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On the Acoustic Noise Radiated by PWM AC Motor Drives

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Preliminary communication

The paper presents and analyses the experimental acoustic noise of AC motors controlled by drives using different PWM techniques. After a discussion upon PWM methods concerning noise reduction, measure based comparisons are interpreted. Five criteria are taken into account: motor type, motor power, rotor speed, switching frequency and PWM method.

Key words: noise acoustical and electromagnetic, modulation strategies, AC machines, variable speed drives

1 INTRODUCTION

One of the problems of the PWM controlled AC motors is the acoustic noise that could become unacceptable when used in silent environments. Noise reduction has constituted a difficult study point for the last years. A great part of this acoustic noise has electromagnetic origin. The harmonic spectrum of the PWM voltage supply is very rich and every frequency has direct effects on the motor acoustics. Many studies have been made in order to obtain an acoustic model of the AC motor, but usually without taking into account the type of the PWM supply [10, 7, 8]. However, different PWM techniques produce different types of motor acoustic noise [5, 2, 10]. It is very difficult to give quantitative criteria for the classification of these last ones because the acoustic noise depends a lot on the human ear. It is even more difficult to give a simple relation between the motor acoustic noise and its PWM supply.

We will firstly make a discussion on the PWM methods from the acoustic noise reduction perspective. Then we will make a qualitative and quantitative comparison between acoustic noises produced by different most spread PWM. General tendencies of noise will be given and remarks on noise electromagnetic origin in a pragmatic approach will be done in order to show the direct relation between the motor line voltage and acoustic noise. A black-box model could materialize this relation.

2 THE ACOUSTIC NOISE AND THE AC MOTOR DRIVES

The acoustic noise of the AC motor is due to the mechanical vibrations of the motor structure (mainly stator, base-plate, casing), but also to acoustic vibrations (air turbulences) created by the movement of the rotor.

The acoustic noise can be divided into three parts [2]: a part of what we hear is *mechanical* noise, the second is *aero-dynamical* noise and the largest part of the noise spectrum has *electromagnetic* origins. The mechanical noise is due to surface accidents, eccentricities, too accentuated or insufficient axial or radial displacement, fake round, too dense grease, bad finishing, shaft displacement, rust. The aero-dynamical noise is mainly constituted by the air turbulences, the siren effect and the cavity resonance noise. These two noise types are practically independent from the electrical supply of the motor. Their frequencies in a Fourier analysis occupy the low part of the spectrum (usually less than 2000 Hz in industrial applications using $P < 55$ kW, 2 or 4 poles motors, compare Figure 8 and Figure 9).

The electromagnetic part of the noise is related to the power supply. We can have a general look from Figure 2 upon the direct relation between the AC motor line voltage spectrum and the measured noise spectrum. For low and medium speed and low nominal speed motors we can practically neglect the mechanical and the aero-dynamical noise.

The electromagnetic noise is produced by the magnetic forces that appear inside the electrical machine [7, 8, 10]. The simplest manner to explain it is to say that it comes from the excitation of the AC machine modes. These are different types of buckling of the structure as a reaction to the electrical supply. Every frequency that appears in the supply voltage spectrum has its own effect upon the structure. The acoustic noise is therefore the result of all mode excitations due to every harmonic of the voltage supply spectrum. A simple consequence is: less harmonics in the spectrum, lower the noise is. A detailed spectrum study can show that every ray from the voltage spectrum has its own correspondent ray (at the same frequency) in the noise spectrum.

