude. So, random PWM seems to be the good way of noise reduction in this frequency range but the next experience brings to an other point of view with natural sampling capabilities.

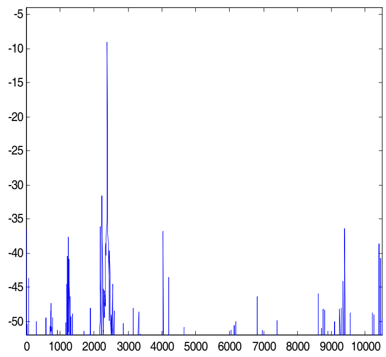
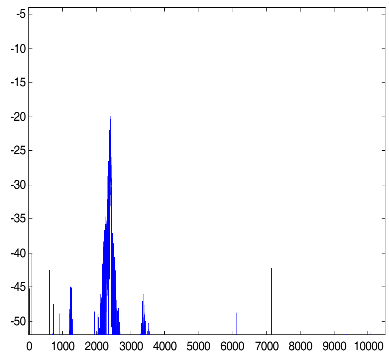
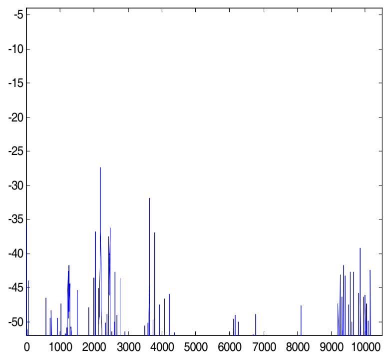
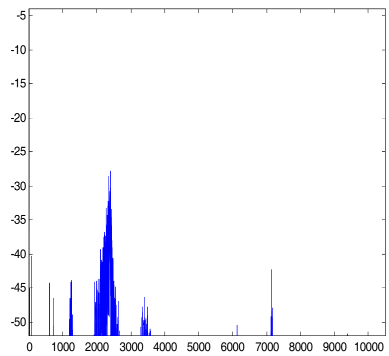
	Natural sampling	Random
F1= 1800		
F2= 1600		
Computing time	350 µs	450 µs

Fig. 6: Vibration amplitude (dBV) versus frequency (Hz) and computing time.

For the F2 switching frequency, natural sampling spectrum shows the higher peak with a –27dBV amplitude which is much more less than the maximum amplitude with the previous random method. This is the consequence of the harmonics current shifting in frequencies, which results in reduction of radial forces near the most important mechanical resonance frequency. This result is very interesting because F2 is lower than F1and it is usually believed that the switching frequency must be increased to reduce acoustic noise. In this switching frequency case, the use of random PWM gives no significant improvements with the higher peak. This is explained by the 1600 Hz switching frequency that brings to excitation forces slightly away from the mechanical resonance. On the contrary, a random PWM spreads the spectral current rank around 1600 Hz and raises like this the mechanical resonance for excitation forces it creates.

5.2 Effect of load

Tests in load condition have been realised to show the influence of load on vibrory behaviour. Experimental tests are now performed with a 50Hz, 10 A RMS, fundamental current. One can verify on the spectra Figure 7 an increase of amplitude for the whole frequency area, even for random or natural sampling and for the two different switching frequencies. However, the fact that the higher peak has not increased a lot must be highlighted (Table II). The increase of the higher peak is less important than the increase of the others. This can be explained by the augmentation of the rotor slip with the load (equation 3) and [10, 11, 12, 13]. In fact, the rotor slip augmentation causes diminution of the mechanical excitation frequency which goes away from the resonance frequency. Thus, a load condition is not necessarily so severe as it could be thought at first if the rotor slip effect and the principal resonance are known.

