A method for choosing the power converter control strategy to reduce the acoustic noise by taking into account the mechanical structure response

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Abstract:

Acoustic noise generated by the association of an electric machine and its converter becomes of prime importance for choosing an electrical drive. Most studies deal with the electromechanical aspects (radial stress on the stator) and mechanical aspects (vibrations and acoustic) in a disassociated way. The presented study proposes to treat the whole problem with one same tool, based on the rotating field theory and a two-dimensions associated spectrum analysis. The aim is to find a control strategy and its parameters (e.g. chopping frequency) associated with electromechanical (slot number and aperture, winding type) and mechanical machine characteristics. The paper is illustrated by an example using a 1.25 kW induction machine associated with a natural sampling power converter.

Introduction

Acoustic noise generated by the association of an electric machine and its converter become of prime importance for choosing an electric drive.

Various strategies for reducing 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 [2], [12] reduce acoustic noises annoyances but may coincide with mechanicalresonances)

On the other hand, most of the studies deal with the electromechanical aspects (radial stress on the stator) and mechanical aspects (vibrations and acoustic) in a disassociated way.

The presented study, proposes to treat the whole problem with the same tool, based on the rotating field theory and a two dimensions associated spectrum analysis. The aim is to find a control strategy and its parameters (e.g. chopping frequency) associated with electromechanical and mechanical machine characteristics. The paper is illustrated by an example using a 1.25 kW induction machine associated with a natural sampling power converter.

1 Principle of rotating field theory

The acoustic noise of electromagnetic origin is principally due to the radial forces applied to the stator. When the saturation is not too strong and the material is a soft ferromagnetic material, the force density can be computed with a good approximation by the MAXWELL Stress Tensor method [4] [3].

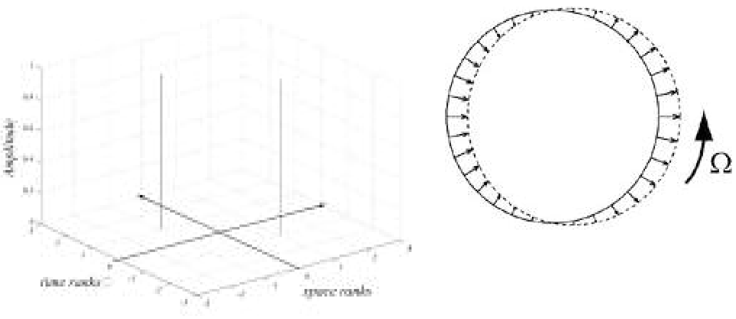
A good way of coupling mechanical response of thestatoric structure with the electromagnetic excitation is the use of spectral - modal - method. In this way, it is convenient to compute force density as the superposition of rotating fields harmonics. This method is known as the *rotating fields theory*. Each field can be decomposed in a superposition of elementary fields with $2m_+$ poles that are revolving in theairgap with the velocity $\frac{n_+ \omega}{m_+}$ (where m_+ and n_+ are positive integers):

$$F(t,\theta) = \sum_{n+} \sum_{m+} F_{n+,m+} \cos(n_+ \omega t \pm m_+ \theta + \varphi_{n+m+}) \qquad (1)$$

We can also decompose these fields in using exponential notation where n and m can now be negative or positive and $\hat{F}_{n,m}$ becomes complex to take into account the phase shift:

$$F(t,\theta) = \sum_{n} \sum_{m} \hat{F}_{n,m}\, e^{j(n\omega t + m\theta)} \qquad (2)$$

This double sum can be represented by a two dimensional spectrum, one dimension to take into account the *time frequencies* and one other to take into account the *space frequencies*. Some examples are given in Figure 1 for a simple direct field with two poles, and in Figure 2 for a sum of two direct fields where $\hat{F}^*$ means the complex conjugate of $\hat{F}$