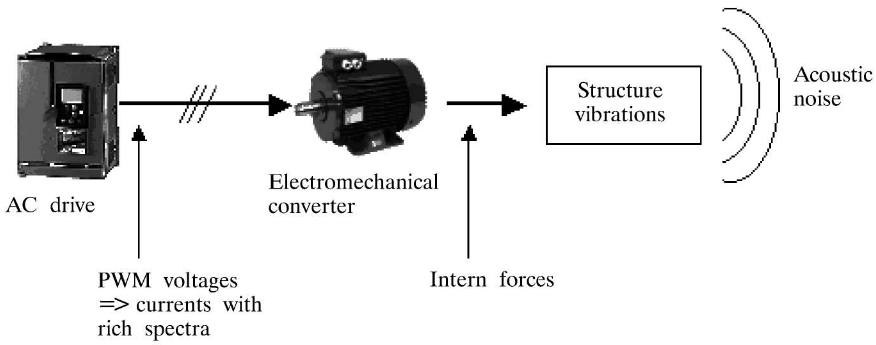


Fig. 1 Noise generation global plan

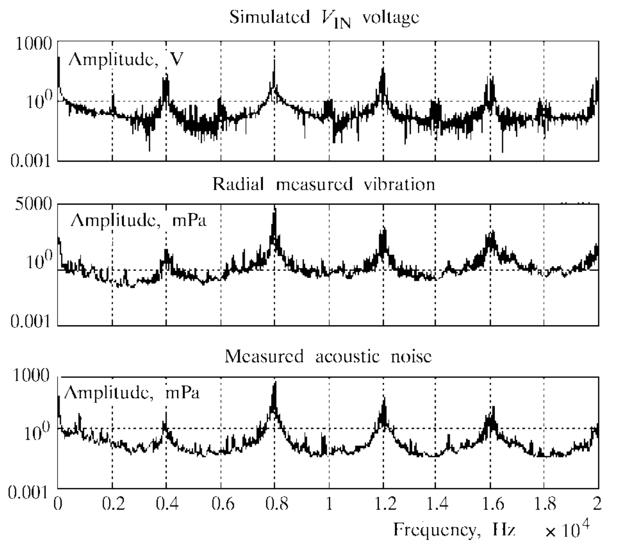


Fig. 2 Voltage, vibration and acoustic noise (air pressure) spectra at f_m=25 Hz, f_{PWM}=4 kHz, LS1.5–1 motor

We will not try to give further details about the components of the noise. We will consider the whole system »PWM supplied AC motor with no load« as a black box with the PWM method as input and the acoustic noise (air pressure) as output.

So, the noise creation mechanism could be simply represented by the chain:

> PWM voltage supply → motor currents → motor vibrations (mainly radial to the shaft) → acoustic noise

which is also shown in Figure 1. The main tool for this analysis will be Fourier transform. As the acoustic noise is proportional to motor currents, motor load operation produce a different acoustic behavior compared to no load operation.

Considering this approach, the noise depends on motor structure, motor power, rotor speed, PWM type and PWM switching frequency. The influence of the speed (which is the main element in variable speed control drives) on the noise can be qualitatively estimated as in Figure 3.

Shortly, the mechanical and the aero-dynamical noise will increase with the number of rpm, while the electromagnetic noise decrease at high speed where the number of PWM switchings decrease because of the neighborhood to the saturation of the reference voltage and secondary effects of the PWM application. The three curves represent qualitatively the weight of the speed in every part of the noise: for example, the electromagnetic noise is emphasized for medium speed in order to show that it represents the greatest part of the entire acoustic noise.

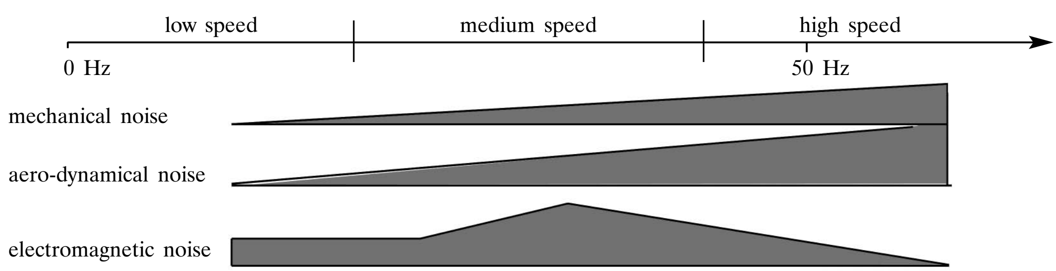


Fig. 3 Noise variation function of motor speed

3 PWM METHODS FOR NOISE REDUCTION

The main studies developed in PWM literature have been focused on:

- inverter linearity zone extension
- switching losses minimization
- acoustic noise diminution.

Almost all new PWM techniques have the same common trace: they are all using in different manners the zero-voltage in order to improve one of the enumerated points. The most known PWM methods are classified in Figure 4 [5].

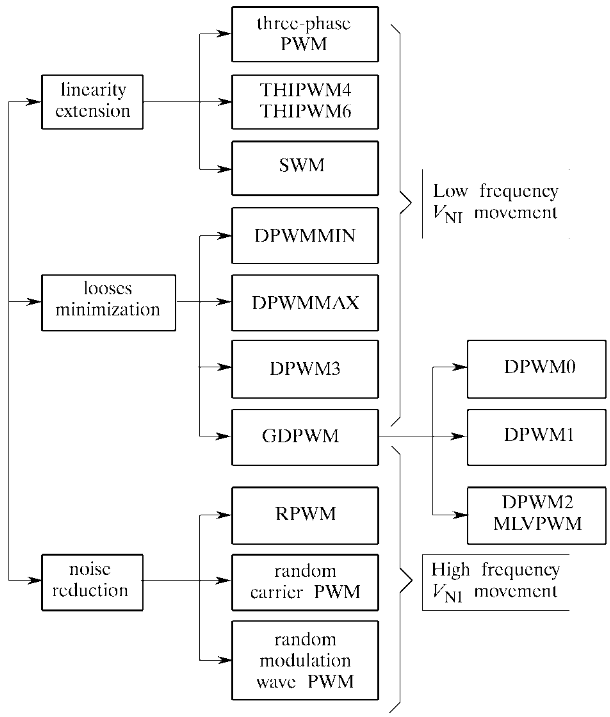
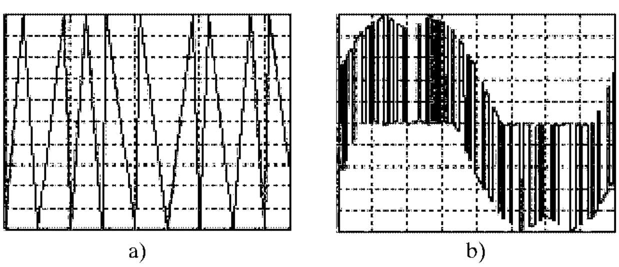


