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Wigner Distribution for the Diagnosis of High Frequency Amplitude and Phase Modulations on Stator Currents of Induction Machine

Baptiste Trajin, *IEEE Student Member*, Marie Chabert, Jeremi Regnier, *IEEE Member*, Jean Faucher, *IEEE Member*

Abstract—This paper deals with mechanical fault monitoring in induction machines from stator current measurements. The considered faults lead to amplitude and/or phase modulations of the measured stator current. The different faults can be characterized by their time-frequency signatures via the Wigner distribution. The time-frequency representations apply to complex signals that may be obtained through the Hilbert transform of the real measured signal. In case of high frequency modulations, it can not be taken advantage of the time frequency signatures. This study proposes an alternative complex signal representation for modulated stator currents. The so-called space vector is obtained through the Concordia transform. From three stator current measurements, the Concordia transform builds a complex vector which conveniently carries the information about phase and amplitude modulations. This paper applies and compares the Wigner distribution computed with the Hilbert and Concordia transforms in case of simulated and experimental signals with various modulation frequency ranges.

Index Terms—Diagnosis, High frequency modulations, Induction motor, Wigner Distribution.

I. INTRODUCTION

MONITORING techniques are intensively investigated to increase the reliability and safety of industrial systems containing induction motors. Stator current based monitoring can be preferred to an expensive vibration analysis for mechanical fault detection. Indeed, current signals are often already available for control purpose. Detection of mechanical faults such as shaft eccentricity or load torque oscillations is traditionally based on the stator current spectral analysis [1]. Eccentricity and load torque oscillations have been shown to produce amplitude and phase modulation of the stator current respectively. A time-frequency representation such as Wigner distribution allows to detect and classify the defaults according to their signatures [2]. This method handles a complex signal obtained from the Hilbert transform of the real observed signal under the Bedrosian theorem conditions. However, mechanical faults such as bearing or gear box faults may induce specific harmonics whose frequencies violate these conditions [3]. Consequently, such faults induce high frequency modulations

on stator currents. The diagnosis from the time-frequency signatures can thus be misleading.

The Concordia transform, is often used in electrical engineering for control purposes [4] and to detect electrical or mechanical static converter defects, unbalanced electrical systems, machine stator electric defects, mechanical eccentricity or bearing defects [5], [6]. This paper proposes the Concordia transform as an alternative to the Hilbert transform to build a complex vector, in the case of three-phase electrical drives. Then, a time-frequency analysis through the Wigner distribution can be performed, even when the Bedrosian theorem conditions are not verified. Section II recalls stator current model of the induction machine in case of eccentricity and/or load torque oscillations. The effect of dynamic eccentricity and load torque oscillations on the stator current are presented. Moreover, signal processing methods are introduced. Section III derives the Wigner distribution of modulated stator currents obtained with the Hilbert analytic signal and the Concordia space vector. Differences between Wigner distributions are underlined considering the Bedrosian theorem limitations. Section IV compares the Wigner distribution on simulated stator currents with various modulation frequency ranges in steady state and variable frequency applications. Finally, section V derives the Wigner distribution and the associated modulation signatures from the Hilbert or Concordia complex signals on experimental stator currents.

II. STATOR CURRENT MODEL AND SIGNAL PROCESSING METHODS

In electrical drives, eccentricity and load torque oscillations are the main mechanical faults investigated for diagnosis purposes. It has been demonstrated that eccentricity leads to amplitude modulation (AM) and load torque oscillations lead to phase modulation (PM) on the stator currents [2]. Wigner distribution may be used in variable speed applications to distinguish load torque oscillations and eccentricity [7]. AM and PM (i.e. eccentricity and load torque oscillations) are distinguishable using phase shift of sideband components of Wigner distribution of stator currents. However, few papers deal with high frequency modulations induced by bearing faults for instance [8].