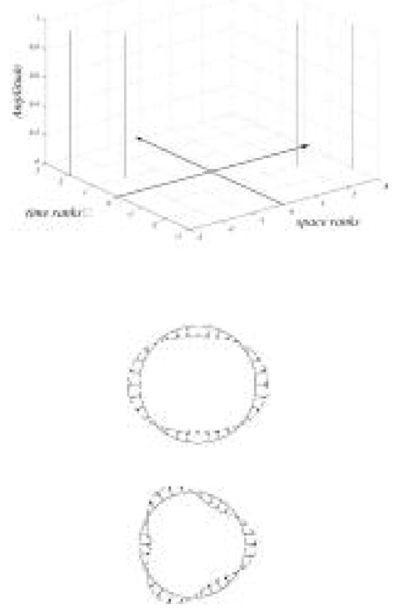


$$F(t, \theta) = F \cos(\omega_0 t - \theta + \phi)$$

$$= \hat{F} \cdot e^{j\omega_0 t} e^{-j\theta} + \hat{F}^* \cdot e^{-j\omega_0 t} e^{j\theta}$$

$$\Omega = -\frac{n.\omega_0}{m} = +\omega_0$$

Figure 1: amplitude of a direct monochromatic rotating field



$$F_1(t,\theta) = F_1 \cos(\omega_O t - 2\theta + \varphi 1)$$

$$= \hat{F}_1 \cdot e^{j\omega_0 t} e^{-j2\theta} + \hat{F}_1^* \cdot e^{-j\omega_0 t} e^{j2\theta}$$

$$\Omega_1 = -\frac{n_1.\omega_0}{m_1} = +\frac{\omega_0}{2}$$

$$F_2(t,\theta) = F_2 \cos(2\omega_O t - 3\theta + \varphi_2)$$

$$= \hat{F}_2 \cdot e^{j2\omega_0 t} e^{-j3\theta} + \hat{F}_2^* \cdot e^{-j2\omega_0 t} e^{j3\theta}$$

$$\Omega_2 = -\frac{n_2.\omega_0}{m_2} = +\frac{2\omega_0}{3}$$

Figure 2: superposition of two direct revolving fields

2 Application to induction machine

Revolving field theory is not a recent tool for the electric machine modelisation. For example, it was already used in [1], the *classical book* on induction machine design. We can also notice that a book is entirely dedicated to this approach [8].

With the apparition of numerical analysis, this tool had lost a great part of its power, nevertheless, with the generalisation of power converters, this tool becomes again well adapted to take into account the numerous harmonics that are due to non-sinusoidal currents [5] [7].

With the Pulse Width Modulation power converter, the classical use of revolving fields theory as described in the previous references are not well adapted and the authors have developped an extension of this method based on the discrete FOURIER transform in time and space and matrix computation.

For any P.W.M. converter strategy (with stationary hypothesis), the voltage spectrum can be computed as long as the time voltage waveform is known. For example, for a natural sampling PWM strategy, Figure 3 (a) reports the voltage between a phase and the reference potential of the power converter (a_{top}); voltage between a phase and the neutral reference of the machine (star coupling) (a_{middle}); voltage between two phases (a_{bottom}) of the machine. After a discretisation, we can use a numerical method - Fast Fourier Transform - to obtain the *time spectrum* of the voltage (Figure 3 (b)). With the use of an equivalent diagram as described in [9], we can obtain the relation between voltages and currents and therefore obtain the current spectrum.

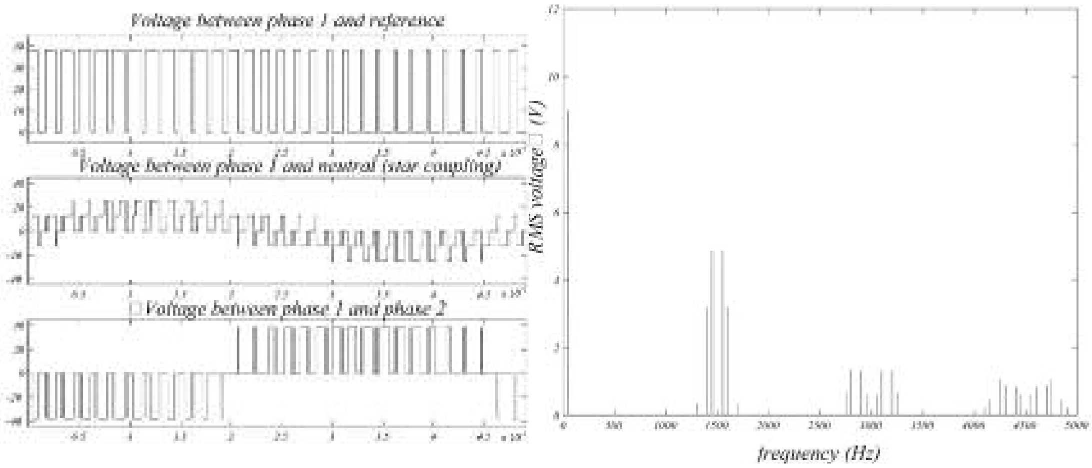


Figure 3: (a) voltage between a phase and the reference potential of the converter (a_{top}); voltage between a phase and the Y point (a_{middle}); voltage between two phases (a_{bottom}); (b) Spectrum of (a_{middle})

