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SPACE VECTOR ANALYSIS FOR THE DIAGNOSIS OF HIGH FREQUENCY AMPLITUDE AND PHASE MODULATIONS IN INDUCTION MOTOR STATOR CURRENT

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ABSTRACT

This paper deals with mechanical fault monitoring in induction machines from stator current measurements. At variable speed, the different faults can be characterized by their time-frequency signatures. However, the time-frequency representations apply to complex signals for a univocal phase and modulus definition. Under usual modulation conditions, this complex signal is the analytic signal obtained through the Hilbert Transform of the real measured signal. Indeed, classical mechanical faults result in modulation frequencies which are lower than the carrier frequency. The analytic signal complex envelope and instantaneous frequency thus provide the amplitude and phase modulations respectively.

However, bearing faults, for instance, may produce high frequency modulations. Then, the analytic signal phase and modulus each carry information on both phase and amplitude modulations. This study proposes an alternative complex signal representation in this case. The proposed representation, namely the Concordia Transform, takes advantage of the additional information available in the case of a three phase machine. By using two stator currents, the Concordia Transform builds a complex vector which conveniently carries the information about phase and amplitude modulations. This paper applies the Hilbert and Concordia Transforms to simulated and experimental signals and provides a diagnosis of amplitude or phase modulation in various conditions.

KEYWORDS

Induction Machine, Current Analysis, High Frequency Modulations, Hilbert Transform, Bedrosian Theorem, Concordia Transform

1. 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 purposes. Detection of mechanical faults such as shaft eccentricity or load torque oscillations is traditionally based on the stator current spectral analysis [1]. In variable speed applications, time-frequency analysis such as Wigner distribution is preferred [2] and related signatures allow to determine the fault origin. However, this method needs a complex signal obtained with the Hilbert Transform under the Bedrosian theorem conditions. This paper proposes the Concordia Transform as an alternative, for three-phase signal electrical drives, when these conditions are not verified. Section 2 presents the effect of load torque oscillations and dynamic eccentricity on the stator current. Section 3 reminds the Hilbert Transform, the Bedrosian theorem

and the Concordia Transform is introduced to build complex signals. Section 4 underlines the differences between the analytic signal and the Concordia complex vector in case of high frequency modulations. Finally section 5 applies the two techniques to experimental stator currents with load torque oscillations to validate the approach.

2. STATOR CURRENT MODEL WITH MECHANICAL FAULTS

Eccentricity and load torque oscillations are the main mechanical faults investigated in diagnosis purposes [2].

A. Eccentricity

In case of eccentricity, the rotor rotational centre is different from the geometrical stator centre. The point of minimum airgap length is not stationary [3]. The modified airgap permeance causes an amplitude modulation (AM) of the fundamental flux density wave and consequently causes an AM of the stator current $i_{am}(t)$ that expresses as:

$$i_{am}(t) = I_1[1 + \alpha \cos(\omega_d t)] \cos[\omega_s t - \varphi_i]$$

where I_1 denotes the stator current fundamental component amplitude, α the AM index, ω_d the fault pulsation, ω_s the supply pulsation and φ_i the initial phase.

B. Load Torque Oscillations

In case of load torque oscillations, the mechanical torque can be described by $\Gamma_{load}(t) = \Gamma_{const}(t) + \Gamma_d \cos(\omega_d t)$ where Γ_d is the amplitude of the load torque oscillation and ω_d the fault pulsation. In presence of load torque oscillations, the induction motor stator current can be considered as the sum of two components resulting from the stator and rotor magnetic fields with respective amplitudes I_{st} and I_{rt} . The rotor component is a phase modulated sinusoidal signal [4]:

$$i_{pm}(t) = I_{st} \sin(\omega_s t + \varphi_s) + I_{rt} \sin[\omega_s t + \beta \cos(\omega_d t)]$$

where β is the phase modulation (PM) index proportional to Γ_d / ω_d^2 .