A. Fault currents in three-phase induction machines

In three-phase machines, combination of mechanical faults, eccentricity and load torque oscillations, lead to simultaneous

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amplitude and phase variations on the stator currents. Consequently the three-phase currents can be written in a simple form by (1).

$$i_k(t) = a(t) \cos(\psi(t) - \phi_k), \quad k = 1, 2, 3 \quad (1)$$

with:

$$\begin{cases} a(t) = I[1 + \alpha \cos(2\pi f_{am}t + \phi_{am})] \\ \psi(t) = 2\pi f_s t + \beta \sin(2\pi f_{pm}t + \phi_{pm}) + \phi \\ \phi_k = (k-1)\frac{2\pi}{3}, k = 1, 2, 3 \end{cases}$$

Note that null AM and PM indexes ($\alpha = 0$ and $\beta = 0$) correspond to the stator current model in healthy conditions. In (1), the modulation terms are assumed to be in phase. This assumption can be verified by considering $i_1(t) + i_2(t) + i_3(t) = 0, \forall t$.

B. Analytic signal via the Hilbert transform

The study of amplitude and/or phase modulation through the Wigner distribution requires the construction of a complex signal from the real observed signal for a univocal instantaneous phase and amplitude definition [9]. The classical way to define the instantaneous phase and amplitude is to associate a complex signal to the measured real signal $x(t)$ through the Hilbert transform (HT). The definition of the analytic signal $z(t)$ (2) can be given in the frequency domain [10] along the frequency f .

$$Z(f) = X(f) + j[-j \operatorname{sgn}(f)]X(f) = X(f) + jH(f)X(f) \quad (2)$$

where $Y(f)$ denotes the Fourier Transform of $y(t)$.

$$\text{with } \operatorname{sgn}(f) = \begin{cases} +1 & \text{for } f > 0 \\ 0 & \text{for } f = 0 \\ -1 & \text{for } f < 0 \end{cases}$$

$H(f) = -j \operatorname{sgn}(f)$ is the Hilbert filter transfer function. Assume $z(t) = a(t)e^{j\psi(t)}$ with $a(t)$ non negative and $\psi(t)$ defined modulo 2π , then $a(t)$ and $\psi(t)$ are the instantaneous amplitude and phase respectively. Note that constructing the analytic signal via the Hilbert transform amounts to eliminating negative frequencies in the spectrum. When a modulation transfers significant components into the negative frequencies, the Hilbert transform may yield misleading interpretations [11]. Indeed, the Hilbert transform is submitted to the Bedrosian theorem conditions in case of modulated signals [12]. The main restriction is that the carrier frequency must be higher than the modulation frequency. When Bedrosian theorem conditions are respected, the analytic signal resulting from a stator current given in (1) expresses as (3).

$$\tilde{i}_k(t) = a(t)e^{j(\psi(t) - \phi_k)}, \quad k = 1, 2, 3 \quad (3)$$

Thus, in order to obtain a complex signal, two components in quadrature have to be defined. Under Bedrosian theorem conditions, the Hilbert transform allows to compute a component in quadrature to a unique real signal. However, several mechanical faults produce high frequency modulations that do not respect the Bedrosian theorem conditions. In this

case, another method is proposed to construct an appropriate complex signal.

C. Space vector via the Concordia Transform

In case of three-phase electrical machines, three stator current measurements are available. From these measurements, two components in quadrature may be obtained through the Concordia transform (CT). This transformation, applied to a three-phase system that satisfies $x_1 + x_2 + x_3 = 0$ along time, can be expressed via the Concordia matrix in (4). Note that the matrix has been normalized for further interpretation. Applying this matrix to variables from a three-phase machine gives a two-phase quadrature system [13].

$$\begin{pmatrix} x_\alpha \\ x_\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \sqrt{\frac{3}{2}} & 0 \\ \frac{1}{\sqrt{2}} & \frac{2}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \quad (4)$$

This transformation allows to obtain the two components of a space vector by using two electrical variables. Then, a complex vector is built $\tilde{x}(t) = x_\alpha(t) + jx_\beta(t) = a(t)e^{j\psi(t)}$. This method is widely implemented in electrical drives for control purposes and thus can be used for electrical machines monitoring applications [5]. According to this definition, the Concordia transform provides the same results as the Hilbert transform when the Bedrosian theorem conditions are valid. However, when the Bedrosian theorem conditions are not valid, no restrictions exist on the definition of the complex signal using the Concordia Transform. Differences between analytic signal and space vector analysis are underlined in [8].