We can also describe the *spatial spectrum* of the machine. The *winding function* represents the spatial distribution of the winding around the airgap. With the same computation as previously - FFT -, we can obtain the space spectrum of the winding. Figure 4 reports the winding function and its space spectrum for a classical three phases induction machine: 4 poles, 24 slots in the stator, double layer and shortened pitch.

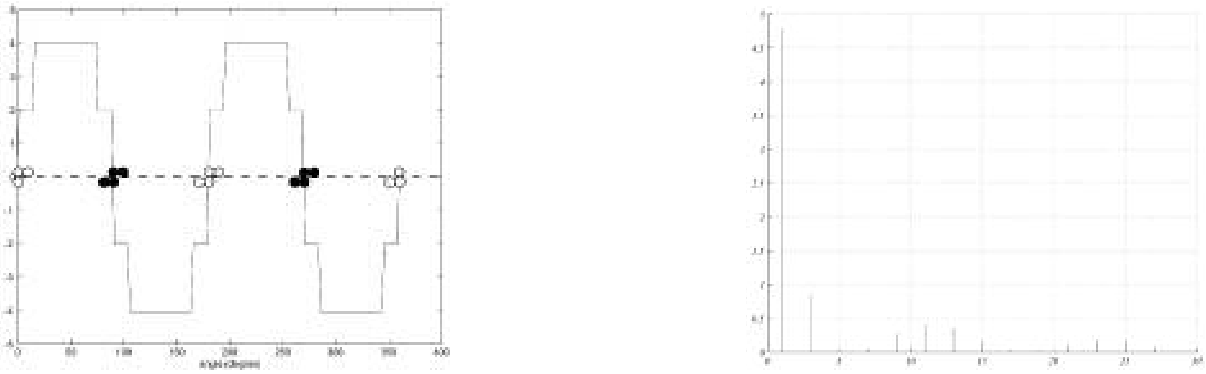


Figure 4: (a) winding function and (b) its spectrum for a 24 slots stator

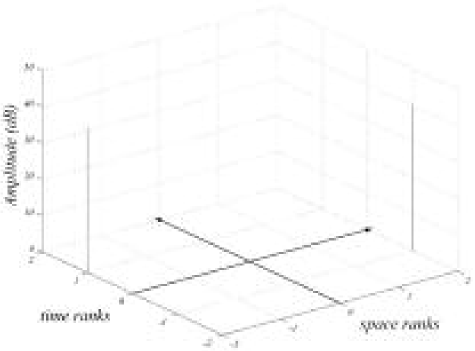
The current spectrum and winding function spectrum will be used in vector forms for each phase of the machine. If [î] (respectively $[\hat{w}]$) is the matrix composed by all the currents (respectively winding functions) spectrum vector for each phase of the machine ($\left[\hat{i}\right]=\left[\left\{\hat{i}_1\right\}+\left\{\hat{i}_2\right\}....\left\{\hat{i}_k\right\}...\left\{\hat{i}_z\right\}\right];\left[\hat{w}\right]=\left[\left\{\hat{w}_1\right\}+\left\{\hat{w}_2\right\}....\left\{\hat{w}_k\right\}...\left\{\hat{w}_z\right\}\right]$), we can explain the magnetomotive forces as:

$$\left[\hat{Fmm}\right]=\frac{1}{2}.\left[\hat{w}\right].\left[\hat{i}\right]^T \tag{3}$$

This magnetomotive force matrix can be viewed as a table containing the complex amplitude of the revolving field with time rank n and space rank m (with 2m pole and velocity n(ω)/m] as explained in the equation (2)).

$$\begin{array}{cc} & n.\,\omega \\ \left[\hat{Fmm}\right] = m\ldots & \begin{bmatrix} & \vdots & \\ \ldots\ldots & \hat{Fmm}(n\omega, m) & \\ & & \end{bmatrix} \end{array}$$