Note that, for simplicity, the stator current can be simplified in a single phase modulated signal. Moreover, for bearing or gear box monitoring, the load torque oscillations frequency is a high multiple of the rotating frequency. As a consequence, the fault frequency is higher than the fundamental frequency. This point is of strong interest for the definition of a complex signal resulting from stator current measurements.

C. Fault Currents in Three-Phase Induction Machines

In three-phase machines, the fault currents, in case of eccentricity and torque oscillations, can be written in a simple form in (1):

$$\begin{aligned} i_1(t) &= I_1[1 + \alpha \cos(\omega_{d1} t + \varphi_{d1})] \cos[\omega_s t + \beta \cos(\omega_{d2} t + \varphi_{d2})] \\ i_2(t) &= I_2[1 + \alpha \cos(\omega_{d1} t + \varphi_{d1})] \cos[\omega_s t + \beta \cos(\omega_{d2} t + \varphi_{d2}) + 2\pi/3] \\ i_3(t) &= I_3[1 + \alpha \cos(\omega_{d1} t + \varphi_{d1})] \cos[\omega_s t + \beta \cos(\omega_{d2} t + \varphi_{d2}) + 4\pi/3] \end{aligned} \quad (1)$$

where I_1, I_2, I_3 are the amplitudes of stator currents: it can be assumed that $I_1=I_2=I_3$, α and β are the AM and PM index respectively, ω_{d1} and ω_{d2} are AM and PM pulsations respectively, φ_{d1} and φ_{d2} are arbitrary phases and ω_s is the fundamental (carrier) pulsation.

Notice that the AM and PM indexes can be null: $\alpha=\beta=0$ corresponds to the healthy case.

3. HILBERT AND CONCORDIA TRANSFORMS

For time-frequency analysis based on Wigner Distribution for instance, a complex signal has to be associated to the real observed signal in order to have an univocal phase and amplitude definition. In several applications, the complex signal is obtained through the Hilbert Transform (HT) of a unique real signal.

A. Analytic Signal [5]

The complex analytic signal $z(t)$ theoretically allows to define a univocal phase and modulus associated to a real signal $x(t)$. The definition of the analytic signal is generally given in the frequency domain with respect to frequency f :

$$Z(f) = X(f) + j[-j.\text{sign}(f)]X(f) = X(f) + jH(f).X(f) \text{ with } \text{sign}(f) = \begin{cases} +1 & \text{for } f > 0 \\ 0 & \text{for } f = 0 \\ -1 & \text{for } f < 0 \end{cases} \quad (2)$$

where $Z(f)$ denotes the Fourier Transform (FT) of $z(t)$.

$H(f) = -j \text{sign}(f)$ is the Hilbert filter transfer function. Note that the analytic signal computation requires the Fourier Transform derivation $X(f) = \int_{-\infty}^{+\infty} x(t)e^{-j2\pi ft} dt$ and thus the knowledge of the signal $x(t)$ on the whole time domain.

B. Bedrosian Theorem

1. Bedrosian theorem conditions

In case of modulated signal analysis, the HT is submitted to the Bedrosian theorem. Given a phase and amplitude modulated real signal $x(t) = a(t)\cos(\varphi(t))$, the imaginary part of the analytic signal is expected to express as $\Im[z(t)] = h(t) * [a(t)\cos(\varphi(t))] = a(t)\sin(\varphi(t))$. Hence $z(t) = a(t)e^{j\varphi(t)}$ and the phase and amplitude modulations can be studied separately. The commutation between convolution and multiplication is only possible under the conditions of the Bedrosian theorem: the time varying amplitude should have the characteristics of a low-pass signal whereas $\cos(\varphi(t))$ should be a high-pass signal [6] as depicted in Fig. 1, where c is an arbitrary constant. Moreover, the bandwidth of $\cos(\varphi(t))$ has to be relatively small.