D. Wigner Distribution

The Wigner distribution (WD) is a time-frequency energy distribution. The WD $W_z(t, f)$ of a complex signal $z(t)$ is defined as (5) along time t and frequency f [10].

$$W_z(t, f) = \int_{-\infty}^{\infty} z\left(t + \frac{\tau}{2}\right) z^*\left(t - \frac{\tau}{2}\right) e^{j2\pi f\tau} d\tau \quad (5)$$

where z^* denotes the conjugate of z . The WD can be seen as the Fourier transform (FT) of the kernel $K_z(t, \tau)$ (6) with respect to the delay variable τ .

$$K_z(t, \tau) = z\left(t + \frac{\tau}{2}\right) z^*\left(t - \frac{\tau}{2}\right) \quad (6)$$

III. WIGNER DISTRIBUTION OF MODULATED STATOR CURRENTS

A. Wigner Distribution of steady state amplitude modulated stator currents

1) *Wigner Distribution using Analytic signal of stator current:* Considering an amplitude modulated stator current according to the stator current model in (1) with $\phi = \phi_{am} = 0$ and $\beta = 0$, the FT $I_1(f)$ of stator current $i_1(t)$ is expressed as (7) where $*$ is the convolution product. The FT of the analytic signal equals (8).

$$I_1(f) = I \left[\delta(f) + \frac{\alpha}{2} [\delta(f - f_{am}) + \delta(f + f_{am})] \right] * FT [\cos(2\pi f_s t)] \quad (7)$$

$$\tilde{I}_1(f) = I \delta(f - f_s) + \frac{I\alpha}{2} \delta(f - f_s - f_{am}) + \frac{I\alpha}{2} \delta[f - \text{sgn}(f_s - f_{am}) (f_s - f_{am})] \quad (8)$$

According to the expression of the analytic signal of AM signals (8), the WD is obtained. First of all, the resulting analytic signal $\tilde{i}_1(t)$ is expressed in the time domain (9).

$$\tilde{i}_1(t) = I e^{j2\pi f_s t} + \frac{I\alpha}{2} e^{j2\pi(f_s + f_{am})t} + \frac{I\alpha}{2} e^{\text{sgn}(f_s - f_{am}) j2\pi(f_s - f_{am})t} \quad (9)$$

According to the general considerations concerning AM stator currents ($\alpha \ll 1$), terms that are proportional to α^2 are neglected in the kernel computation, leading to (10) and to the WD (11).

$$K_{i_1}(t, \tau) = I^2 e^{j2\pi f_s \tau} + I^2 \alpha \left[\cos(2\pi f_{am} t) e^{j2\pi(f_s + \frac{f_{am}}{2})\tau} + \cos \left(2\pi \left[(1 - \text{sgn}(f_s - f_{am})) f_s + \text{sgn}(f_s - f_{am}) f_{am} \right] t \right) \times e^{j2\pi \left[(1 + \text{sgn}(f_s - f_{am})) \frac{f_s}{2} - \text{sgn}(f_s - f_{am}) \frac{f_{am}}{2} \right] \tau} \right] \quad (10)$$

$$W_{i_1}(t, f) = I^2 \delta(f - f_s) + I^2 \alpha \left[\cos(2\pi f_{am} t) \delta \left(f - f_s - \frac{f_{am}}{2} \right) + \cos \left(2\pi \left[(1 - \text{sgn}(f_s - f_{am})) f_s + \text{sgn}(f_s - f_{am}) f_{am} \right] t \right) \times \delta \left(f - (1 + \text{sgn}(f_s - f_{am})) \frac{f_s}{2} + \text{sgn}(f_s - f_{am}) \frac{f_{am}}{2} \right) \right] \quad (11)$$

When $f_s > f_{am}$, it can be noticed in (11) that the WD expresses as (12).

$$W_{i_1}(t, f) = I^2 \delta(f - f_s) + I^2 \alpha \cos(2\pi f_{am} t) \delta \left(f - f_s - \frac{f_{am}}{2} \right) + I^2 \alpha \cos(2\pi f_{am} t) \delta \left(f - f_s + \frac{f_{am}}{2} \right) \quad (12)$$

In this case, the sideband components are sinusoidal of frequency f_{am} . Moreover, the two oscillating sideband components are in phase which is characteristic to low frequency amplitude modulated signals [2].

