Tifany SZKUDLAPSKI[1], Jean-Philippe[1] LECOINTE, Fabrice. MORGANTI[1], Jean-François BRUDNY[1]

UArtois, LSEE, F-62400 Béthune, France Univ. Lille Nord de France, F-59000 Lille, France (1)

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AC rotating machine radial vibrations: a principle to reduce the PWM switching effects

***Abstract**. This paper concerns the magnetic noise of AC machine variable PWM speed drives and more particularly, the control of certain chosen radial vibrations generated by the switching and responsible of very high magnetic noise components. The adopted strategy, when it is not possible to change the switching frequency, consists in making homopolar some chosen switching harmonic three-phase systems at the origin of this undesirable phenomenon.*

***Streszczenie** W artykule omówiony został problem szumu magnetycznego od maszyny elektrycznej prądu zmiennego z regulacją prędkości typu PWM, a bardziej szczegółowo zajęto się kontrolą pewnych wybranych drgań promieniowych generowanych przez włączenia i odpowiedzialnych za bardzo wysoki poziom szumu magnetycznego. Zaadaptowana strategia, w przypadku niemożności zmiany częstotliwości włączeń, polega na wykonaniu homopolarnych systemów trójfazowych. **Szumy w maszynie prądu zmiennego z regulacja PWM**.*

Keywords: PWM supply, switching harmonic control, AC variable-speed drives, noise of magnetic origin
Słowa kluczowe: zasilanie PWM, kontrola harmonicznych włączeń, napędy o zmiennej prędkości, szum pochodzenia magnetyczego

Introduction

The radial vibrations and, consequently, the magnetic noise produced by three phase AC electrical rotating machines, result from the space harmonics (due to the wires located in a finite number of slots) [1], the variable reluctance effects due to the slots, the eccentricity and the saturation [2]. Many studies have been done in order to reduce these kinds of components of magnetic origin for the machines connected to the grid. With the development of AC electrical drives and the use of PWM inverters controlled with a classical single symmetrical triangular carrier, an important magnetic noise is sometimes generated by the switching [3]. Methods have been developed in order to reduce these noise components by adjusting the switching frequency [4], the carrier waveform [5] or the machine design [6, 7].

The aim of this paper is to show that, for a given switching frequency, some radial vibration components can become null or may be significantly reduced by choosing appropriate 3 symmetrical triangular carriers. After an accurate identification of the voltage supply harmonics in order to define easily on which parameter to act, the authors analyze the consequences of the control on the radial vibration spectrum.

Analytical model of the PWM

The PWM analytical model [8] consists in substituting a sinusoidal carrier to the traditional triangular carrier, these two signals presenting the same peak values (Fig. 1.). Let us denote V_{rq} Vand v_{cq} the phase *q* (*q*=1, 2 or 3) reference and carrier signals whose angular frequencies are respectively *ω* (frequency *f*) and *mω* (frequency f_{pwm}=*mf*). *m* is defined as the modulation index and the *r* adjusting coefficient is equal to the unit. Thus, v_{rq} and v_{cq} can be respectively expressed by relations (1), where *θ=ωt* and *Φq=(q-1)2π/3*. ξ_q is phase difference which depends on the chsen temporal origin. For a classical PWM, ξ_q is the same whatever *q*.

$$(1)\quad v_{rq} = \hat{v}\sin(\theta-\varphi_q)\ \textit{and}\ v_{cq} = \hat{v}\sin[m(\theta-\xi_q)]$$

The Figure 2 shows the inverter connected to a load star connected and the method, presented in [8], shows that w_q can be expressed by expression (2), where n_1 and n_2 are positive or null integers, $N^+=n_1+n_2$ and , $N^-=n_1-n_2$.

$$(2)\quad \mathrm{w_q} = \sum_{n_1=0}^{\infty}\sum_{n_2=0}^{\infty}\left(w_q^{(k_1)} - w_q^{(k_2)}\right)$$

where

$$(3)\quad \begin{cases} w_q^{(k_1)} = \hat{w}^{(k)}\sin\left(k_1\theta - N^-\varphi_q - mN^+\xi_q\right) \\ w_q^{(k_2)} = \hat{w}^{(k)}\sin\left(k_2\theta - N^+\varphi_q - mN^-\xi_q\right) \end{cases}$$