Fig. 4 PWM classification function of the zero-voltage movement

Noise reduction techniques are usually based on random modulation. The three most known principles are: *random frequency PWM*, *random carrier PWM* and *random modulation wave PWM*. The first one uses the idea of changing f_{PWM} each sample period. The second one uses random triangle carrier (Fig. 5,a)) and the third one, a part of the bus voltage randomly added or subtracted from the modulation wave as in Figure 5,b) (both patented by Schneider Electric [1]).



a) b)

Fig. 5 Random carrier and random modulation wave PWM

The result is the same: the spectral energy of the motor line voltage is scattered on a large horizon so that high harmonics around k^*f_{PWM} disappear. The same result is seen in the noise spectrum.

We can show an experimental result for the random modulation wave PWM in Figure 7. The 4 kW ATB motor is not loaded. $f_m = 25$ Hz and $f_{PWM} = 4$ kHz. The measured V_{21} voltage is applied to the motor using an ATV58 drive. A dSpace card based system is used for measuring and analysis.

Figure 7 represents an experimental result for the random frequency PWM with a 1.5 kW LS motor.

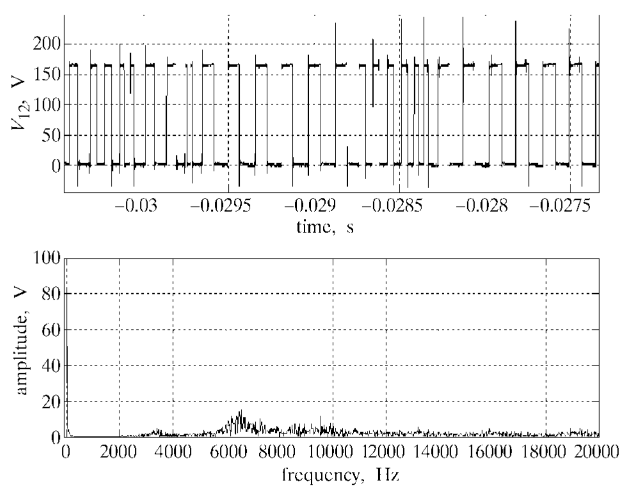


Fig. 6 Experimental V_{12} voltage and its spectrum for random frequency PWM

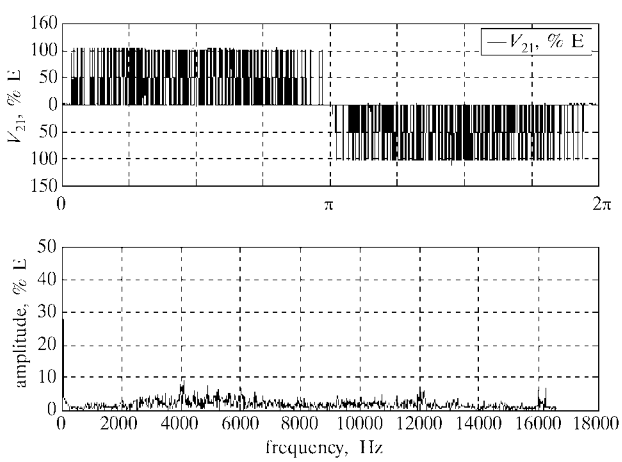


Fig. 7 Experimental V_{21} voltage and its spectrum for random modulation wave PWM

$f_m = 25$ Hz and the average switching frequency is $f_{PWM} = 4$ kHz. Depending on the rule used for random generation the frequency spectrum may vary from case to case. This concerns all the three named random PWM techniques.