Obviously, according to (11), when $f_s < f_{am}$ oscillating components appear at $f_s + \frac{f_{am}}{2}$ and $\frac{f_{am}}{2}$ with oscillating frequency of f_{am} and $2f_s - f_{am}$ respectively (13). Consequently, it becomes impossible to estimate the phase shift between sideband components and then to diagnose the AM.

$$W_{i_1}(t, f) = I^2 \delta(f - f_s) + I^2 \alpha \cos(2\pi f_{am} t) \delta \left(f - f_s - \frac{f_{am}}{2} \right) + I^2 \alpha \cos(2\pi(2f_s - f_{am})t) \delta \left(f - \frac{f_{am}}{2} \right) \quad (13)$$

2) *Wigner distribution using space vector of stator currents:* Using the Concordia space vector, it can be demonstrated that the space vector resulting from amplitude modulated stator currents expresses as (14). Thus, the WD expresses as (12) whatever the values of f_s and f_{am} . The amplitude modulation can thus be detected for any modulation frequency.

$$\tilde{i}(t) = I e^{j2\pi f_s t} + \frac{I\alpha}{2} e^{j2\pi(f_s + f_{am})t} + \frac{I\alpha}{2} e^{j2\pi(f_s - f_{am})t} \quad (14)$$

B. Wigner Distribution of steady state phase modulated stator currents

1) *Wigner Distribution using Analytic signal of stator current:* Considering a phase modulated stator current according to the stator current model in (1) with $\phi = \phi_{pm} = 0$ and $\alpha = 0$, using the *Jacobi-Anger* expansion [14], the FT $I_1(f)$ of stator current $i_1(t)$ is expressed as (15).

$$I_1(f) = \frac{I}{2} \sum_{k=-\infty}^{+\infty} J_k(\beta) \delta(f - f_s - k f_{pm}) + \frac{I}{2} \sum_{k=-\infty}^{+\infty} J_k(\beta) \delta(f + f_s + k f_{pm}) \quad (15)$$

where $J_k(\beta)$ denotes the k -th order Bessel function of the first kind.

Thus, considering $\beta \ll 1$, the FT is simplified in (16) with $J_0(\beta) \simeq 1$, $J_1(\beta) \simeq \frac{\beta}{2}$ and $J_{-1}(\beta) = -J_1(\beta)$.

$$I_1(f) = \frac{I}{2} \delta(f \pm f_s) + \frac{I\beta}{4} \delta(f - f_s - f_{pm}) + \frac{I\beta}{4} \delta(f + f_s + f_{pm}) - \frac{I\beta}{4} \delta(f - f_s + f_{pm}) - \frac{I\beta}{4} \delta(f + f_s - f_{pm}) \quad (16)$$

Thus, a general expression of the analytic signal depending on the sign of $f_s - f_{pm}$ is given in (17) for $f_s \neq f_{pm}$.

$$\tilde{I}_1(f) = I \delta(f - f_s) + \frac{I\beta}{2} \delta(f - f_s - f_{pm}) - \frac{I\beta}{2} \delta[f - \text{sgn}(f_s - f_{pm})(f_s - f_{pm})] \quad (17)$$

For $\beta \ll 1$, terms proportional to β^2 are neglected in the computation of the Kernel $K_{i_1}(t, \tau)$, leading to (18) and to the WD (19).

$$K_{i_1}(t, \tau) = I^2 e^{j2\pi f_s \tau} + I^2 \beta \left[\cos(2\pi f_{pm} t) e^{j2\pi(f_s + \frac{f_{pm}}{2})\tau} - \cos \left(2\pi \left[(1 - \text{sgn}(f_s - f_{pm})) f_s + \text{sgn}(f_s - f_{pm}) f_{pm} \right] t \right) \times e^{j2\pi \left[(1 + \text{sgn}(f_s - f_{pm})) \frac{f_s}{2} - \text{sgn}(f_s - f_{pm}) \frac{f_{pm}}{2} \right] \tau} \right] \quad (18)$$

$$W_{i_1}(t, f) = I^2 \delta(f - f_s) + I^2 \beta \left[\cos(2\pi f_{pm} t) \delta \left(f - f_s - \frac{f_{pm}}{2} \right) - \cos \left(2\pi \left[(1 - \text{sgn}(f_s - f_{pm})) f_s + \text{sgn}(f_s - f_{pm}) f_{pm} \right] t \right) \times \delta \left(f - (1 + \text{sgn}(f_s - f_{pm})) \frac{f_s}{2} + \text{sgn}(f_s - f_{pm}) \frac{f_{pm}}{2} \right) \right] \quad (19)$$