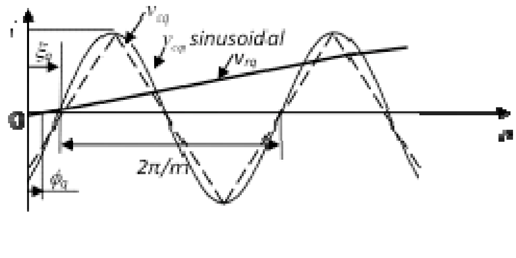

Fig.1. PWM with triangular and sinusoÏdal carrier

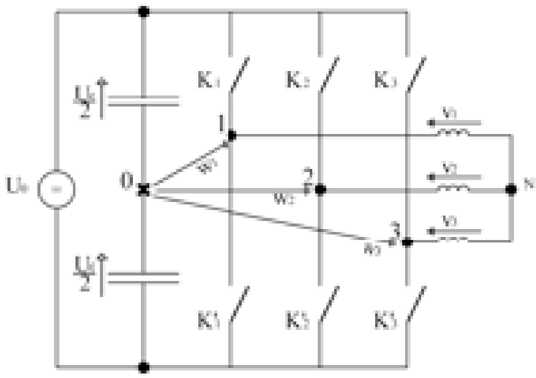

Fig. 2. Three-phase PWM inverter Acoustic noise and radial vibration reduction

(4)

$$\hat{w}^{(k)} = -\frac{(-1)^{n_1}4\mathrm{U_0}/\pi^2}{(2n_1+1)(2n_2+1)}$$

$$\text{and}\quad \begin{cases} k_1 = mN^+ + N^- = n_1(m+1) + n_2(m-1) + m \\ k_2 = mN^- + N^+ = n_1(m+1) - n_2(m-1) + 1 \end{cases}$$

An harmonic of rank *k* results from the combination of several terms characterized by n_1 and n_2, which define k_1

and k_2. Let us consider a single carrier signal. According to the second equation of (1), it comes $\xi_q = \xi 0$ regardless of q:. In this case, the $w^{(k)}_q$ harmonic three-phase systems due to the PWM are in clockwise (C), in anticlockwise (A) or homopolar (H). As $v_q=(2w_q-w_{q+1}-w_{q+2})/3$, it is possible to apply the superposition principle and to define a similar relation for the harmonics $v^{(k)}_q=(2w^{(k)}_q-w^{(k)}_{q+1}-w^{(k)}_{q+2})/3$, from which it can be deduced that :

(5)
$$\begin{cases} v_q^{(k)} = w_q^{(k)} \text{ for the clockwise or anticlockwise systems} \\ v_q^{(k)} = 0 \text{ for the homopolar systems} \end{cases}$$

The Numerical simulations of the PWM with a triangular carrier (PWMST), obtained with Matlab^{TM}, are compared to the values given by the PWM with a sinusoidal carrier (PWM^{SS}). Slight differences appear between in the spectra of the PWMST and PWM^{SS} amplitudes. However, the Figure 3.b) shows that the phase differences between v_1 and v_2 are 2π/3 and 4π/3, which correspond to (C) and (A) systems. The same values are found, whatever the carrier. Thus, the great advantage of the analytical PWM^{SS} model is the determination of the phase difference. Moreover, as no phase differences are equal to 0, no (H) system exists, according to (5).