The random frequency PWM has its DDT equivalent named RS (*Random Switching Frequency*), the random carrier PWM has almost the same principle as the RCD (*Random Displacement of the pulse Centre*) and the random modulation PWM is equivalent to the RZD (*Random Distribution of the Zero-voltage vector*). The RZD and the RCD are somehow different from theirs homologues from the modulation wave/carrier technique [1, 6].

We can classify these PWM methods as methods with high frequency zero-voltage movement because the reference voltage applied to the inverter changes its value every sampling period. For the random frequency PWM or the random carrier PWM the zero-voltage is equal to 0 between two sampling instants. For the random modulation wave PWM we have to wait a whole revolution period in order to obtain the average value of V_{NO} equal to 0.

4 EXPERIMENTAL NOISE COMPARISON

In order to have a better insight of the acoustic noise origins almost 200 different measures have been taken following five comparison criteria:

- motor type (Leroy Somer, Unelec or Toshiba)
- motor power (0.75 or 1.5 kW)
- rotor speed
- PWM method (three-phase PWM, random modulation PWM, DPWM1 and DPWMMIN)
- switching frequency f_{PWM} (2, 4, 8 or 16 kHz).

Details on the 5 motors we have used can be found annexed. Two 1.5 kW LS motors have been chosen in order to see the difference between motors almost identical, but with different ages and different frames. The main difference between T0.75 and LS0.75 motors is that the first one has a smooth frame while the second one has a bladed frame. The difference between U1.5 and LS1.5-1 or LS1.5-2 is the number of poles.

Details on the four PWM techniques can be found in [5]. We have chosen techniques from three different classes: the three-phase PWM is the fixed--frequency classical method the most spread in industrial applications, the random modulation PWM is a technique specially conceived for noise reduction and the DPWM1 and DPWMMIN are used in order to reduce switching looses. All the three PWM types have a different voltage spectrum.

We have used a microphone for the acoustic noise measurements situated at 20 cm from the motor [3]. The A-weighted measured air pressure in dB_A unities is represented in octave-band third parts. An octave is the frequency interval characterized by a ratio of 2/1 reported to the adjacent interval. The base frequency is 12.5 Hz. In order to obtain an A, B or C-weighted signal, a simple network simulating equal acoustic intensity curves processes the measured noise. The A-weighted signal is the most commonly used because it reflects the sensibility of the human ear to different frequencies. Briefly, the A--weighted signal slightly emphasizes frequencies between 1000 Hz and 8000 Hz (medium frequencies), but attenuates low and high frequencies. The effective value of a signal spectrum is not obtained with the well-known formula for effective values. It is directly computed by the measure instrument [3] after amplification and extraction of a certain bandwidth of the signal. This effective value is therefore the image of the energy of the acoustic signal.

If we compare the answers of the five motors to the network power supply (Figure 8) and to the PWM supply at different rotor speeds (Figure 9, Figure 10) we can notice first of all the influence of the PWM supply on the acoustic noise: at the same speed the mechanical and the aero-dynamical noises are almost the same, but noise effective values differ from 5 to 12 dB_A. The exception is U1.5 motor for which the aero-dynamical noise is so important that the PWM has almost no effect at $f_m = 50$ Hz. This is also proven by Figure 10 where the effective value for U1.5 is lower because the speed is lower, while for all the others motors the effective value is greater for $f_m = 25$ Hz compared to $f_m = 50$ Hz because the electromagnetic noise is greater (explanation in Figure 3).

The comparison between LS1.5-1/LS1.5-2 and LS0.75/T0.75 shows that differences between motors with the same power and the same number of poles are not very important at the same speed. The difference between LS0.75/T0.75 is about 2–4 dB_A because of the frame types, but these values are almost un-noticeable reported to variations due to other parameters as speed, PWM methods or f_{PWM}.

The comparison LS1.5-1 or LS1.5-2 on one side with LS0.75 or T0.75 on the other side shows something evident: the noise decreases with *motor power*. The difference is not quite evident for high speed where the aero-dynamical noise is the most important, but becomes more and more evident when the speed decreases (2–4 dB_A at high f_m, 5–12 dB_A at medium and low f_m).

A very interesting result is obtained in Figure 11: the answer of different motors at DPWMMIN supply is identical for the same rotor speed and switching frequency f_{PWM}.