It can be noticed in (19) that when $f_s > f_{pm}$, that the WD expresses as (20).

$$W_{i_1}(t, f) = I^2 \delta(f - f_s) + I^2 \beta \cos(2\pi f_{pm} t) \delta\left(f - f_s - \frac{f_{pm}}{2}\right) - I^2 \beta \cos(2\pi f_{pm} t) \delta\left(f - f_s + \frac{f_{pm}}{2}\right) \quad (20)$$

In this case, the sideband components are sinusoidal of f_{pm} frequency. Moreover, the two oscillating sideband components are in phase opposition which is characteristic to low frequency phase modulated signals [2].

Obviously, according to (21), when $f_s < f_{pm}$, oscillating components appear at $f_s + \frac{f_{pm}}{2}$ and $\frac{f_{pm}}{2}$ with oscillating frequency of f_{pm} and $2f_s - f_{pm}$ respectively. Consequently, it becomes impossible to estimate the phase shift between sideband components and then to diagnose the PM.

$$W_i(t, f) = I^2 \delta(f - f_s) + I^2 \beta \cos(2\pi f_{pm} t) \delta\left(f - f_s - \frac{f_{pm}}{2}\right) - I^2 \beta \cos(2\pi(2f_s - f_{pm})t) \delta\left(f - \frac{f_{pm}}{2}\right) \quad (21)$$

2) Wigner distribution using space vector of stator currents:

As a contrary, using the Concordia space vector, it can be demonstrated that the space vector resulting from phase modulated stator currents expresses as (22). Thus, the WD of a PM signal expresses as (20) whatever the values of f_s and f_{pm} . The phase modulation can thus be detected for any modulation frequency.

$$\tilde{I}(f) = I \delta(f - f_s) + \frac{I\beta}{2} \delta(f - f_s - f_{pm}) - \frac{I\beta}{2} \delta(f - (f_s - f_{pm})) \quad (22)$$

IV. SIMULATED MODULATED STATOR CURRENTS

A. Wigner distribution of modulated steady state stator currents

Consider stator currents as given in (1). Fig. 1 shows the WD for high frequency AM simulated stator currents using the analytic signal and the space vector respectively. The chosen parameters are $I = 10$, $f_s = 50Hz$, $\alpha = 0.1$, $\beta = 0$, $f_{am} = 80Hz$ and $\phi = \phi_{am} = 0$. It can be clearly seen that the WD obtained with the Hilbert analytic signal does not allow to diagnose the amplitude modulation, due to the impossibility of evaluating the phase shift between upper and lower sideband components, as depicted in Fig. 1(a). However, the WD obtained with the Concordia space vector (see Fig. 1(a)) allows to diagnose the amplitude modulation by the evaluation of the phase shift between sideband components. The same conclusions may be achieved by simulating phase modulated stator currents.

B. Wigner distribution of phase modulated variable frequency stator currents

Consider stator currents with a variable fundamental frequency at $f_s(t)$ and a variable frequency phase modulation at $f_{pm}(t)$. It is demonstrated in [7] that the WD of variable frequency stator currents with a variable frequency PM lies in a

central time varying component at $f_s(t)$ that is the fundamental component and sideband components. Fig. 2 depicts WD of simulated phase modulated stator currents with a variable supply frequency. The PM frequency equals $f_{pm} = 1.4f_s$, consequently, the stator currents do not respect the Bedrosian theorem conditions. As for steady state conditions, the WD computed using Concordia space vector leads to sideband components at $f_s(t) \pm \frac{f_{pm}(t)}{2}$ in phase opposition whatever the supply frequency. However, the WD obtained through the Hilbert analytic signal leads to sideband components at $f_s(t) + \frac{f_{pm}(t)}{2}$ and $\frac{f_{pm}(t)}{2}$ frequencies.

Note that the two Wigner distributions are similar in variable frequency applications when the Bedrosian theorem conditions are satisfied. Finally, the Concordia space vector may be used in steady state and variable frequency three phase machines to estimate the WD and to diagnose the amplitude or phase modulation by estimating the phase shift between sideband components. The same conclusions may be achieved by simulating variable frequency amplitude modulated stator currents.