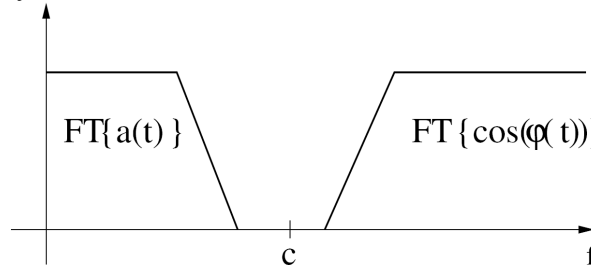


Figure 1 – Illustration of the Bedrosian theorem

As shown in Section 2, in case of bearing or gear box faults, the current signals do not respect the Bedrosian theorem conditions. Another method is then proposed to define a space vector considered as a complex signal.

2. Illustration of the Bedrosian Theorem Conditions

Given a modulated signal $x(t) = A[1 + \alpha \cos(2\pi f_d t)]\cos[\varphi(t)]$ which does not respect the Bedrosian theorem conditions. The FT of signal $x(t)$ is expressed as:

$$X(f) = A \left[\delta(f) + \frac{\alpha}{2} (\delta(f - f_d) + \delta(f + f_d)) \right] * FT[\cos[\varphi(t)]]$$

Assuming that $\varphi(t) = 2\pi f_s t$ with $f_s > f_d$, the FT of the analytic signal equals:

$$Z(f) = A \left(\delta(f - f_s) + \frac{\alpha}{2} (\delta(f - f_s + f_d) + \delta(f - f_s - f_d)) \right)$$

The FT of the complex envelope $a(t) = z(t)e^{-j2\pi f_s t}$ is then:

$$A(f) = A \left(\delta(f) + \frac{\alpha}{2} (\delta(f - f_d) + \delta(f + f_d)) \right) \Leftrightarrow a(t) = A [1 + \alpha \cos(2\pi f_d t)]$$

On the contrary, assuming that $\varphi(t) = 2\pi f_s t$ with $f_s < f_d$, the FT of the analytic signal equals:

$$Z(f) = A \left(\delta(f - f_s) + \frac{\alpha}{2} (\delta(f + f_s - f_d) + \delta(f - f_s - f_d)) \right)$$

The FT of the complex envelope $a(t) = z(t)e^{-j2\pi f_s t}$ is then:

$$A(f) = A \left(\delta(f) + \frac{\alpha}{2} (\delta(f - f_d) + \delta(f + 2f_s - f_d)) \right)$$

It can be clearly seen that an extra harmonic appears at $-2f_s + f_d$ frequency. When the Bedrosian theorem conditions are valid, only the DC component and harmonic at f_d frequency related to the AM exist in the complex envelope.

In current analysis, the instantaneous phase $\varphi(t)$ is generally unknown. As a consequence, the complex envelope is estimated by computing the modulus of the analytic signal. As the modulation index α is lower than 1, terms multiplied by α^2 are neglected. Moreover, by considering the first order of the Taylor development of the square root resulting from the modulus calculation, the estimated complex envelope expresses as (3):

$$a(t) \approx A \left[1 + \frac{\alpha}{2} (\cos[2\pi(2f_s - f_d)t] + \cos[2\pi f_d t]) \right] \quad (3)$$

As previously shown, extra harmonic appears in the spectrum of the complex envelope at $2f_s - f_d$ frequency in comparison to the complex envelope obtained when the Bedrosian theorem conditions are valid.