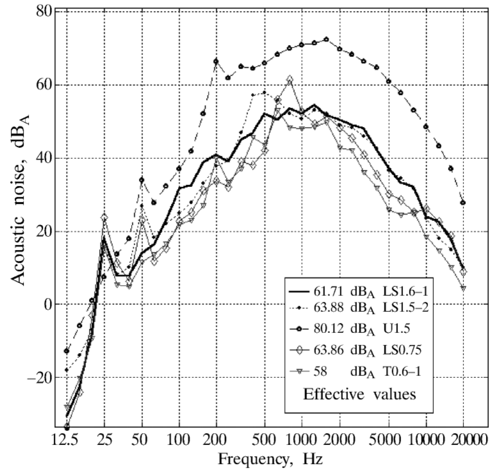


Fig. 8 Spectra comparison function of motor types with sinusoidal supply (50 Hz)

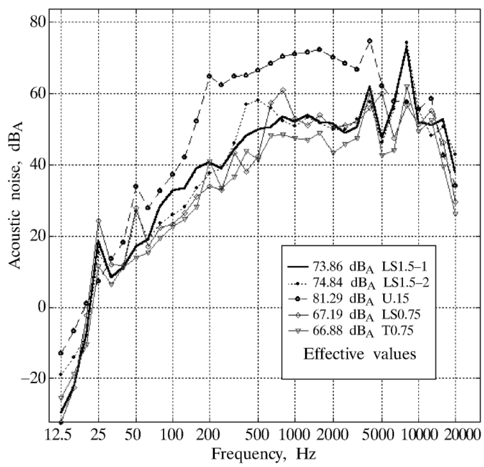


Fig. 9 Spectra comparison function of motor types with three-phase PWM supply, $f_m = 50$ Hz, $f_{PWM} = 4$ kHz

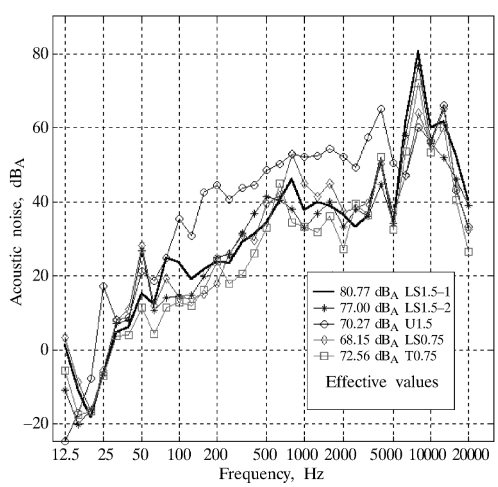


Fig. 10 Spectra comparison function of motor types with three-phase PWM supply, $f_m = 25$ Hz, $f_{PWM} = 4$ kHz

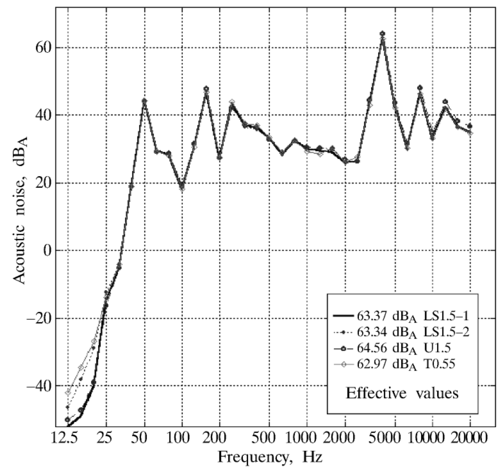


Fig. 11 Spectra comparison function of motor types with DPWMMIN supply, $f_m = 25$ Hz, $f_{PWM} = 4$ kHz

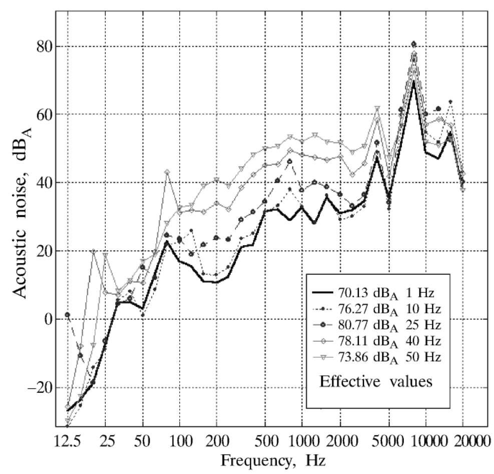


Fig. 12 Spectra comparison function of rotor speed, three-phase PWM, LS1.5-1, $f_{PWM} = 4$ kHz

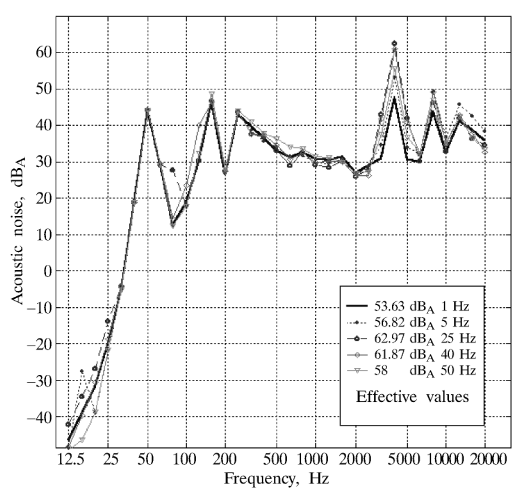


Fig. 13 Spectra comparison function of rotor speed, DPWMMIN, T0.75, $f_{PWM} = 4$ kHz