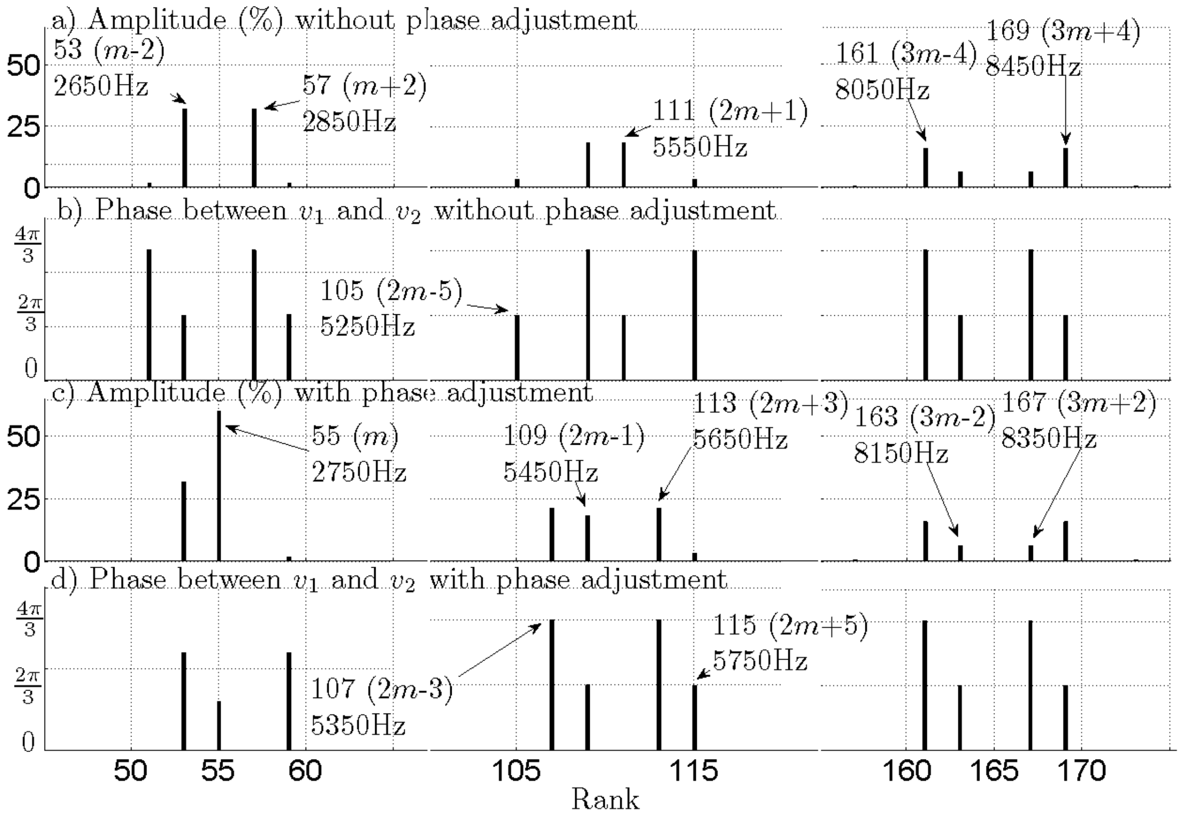

Fig. 3. Experimental v_1 spectrum (in % of the fundamental) and phase difference with triangular carriers and $m=55$ (The frequencies correspond to an operating point with $f=50Hz$)

Voltage harmonic component modification

The principle applied for modifying the voltage harmonic component consists in using 3 distinct carrier signals, which phases are adjusted so that a chosen current system becomes homopolar because it can not flow in the load star connected. Let us consider the 2850 Hz (rank $m+2$) component, which is expressed by (6), when $N^{-*}=1$

(6)
$$w_q^{\left(k_2^*\right)} = \hat{w}^{(k)} \sin\left[k_2^*\theta + (q-1)2\pi/3 - mN^{-*}\xi_q\right]$$

$w_q^{\left(k_2^*\right)}$ can be cancelled if the system becomes homopolar. Therefore, the condition verified by ξ_q is given by (7), where B is a constant.

(7) $$(q-1)2\pi\big/3 - mN^{-*}\xi_q = B \ \ \forall q$$

The method has been experimentally applied with $\xi_q=2\pi(q-1)/3m$ obtained for $B=0$. An inverter is connected to an induction machine and the switching is controlled with a Focusrite sound card. It makes it possible generating the 3 reference signals and the 3 sinusoidal or triangular carrier signals. The Figure 3 shows the v_1 amplitude in percentage of the fundamental and the phase between v_1 and v_2 without (Fig. 3a and b) and with the harmonic suppression (Fig. 3c and d), with triangular carriers (PWM^{ST3}). The cancellation of the rank m+2 component has no impact on the amplitude and the phase of the fundamental but:
- the harmonic components around $3m$ keep the same characteristics,
- the harmonics 57 (2850Hz) and 111 (5550Hz) disappear because they become homopolar,
- the wise of the harmonics 53 (2650Hz) and 109 (5450Hz) has changed,
- components of ranks 55 (2750Hz), 107 (5350Hz) and 113 (5650Hz) appear.

Radial acceleration reduction

As the phase adjustment of the 3 carriers modifies the voltage spectral content, the method can be used to reduce the acceleration spectrum of an induction machine.

The radial accelerations of the external housing of the stator result from the F Maxwell's forces [6]. They are analytically determined from the airgap flux density harmonics. Considering the fundamental component of the magnetomotive force and a constant airgap permeance leads to the relation (8) where *k* and *k'* are the ranks of the switching harmonics generating a force component.

$$\text{(8)}\quad \mathrm{F} = \sum_{k,k'} \mathrm{F}^{(k,k')} = \sum_{\mathrm{k,k'}} \hat{\mathrm{F}}^{(k,k')} \cos\left\{\Pi^{(k,k')}\omega \mathrm{t} - M\alpha^{s}\right\}$$

where $\pi^{(k,k')}=(k\pm k')\omega$ is the angular frequency of a force component and $M=p\pm p$, called the mode number, is its number of attraction points. A force component must be considered if its amplitude is not negligible, if its mode number is small [9], ie, M≤8 and if its frequency is close to a natural resonant frequency of the stator frame [9]. A test carried out with the machine connected to the grid shows a silent machine. Also, only the harmonics due to the switching will be considered.