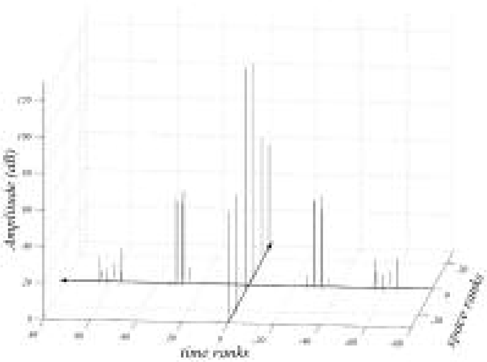
For a perfect current and perfect winding (purely sinusoidal), it leads to matrix and 2D spectrum of the Figure 5.



$$\begin{array}{ccc} & -\omega & +\omega \\ \left[\hat{Fmm}\right] = \begin{array}{c} -p_0 \\ +p_0 \end{array} & \left[\begin{array}{c} 0 \\ \hat{fmm} \end{array}\right. & \left.\begin{array}{c} \hat{fmm}\ * \\ 0 \end{array}\right] \end{array}$$

Figure 5: 2D spectrum and matrix of the fmm for a perfect 4 pole machine ($p_0 = 2$) supplied by a perfect current at frequency $\omega = 1\ \omega_0$

For the true machine (24 slots) supplied by a PWM power converter, it leads to a more complex spectrum reported in Figure 6.



1. there are some space harmonics around the fundamental frequencies of rank = +/- 1 due to the slots

2. there are time harmonics around the chopping frequencies and its multiples (rank = +/- k . 30)

Figure 6: 2D spectrum of the fmm for a non perfect 4 pole machine supplied by a power converter.

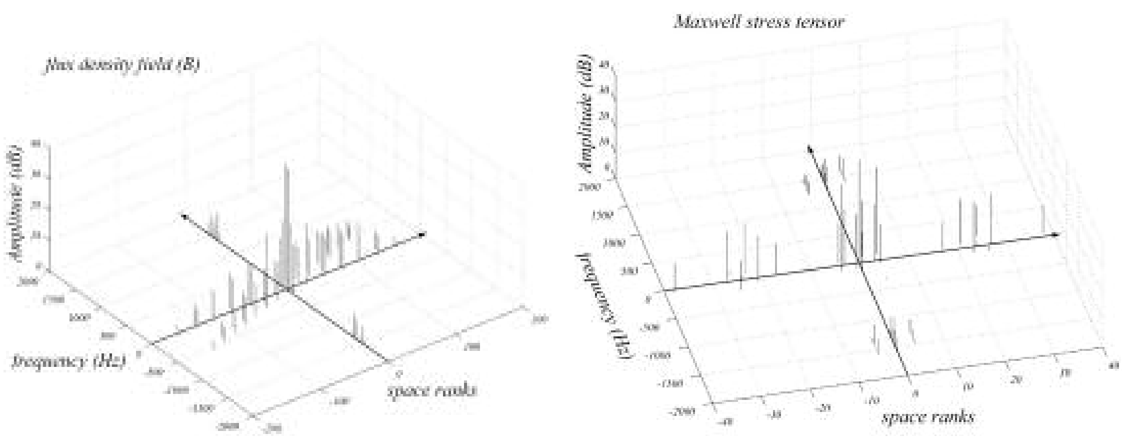
With the use of the *permeance function* λ [10] [8], we can also compute the 2D spectrum of the induction density field of the stator and the rotor. Finally, the total induction density field permits us to compute the MAXWELL stress tensor.

$$\left[\hat{B}\right] = \mu_0 . \left\{\hat{\lambda}\right\} . \left\{\hat{F}_{mm}\right\}^T \qquad (6)$$

$$\left[\hat{f}_{radial} \right] = \frac{1}{2\mu_0} . \left\{ \hat{B}_{total} \right\} . \left\{ \hat{B}_{total} \right\}^T \qquad (7)$$

On Figure 7, we can see that 2D spectrum of the induction density field is richer than the magnetomotive force because it takes into account the slot aperture in stator and rotor. The presence of the teeth plays the role of a modulation by the number of the teeth.

We can conclude that, with the use of the winding and current spectrum, we can obtain the 2D spectrum of the MAXWELL stress tensor. This 2D spectrum displays where the principal radial excitations on the stator are. It will help us to know the vibration response of the structure.