As we can also see in Figure 12 and Figure 13, the variation of the noise function of f_m increases while *speed varies* from 0 Hz to nominal speed, but begins to decrease 10–15 Hz before this last one. This happens at $f_{PWM} = 2$ and 4 kHz, but for $f_{PWM} = 8$ or 16 kHz from half the nominal speed to the nominal speed the noise tends to increase or differences are not noticeable (Figure 18). This happens independently from PWM method, motor type or motor power. What is also interesting to notice is that the effective value of the air pressure (acoustic noise) follows the amplitude of the most important harmonic from the spectrum (8 kHz for three-phase PWM when $f_{PWM} = 4$ kHz, 4 kHz for DPWM1 or DPWMMIN when $f_{PWM} = 4$ kHz).

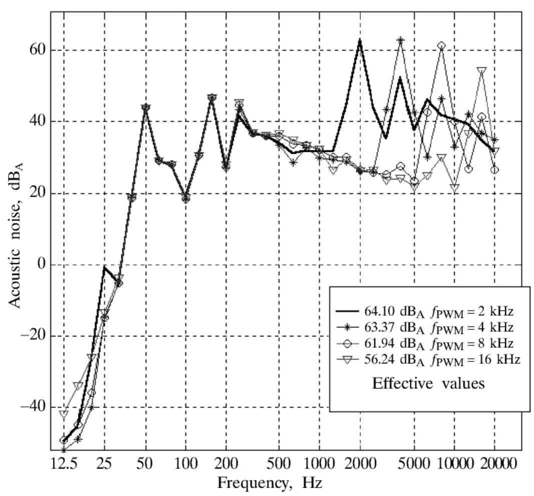


Fig. 14 Spectra comparison function of switching frequency f_{PWM}, LS1.5-1, three-phase PWM, $f_m = 25$ Hz

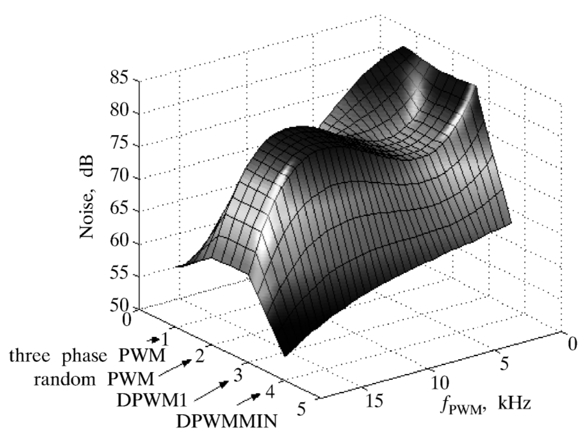


Fig. 15 Noise effective values comparison function of PWM method and switching frequency; LS1.5-1, $f_m = 25$ Hz

Figure 15 shows the general tendencies of the noise. The fact that effective values for random modulation PWM are higher than for example the three-phase PWM is natural: the »quantity« of noise produced by the random PWM is higher, but it is more pleasant because of the large horizon of frequencies that appear in noise spectrum.

The conclusion is also simple when comparing the noise resulted from *different switching frequencies* (Figure 14): the noise generally decreases from 2 to 16 kHz. The effective value difference is from 1 to 13 dB_A between $f_{PWM} = 2$ kHz and $f_{PWM} = 16$ kHz. The maximum corresponds to a comparison at $f_m = 1$ Hz and the minimum at $f_m = 50$ Hz. Even if the differences in effective values are not great, the acoustic sensation is completely different when increasing the switching frequency because the rays from the spectrum move to high frequencies proportionally to f_{PWM} variation. High frequencies are more pleasant to the ear than punctual low frequencies.

The discussion concerning *PWM methods noise variation* is very large and complex. We will limit it to only a few remarks. The entire quantity of air pressure (noise effective value) is not sufficient in order to classify PWM methods. The frequency where high harmonics appear is decisive. It is for this reason that random PWM is a technique that »reduces« the noise: there is no ray with high dB value in the spectrum, even if the total effective value is sometimes higher reported to other PWM techniques.