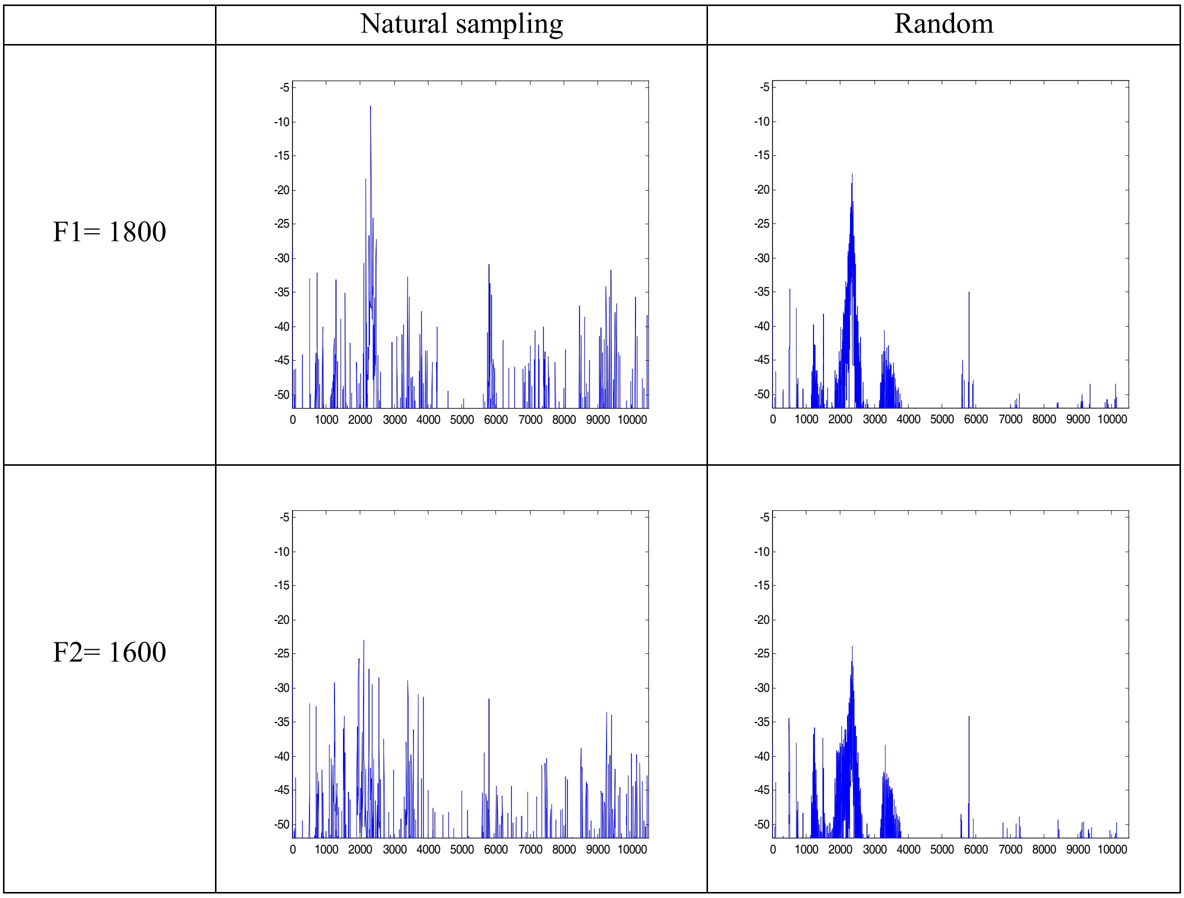


Fig. 7: Vibration amplitude (dBV) versus frequency (Hz) in load condition.

	No load		Load	
	Natural sampling	Random	Natural sampling	Random
F1=1800Hz	-9	-20	-7.5	-18
F2=1600Hz	-27	-27	-23	-23

Table II: Vibration amplitude (dBV) of the higher peak.

Table II summarised the vibration amplitude of the higher peak in load and no load condition for the two PWM strategies and the two frequencies studied. One can notice the effectivness of random PWM either in load and no load condition for the 1800Hz switching frequency. However, there is no difference between the two PWM strategies for the 1600Hz switching frequency. The advantage given by random PWM with the minimisation of the current harmonics is lost because the multiplication of harmonics leads to meet the mechanical resonance. One can notice too, the relatively low difference between load and no load condition.

6. Conclusion

In this paper a comparison of natural sampling and random PWM for reducing acoustic annoyances is performed. The comparison shows the crucial importance of stator mechanical response. So, this study brings to a new point of view: the knowledge of most important resonance modes and frequencies permits a very good effectiveness of a non random sampling PWM even with a lower switching frequency. Furthermore the fact that the machine is loaded is not necessarily so severe as it could be thought at first for acoustic considerations.

Random PWM keeps interest in a number of situations. A special one is the use of random PWM to find the most important resonance frequencies when there is no a priori knowledge of mechanical response of the machine under study. DSP implementation with C language allows great flexibility in programming, which is very interesting for the performances comparison of PWM control strategies. New DSP systems allow very easy programming of efficient control strategies with relatively low computing times and so may improve efficiently the association of power converter and electric machine.
Furthermore, the acoustic noise produces by random PWM is not so pleasant to ear and gives a sensation of bad quality of the motor. This last point is very embarrassing for lots of industrial applications. Therefore other tools should be used to take into account the human perception of sound. Some tools are still existing in psycho-acoustic, the used of these tools should be very interesting for electromechanical domain in the future.

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