V. EXPERIMENTAL STATOR CURRENTS

A $5.5kW$, 2 pole pair induction machine is supplied by an adjustable frequency PWM inverter. The motor is connected to a DC machine used as a load which is connected to a resistor through a DC/DC converter that controls the DC motor armature current. The reference current of the DC/DC converter is composed of an oscillating component plus an offset in order to induce load torque oscillations around a mean load torque value.

Experimental stator currents are measured on the machine in two steady state conditions, where the supply frequency equals $f_s = 13.3Hz$ and then $f_s = 50Hz$ with a load torque oscillation of frequency $f_{osc} \simeq 20Hz$. Thus, the stator currents are high and low frequency phase modulated signals. In Fig. 3(a), the WD is obtained through the Hilbert analytic signal. In Fig. 3(b), the WD is computed using the Concordia space vector. In low frequency modulation case, the two WD are similar with sideband components in phase opposition at $f_s \pm \frac{f_{osc}}{2}$ frequencies. However, it can be remarked in high frequency modulation case that the WD computed using the Hilbert analytic signals leads to a sideband component at $f_s + \frac{f_{osc}}{2}$ frequency and a component at $\frac{f_{osc}}{2}$ frequency oscillating at $2f_s - f_{osc}$ frequency. Only the WD using the Concordia space vector leads to sideband components at $f_s \pm \frac{f_{osc}}{2}$ frequencies oscillating at f_{osc} frequency. Consequently, it is demonstrated on real stator currents that the CT allows to detect the modulation using the WD for high and low frequency modulations in steady state conditions.

Moreover, Fig. 4 depicts a zoom of the WD obtained with the Concordia space vector in case of high frequency modulation (see Fig. 4(a)) and low frequency modulation (see Fig. 4(b)). In each case, the phase shift between sideband oscillating components may be evaluated. The sidebands components are almost in phase opposition, that is characteristic of phase modulation and proving the presence of load torque oscillations on the shaft of the machine.

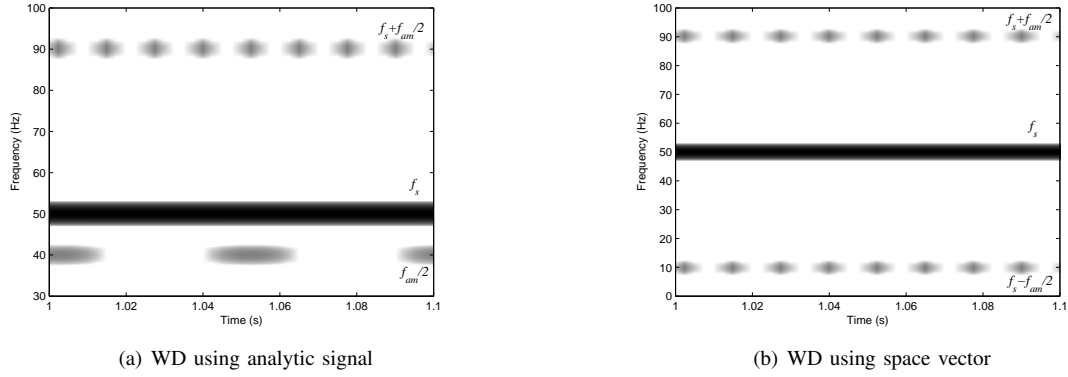


Fig. 1. WD for high frequency AM simulated stator currents computed using HT and CT