At $f_m = 50$ Hz the differences between PWM methods are not notable because of the influence of the aero-dynamical noise. Sometimes the spectra are identical. At low speed the efficiency of random PWM when speaking about noise reduction is the

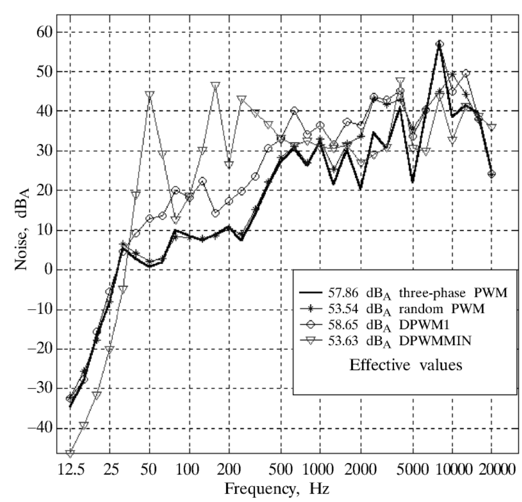


Fig. 16 Spectra comparison function of PWM method, $f_m = 1$ Hz, T0.75, $f_{PWM} = 4$ kHz

best (Figure 16). Even if in most cases the effective value of DPWMMIN is lower than for other PWM methods, the noise does not reduce by the same ratio because rays at low frequencies that are more perceptive to the ear appear in the spectrum. The efficiency of the random PWM is no more evident when $f_{PWM}=2$ kHz or $f_{PWM}=16$ kHz.

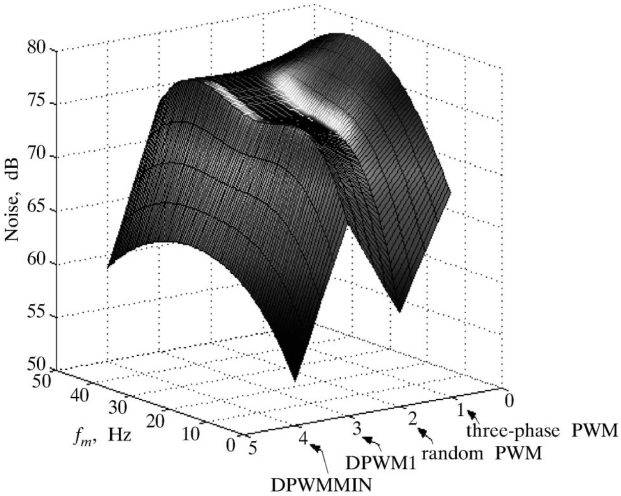


Fig. 17 Noise effective values comparison function of PWM method and rotor speed; LS1.5-1, $f_{PWM}=4$ kHz

Figure 17 presents a comparison of noise effective power reported to PWM method and rotor speed. For different f_{PWM} and different motors the general behavior is the same:

- the efficiency of the random PWM at $f_{PWM}=4$ kHz is clear. Even if for some f_{PWM} the random PWM presents a higher effective value than the other methods, the acoustic sensation is more acceptable than the DPWM1 or the three-phase PWM.
- the fixed frequency three-phase PWM produces the highest-level noise reported to other methods at the same switching frequency (4 kHz) and for medium and high rotor speed.
- on the other hand, even if the effective value of the DPWM1 is lower than that of the three-phase PWM, in reality the noise produced by the DPWM1 is the worst at any switching frequency.

At low f_m the well-known noise produced by a two-phase PWM (as DPWM1 in this case) increases its effective measured value (Figure 17, Figure 18). It is a repetitive noise that seems to have 6 times the frequency of the reference (6^*f_m). The repetitive voltage saturation levels of the PWM method explain this. The proof is that for DPWMMIN which has three voltage saturation levels, the noise's

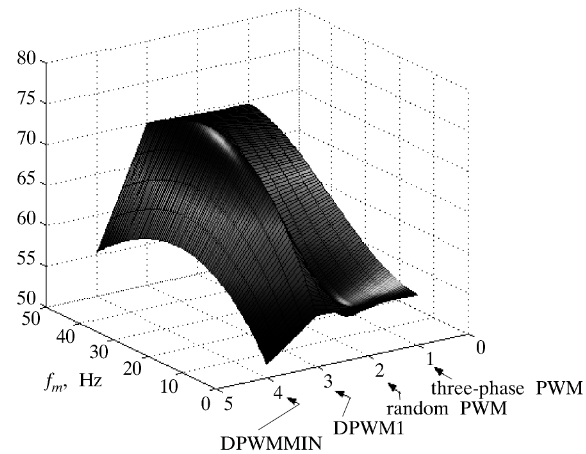


Fig. 18 Noise effective values comparison function of PWM method and rotor speed; T0.75, $f_{PWM}=8$ kHz

spectrum presents a ray at 3^*f_m. The noise we hear is repetitive at a frequency 3^*f_m and it is therefore lower than the noise of the DPWM1 method. The image of this fact when speaking about V_{iN} voltage spectrum consists in more peer harmonics near $f_{PWM}=4$ kHz ray for DPWM1 and less odd harmonics for DPWMMIN (Figure 19), but more peer harmonics near $2^*f_{PWM}=8$ kHz for DPWMMIN and less odd harmonics for DPWM1.