The Fig. 4a and 4b present the results obtained with a PWM^{ST} and a PWM^{ST3} (f=50Hz and m=55). With the PWM^{ST}, significant acceleration harmonics appear at 5400Hz, 5500Hz and 5600Hz (Fig. 3a). They result from the combination of flux density harmonics of ranks close to 110 with the fundamental component. The Table 1, which presents the *k* and *k'* values at the origin of the main acceleration components confirms that the toothing and the space harmonic have a low influence.

A group of acceleration components is situated between 5kHz and 6kHz. The spectrum of the voltage v_1 presented in Fig. 3a shows that voltage harmonic components of rank 109 (5450Hz) and 111 (5550Hz) have the highest amplitudes. Two lateral components are also visible at 5250Hz (rank 105) and 5750 Hz (rank 115). The Table 1 shows that the combinations of these voltage components with the fundamental are at the origin of the 5300, 5400, 5500, 5600 and 5700Hz components (Fig. 4a), which mode numbers are 0 or 4. It can be noted that:

- The 5500Hz component results from the combination of 2 pairs of flux density components (rank 1 combined with rank 109 and rank 1 with rank 111). The two acceleration components at 5500Hz have different mode numbers (0 and 4).
- The 5300Hz and 5400Hz are components of mode 0 and 4, respectively. The amplitude of the 5300 Hz acceleration component is similar to the 5400Hz component although the 5250Hz voltage harmonic, which generates the first force component, has an amplitude 5,5 times lower than the amplitude of the 5350Hz harmonic, which generates the 5400Hz acceleration. The explanation is given by the analytical model provided by Alger [1]. Indeed, he specifies that, for an inducton machine, the ratio between the Y_{s0} and Y_{sM} static deformations due to forces of mode number 0 and M is given by $Y_{sM}/Y_{s0}\approx 147[p/(M^2-1)]^2$. In these conditions and for the considered machine, $Y_{s4}/Y_{s0}\approx 2.61$. That explains why the 5300Hz – mode 4 component and the 5400Hz – mode 0 component have similar amplitudes. The theoretical ratio is not exactly verified because the accelerometer measures the dynamic accelerations [10].

The Fig. 4b shows the acceleration spectrum for the PWM^{ST3} when the phase of the carriers is adjusted to eliminate 2850Hz voltage component. Several changes appear on the spectrum :

1) The 2700Hz (rank 54) acceleration component is reduced. Indeed, in addition to the force of mode 4 due to the combination of harmonics 1 and 53, a force component resulting from the harmonics 1 and 55 appears at the same frequency but with a mode 0. The combination of these two forces leads to a reduction. The reason of these can be explained by the combination of acceleration components of same frequency but with different mode numbers. Let us consider two components of mode 0 and 4 expressed by $F_0=A_0\cos(\omega t)$ and $F_4=A_4\cos(\omega t-4\alpha_4-\varphi_4)$ where φ_4 is the phase of the mode 4 component. With $\alpha^s=0$, the amplitude of the sum of F_0 and F_4 is given by:

$$\text{(9)}\quad \hat{F}_{04} = \sqrt{\left(A_0 + A_4 cos\varphi_4\right)^2 + \left(A_4 sin\varphi_4\right)^2}$$

It shows that $\hat{F}_{04}$ varies according to φ_4 : some values of φ_4 leads to $\hat{F}_{04}$ lower than A_4. Thus, two forces can lead to a lower resulting acceleration.

2) The 2800Hz (rank 56) acceleration component is increased of 97.9%. This component, generated by the combination of the 2850Hz harmonic with the fundamental component, was too low before the adjustment because its mode was 0. After the phase adjustment, this acceleration component is generated by the 2750Hz voltage harmonic, which amplitude is almost 1.9 times higher. Moreover, the force has a mode 4, which generates higher static deformations.

3) The 5300Hz acceleration component is greatly increased. The force of mode 4, which generates it with the PWM^{ST}, disappears because the 5250Hz voltage harmonic is eliminated. With the PWM^{ST3}, the force is a mode 0 but the 5350Hz harmonic, which generates it, has an amplitude 6,5 times higher than the 5250Hz component.