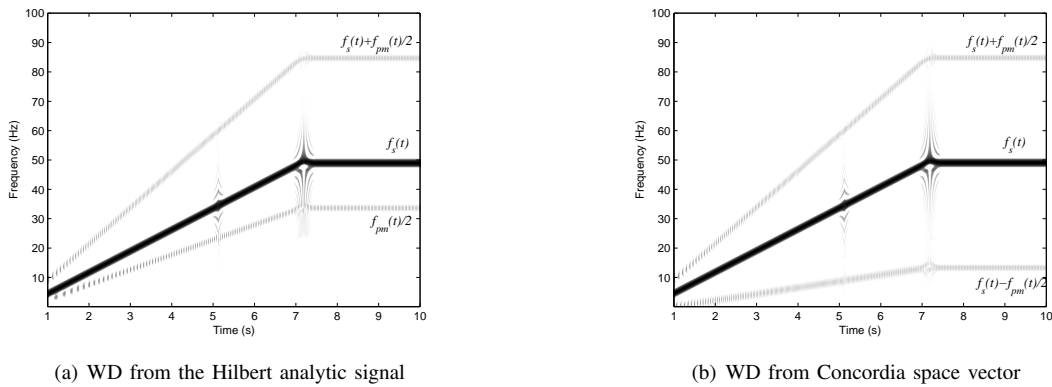


Fig. 2. WD for high frequency PM simulated stator currents computed using HT and CT with variable fundamental frequency

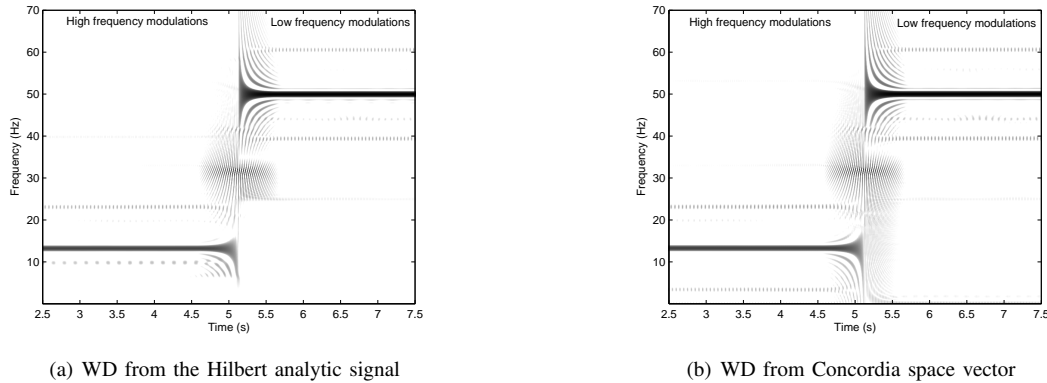
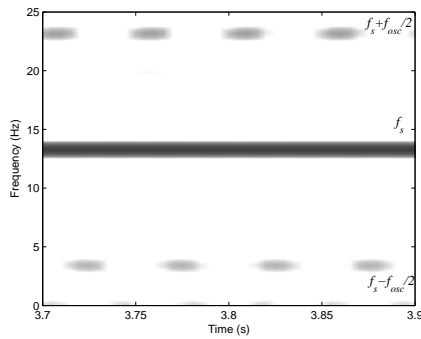


Fig. 3. WD for high and low frequency PM experimental stator currents computed using HT and CT in steady state conditions

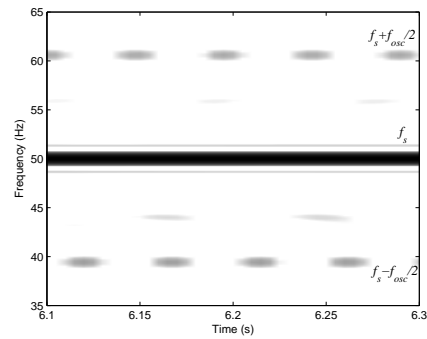
VI. CONCLUSION

Time-frequency analysis requires the definition of a complex signal. This paper has compared the Wigner distribution obtained with the Hilbert and Concordia transforms in case of low and high frequency phase modulations. This comparison is first conducted theoretically and then through simulated and experimental signals. The application to the time-frequency diagnosis based on Wigner distribution is developed. The Concordia transform provides an appropriate signal representation in the low and high frequency modulation

cases. On the contrary, the Hilbert transform is limited, by the Bedrosian theorem conditions, to the analysis of low frequency modulation signals. Phase modulations, resulting from load torque oscillations, can be detected using the Wigner distribution of the complex signal. The Wigner distribution via Concordia transform provides a clear diagnosis of phase modulations through the estimation of the phase shift between sideband components whatever the modulation frequency. As a consequence, when at least two stator current components are available, the Concordia transform should be preferred to build the complex signal required for the time-frequency analysis.



(a) High frequency PM



(b) Low frequency PM

Fig. 4. Zoom of the WD from the Concordia space vector

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