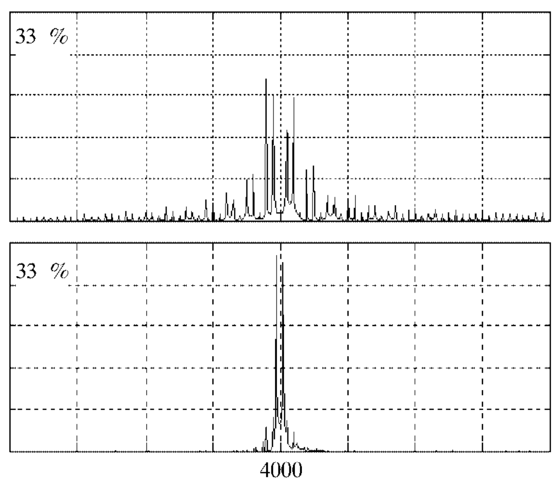


Fig. 19 Harmonic comparison for DPWM1 (up) and DPWMMIN (down) voltage spectrum near $f_{PWM}=4$ kHz ($f_m=25$ Hz)

5 CONCLUSION

The motor line voltage directly influences the acoustic noise produced by the motor. We can remark this by comparing a simple voltage spectrum to the noise spectrum (measured air pressure). Three criteria related to power supply (PWM method, switching frequency and modulation frequency) as well as other two criteria related to the motor (motor type and power) are considered as noise comparison criteria in this paper. The comparison is based on air pressure experimental measures. The interpretation of the results evidences general tendencies of the acoustic noise and the fact that the PWM method is essential when speaking about noise generation. Extreme cases as the DPWMMIN method show that the result on the acoustic noise can be identical when using different motor types or powers, but the same PWM method.

An important remark to be done is that the intensity of the noise (quantified by the effective value in dB_A) is not the most important element to be reduced in order to reduce noise: the random PWM produces more acceptable noise as other methods even if the intensity of it can be greater than for any other PWM method.

MOTORS CHARACTERISTICS

LS1.5-1
Leroy Somer 1.5 kW, type LS90LT, 4 poles, 50 Hz, 1420 tr/min, cos 0.83, 380 V, 3.7 A

LS1.5-2
Leroy Somer 1.5 kW, type LSMV90L, 4 poles, 50 Hz, 1425 tr/min, cos 0.86, 380 V, 3.4 A

U1.5
Unelec 1.5 kW, type F90SC12, 2 poles, 50 Hz, 2820 tr/min, 380 V, 3.4 A

LS0.75
Leroy Somer 0.75 kW, type LS80L2, 4 poles, 50 Hz, 1400 tr/min, cos 0.75, 380 V, 2.1 A

T0.75
Toshiba 0.75 kW, type IK 6204 ZZ, 4 poles, 50 Hz, 1410 tr/min, 400 V, 1.9 A

GLOSSARY

E bus voltage
f_m reference modulated wave frequency
f_{PWM} PWM switching frequency
P motor power, kW
V_{iN} $i = 1, 2, 3$ motor line voltage
V_{ij} $i, j = 1, 2, 3$ motor line-to-line voltage
V_{NO} zero-voltage
DDT direct digital technique (for PWM implantation) [5]
DPWM discontinuous PWM [5, 9]
DPWM0, 1, 2, MLVPWM, DPWMMIN, DPWMMAX different discontinuous PWM techniques
GDPWM generalised discontinuous PWM [5]
PWM Pulse Width Modulation
RPWM random frequency PWM [6]
SPWM sinusoidal PWM [5]
SVM space vector modulation [5]
THIPWM4 or 6 PWM with 3rd harmonic injection [5]
Three-phase PWM PWM with V_{medium} injection with modulation wave/triangular carrier implantation [5]

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O emisiji buke iz izmjeničnih pogona upravljanih pulsno-širinskom modulacijom. U radu se izlaže eksperimentalna analiza buke emitirane iz izmjeničnih pogona upravljanih različitim postupcima pulsno-širinske modulacije (PWM). Nakon izlaganja utjecaja izbora PWM postupka na stupanj redukcije buke, uspoređeni su i interpretirani mjerni rezultati. Uzeto je u obzir pet kriterija: tip motora, snaga motora, brzina vrtnje, sklopna frekvencija i tip PWM postupka.

Ključne riječi: akustička i elektromagnetska buka, strategije modulacije, izmjenični strojevi, pogoni s promjenljivom brzinom vrtnje

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