(a) (b)

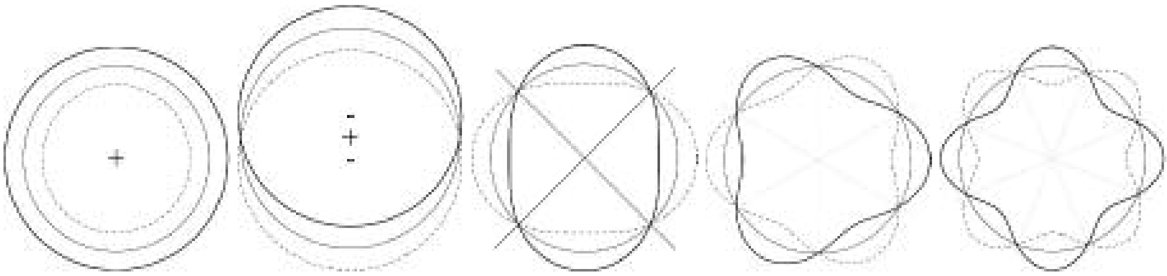
Figure 7: (a) 2D spectrum amplitude of the induction density field and (b) the Maxwell stress tensor

3 Modal analysis for electric machines

To reduce the noise of mechanical systems, it is essential to avoid coincidence between excitation and natural behaviour of the structure **(frequencies and shapes).** In this way, it is necessary to determine these natural frequencies. For the acoustic noise of electromagnetic origin in electric machines, it is well known that the most radiating surfaces are the stator structures. Therefore, it is important to avoid resonance of the stator. Lots of papers exist on the analytical or numerical determination of the natural behaviour of stator [6] [13] [14] [15] and we always notice that for induction motors, in the plane of a sheet, the modes shapes at lower frequencies are not very different from a sinusoidal shapes. For the n mode, we have the U_n mode shape as:

$$U_n(\theta) = A_n.\sin(n\theta) \qquad [8]$$

For n = 0, we usually speak about a purely extensional mode because the deformation is principally due to extension rather than flexion. For n = 1, *in the plane of a sheet*, we can notice a rigid body motion - without deformation - and finally for $n \geq 2$, we speak about flexural modes (Figure 8).



n = 0 n = 1 n = 2 n = 3 n = 4

Figure 8: mode shapes for the lower frequencies in the plane of the sheet

We can describe each natural mode with the node number of his mode shape - its spatial rank - and its frequency - its time rank. With the same description as previously, we can affect a time and space rank for each mode, and report the natural behaviour in a 2D spectrum (in time and space).

Moreover, various studies have shown that only low order modes contribute to generate acoustic noise [1], [9], [16], [17]. Generally, orders greater than 3 can be neglected.

In our study, we experiment a 1.25 kW induction machine. The natural behaviour was computed and measured. This was reported in Figure 9 (b).

4 Proposed method to reduce the acoustic noise

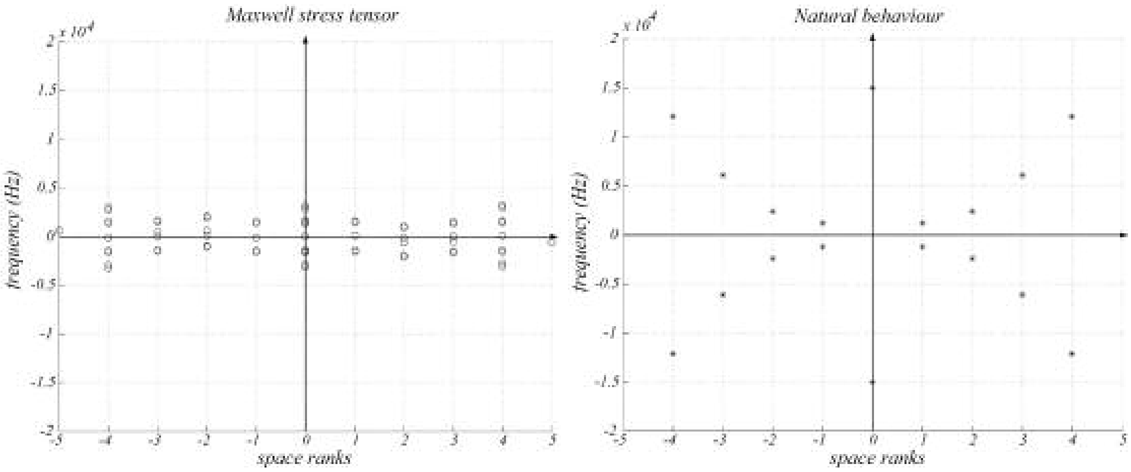
To reduce the noise, it is essential to avoid coincidence between natural behaviour and excitations. For a space rank, with the use of modal analysis, only excitations with the same space rank can be projected on this mode shape (modal superposition) [9]. After the projection on modal basis, it will lead to a second order Ordinary Differential Equation with modal excitation instead of Partial Differential Equation. The deformation u can be explained in the basis formed by the mode shapes $U_i(\theta)$, the *time dependancies* $\phi_i(t)$ is therefore the amplitude of each coordinate (mode shape) (for further explainations on modal analysis, see [11]):