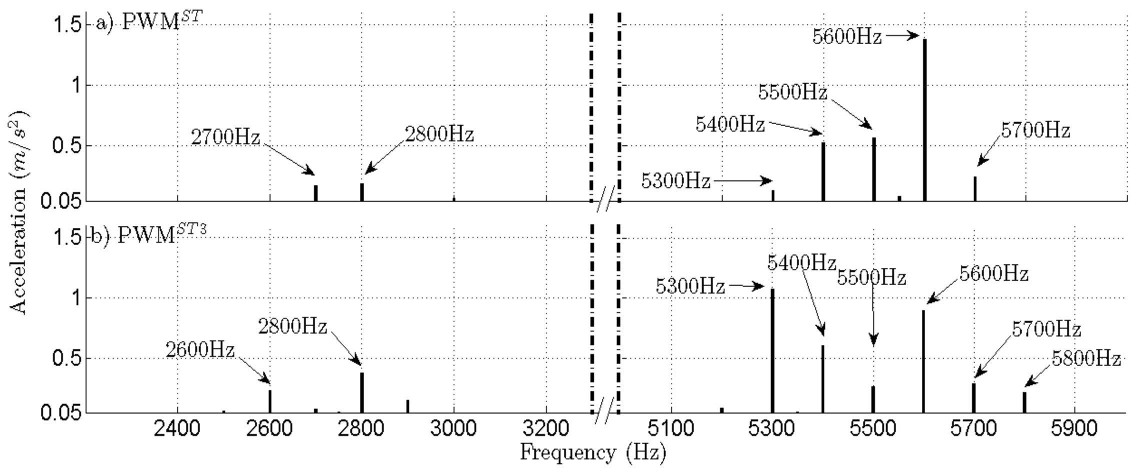

Fig 4 . Acceleration spectrum

Table 1. Force components without and with phase adjustment

Without phase adjustment					With phase adjustment				
k	k' (Frequency)	M	$\Pi^{(k,k')}$	Frequency	k	k' (Frequency	M	$\Pi^{(k,k')}$	Frequency (Hz)
1	51 (2550)	4	52	2600					
1	53 (2650)	0	-52	2600	1	53 (2650)	0	-52	2600
1	53 (2650)	4	54	2700	1	53 (2650)	4	54	2700
					1	55 (2750)	0	-54	2700
					1	55 (2750)	4	56	2800
1	57 (2850)	0	-56	2800					
1	105 (5250)	4	106	5300					
					1	107 (5350)	0	-106	5300
					1	107 (5350)	4	108	5400
1	109 (5450)	0	-108	5400	1	109 (5450)	0	-108	5400
1	109 (5450)	4	110	5500	1	109 (5450)	4	110	5500
1	111 (5550)	0	-110	5500					
1	111 (5550)	4	112	5600					
					1	113 (5650)	0	-112	5600
					1	113 (5650)	4	114	5700
1	115 (5750)	0	-114	5700	1	115 (5750)	0	-114	5700

4) The 5400Hz and 5500Hz acceleration components increase of 15% and decrease of 53% respectively. The 5400Hz acceleration component is due to the combination of two forces resulting from the combination of the 5350Hz and 5450Hz voltage harmonics with the fundamental. For the 5500Hz, that is the contrary; before the adjustment, the acceleration is due to two force components and with the PWM^{ST3}, the mode 0 disappears.

5) The 5600Hz component is reduced (34,8%) because it is generated by harmonics 113 and the fundamental and the its mode number becomes null instead of 4 initially. The rank 113 voltage harmonic also generates an additional force at 5700Hz, explaining the increasing of the acceleration at this frequency.

Conclusion

In this paper, the authors use a PWM analytical model to show that adjusting the phase angles of three distinct carrier signals can modify significantly the acceleration behaviour of an induction machine. The authors show experimentally the impact on the accelerations of an induction motor. The reduction can be more drastic if the force components are close to a natural resonance frequency.

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***Authors**: Prof. Jean-Philippe Lecointe, LSEE, Faculté des Sciences Appliquées Technoparc Futura 62400 Béthune France, , E-mail: jphilippe.lecointe@univ-artois.fr ;*

Dr. Fabrice Morganti, LSEE, Faculté des Sciences Appliquées Technoparc Futura 62400 Béthune France, , E-mail: fabrice.morganti@univ-artois.fr;

Prof. Jean-François Brudny, LSEE, Faculté des Sciences Appliquées Technoparc Futura 62400 Béthune France,
E-mail: jfrancois.brudny@univ-artois.fr ;

Tifany Szkudlapski, tifany.szkudlapski@univ-artois.fr