$$u(\theta,t) = \sum_i \phi_i.U_i(\theta) \qquad (9)$$

For the space rank n, with Q_n the modal force - the force projected on this mode shape - and ω_n the natural frequency of this mode, we obtain:

$$\ddot{\phi}_n + \omega_n^{\;2}.\phi_n = Q_n \qquad (10)$$

The only way of reducing the vibrations and therefore the noise is to *place* modal excitation frequency far from natural frequency. Graphically, it can be done by the superposition of the 2D spectrum of the excitation with the 2D spectrum of the natural behaviour (Figure 9).



(a) (b)

Figure 9: top view of the 2D spectrum of the excitation (a) and the natural behaviour of the statoric structure (b)

If we notice a coincidence between an excitation and a natural mode, we have to change the location of this excitation to reduce amplification. It can be done by changing the strategy of the power converter. In our example, it can simply done by changing the chopping frequency of the natural sampling PWM converter.

As an interpretation of the figure 9, (obtained by computing and verified by measures), we can see that the first order natural mode appears for a frequency of 1200Hz and near from an excitation frequency (9a). Nevertheless, this difference of frequency is sufficient to avoid excessive magnetic noise for this mode of vibration.

On the space rank 2, Maxwell stress tensor (figure 9 (a)) and natural response coincides and will generate acoustic noise. For all higher modes, comparing figure 9 (a) and 9 (b) shows that natural modes frequencies and stress tensor excitation become far from each other, so, they will not contribute to generate acoustic noise. As a conclusion, on our experimental test bench, the acoustic noise will be mostly generated by a "mode 2" of vibration at about 2400 Hz.

5.Experimental results on acoustic noise

The acoustic measures have been made in asemi-anechoic room and more comprehensive description of the experimental conditions and results will be described in a next paper or can be found in [9].

In our example, for the n = 2 mode (at frequency equal 2465 Hz), we can decrease the acoustic pressure level by more than 16 dB only by increasing the chopping frequency by 500 Hz. At chopping frequency equal 2500 Hz, we obtain 43 dB of pressure level instead of 59 dB at chopping frequency equal 2000 Hz.

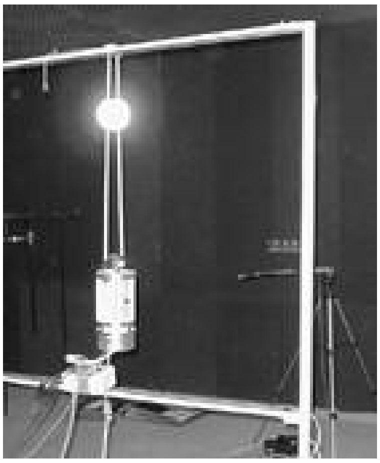


Figure 10: experimental conditions

Conclusion

In this paper, we propose a systematic method to avoid most of acoustic noise generated by the association of an induction machine and its power converter.

This method may be applied to any kind of PWM control strategy , and take into account internal parameters of the electric machine such as stator yoke thickness, contribution to the teeth or even slot apertures.

This method consists in computing radial forces as a superposition of revolving fields. This approach can be represented by a 2D spectrum of excitation. In a second step, we propose the same approach to represent the natural behaviour of the stator. By comparing these two 2D spectrum, we can detect a resonance and so adjust the power converter strategy to avoid resonance. It allows the designer of the machine and converter to adapt his strategy to the machine in view of reducing acoustic noise of electromagnetic origin.

Experimental results (1,25 kW) confirms the validity of the approach. Nevertheless, experimental couplings between the different modes of vibrations, have been detected and remain under investigation.

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