C. Definition of the Concordia Transform

In 1918, Fortescue introduced a method to analyse three-phase sinusoidal systems by using complex space vectors, the direct-, indirect- and zero-sequence components [7]. Considering separately the real and imaginary parts, respectively $x_\alpha(t)$ and $x_\beta(t)$ of the direct-sequence component, the Concordia Transform (CT) can be defined. This transformation, applied to a general three-phase system ($x_1(t)$, $x_2(t)$ and $x_3(t)$), can be expressed with the Clarke matrix in (4). Note that we have normalized the matrix for further interpretation. Applying this matrix to variables from a three-phase machine gives a virtual two-phase machine [8].

$$\begin{pmatrix} x_\alpha \\ x_\beta \end{pmatrix} = \frac{2}{3} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} \quad (4)$$

Moreover, in balanced systems where $x_1 + x_2 + x_3 = 0$ along time, the matrix (4) is simplified in the Concordia matrix (5):

$$\begin{pmatrix} x_\alpha \\ x_\beta \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \sqrt{\frac{3}{2}} & 0 \\ \frac{1}{\sqrt{2}} & \frac{2}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} \quad (5)$$

This transformation allows to obtain the two components of a space vector by using two electrical variables. Then, a complex vector is built $\tilde{x}(t) = x_\alpha(t) - jx_\beta(t) = a(t)e^{j\varphi(t)}$. This method is widely implemented in electrical drives for control purposes [9] and thus can be used for monitoring applications.

D. Analysis of Signal from Concordia Transform

The space vector $\tilde{x}(t)$ resulting from the CT of two sinusoidal signals $x_1(t)$ and $x_2(t)$ with phases of 0° and 120° respectively is calculated in (6).

$$\begin{aligned} x_1(t) &= a(t) \cos(\varphi(t)), \quad x_2(t) = a(t) \cos\left(\varphi(t) + \frac{2\pi}{3}\right) \\ \tilde{x}(t) &= x_\alpha(t) - jx_\beta(t) = a(t)e^{j\varphi(t)} \end{aligned} \quad (6)$$

Then, expression (6) leads to the complex envelope and the instantaneous frequency (IF) of signals. According to these definitions, the CT allows to obtain results similar as the HT when the Bedrosian theorem conditions are valid. However, when the Bedrosian theorem conditions are not valid, no extra harmonics appear in the spectrum of the complex envelope and the IF.

E. Comparison between Hilbert and Concordia Transforms

In case of low frequency modulations, the Hilbert and Concordia Transforms lead to similar results, especially on complex envelope and instantaneous frequency. On the contrary, it has been shown in Section 3.B. that extra harmonics appear on complex envelope in case of high frequency AM using the HT. Table 1 indicates what are the harmonics related to modulations that exist in complex envelope, computed with the modulus of the analytic signal, and IF for low and high frequency modulations at frequency f_d .

		AM		PM	
		Low frequency	High frequency	Low frequency	High frequency
HT	Complex envelope	f_d	$f_d, 2f_s - f_d$	None	$f_d, 2f_s - f_d$
	IF	None	$f_d, 2f_s - f_d$	f_d	$f_d, 2f_s - f_d$
CT	Complex envelope	f_d	f_d	None	None
	IF	None	None	f_d	f_d

Table 1 – Harmonics related to low and high frequency AM and PM

4. ILLUSTRATION WITH SYNTHESIZED DATA

A. Low Frequency Modulations

Theoretically, there is no difference between the analytic signal and the space vector resulting from the CT in case of low frequency modulations, i.e. when the modulation frequencies are lower than the carrier frequency. The stator current model presented in (1) is used to simulate fault currents. Only an AM is considered in this example, the following parameters are used: $I_1 = I_2 = 10$, $\alpha = 0.03$, $\beta = 0$, $\varphi_{d1} = \pi/7$, $\omega_{d1} = 2\pi 20$, $\omega_s = 2\pi 50$. An additive white and Gaussian noise with a controlled variance of 0.003 is also simulated. Fig. 2(a)-(b) show respectively the spectrum of the complex envelope and IF of simulated currents, estimated by the HT and the CT.

As expected, only the complex envelope spectra show the presence of the amplitude modulation. No particular fault harmonic exists in the IF spectra. Moreover, it can be seen that there is no major difference between the variables obtained by the Hilbert and the Concordia Transforms. As a conclusion, the two transforms are similar in case of low frequency amplitude modulation. Table 1 indicates that the two transforms are also similar in case of low frequency PM.

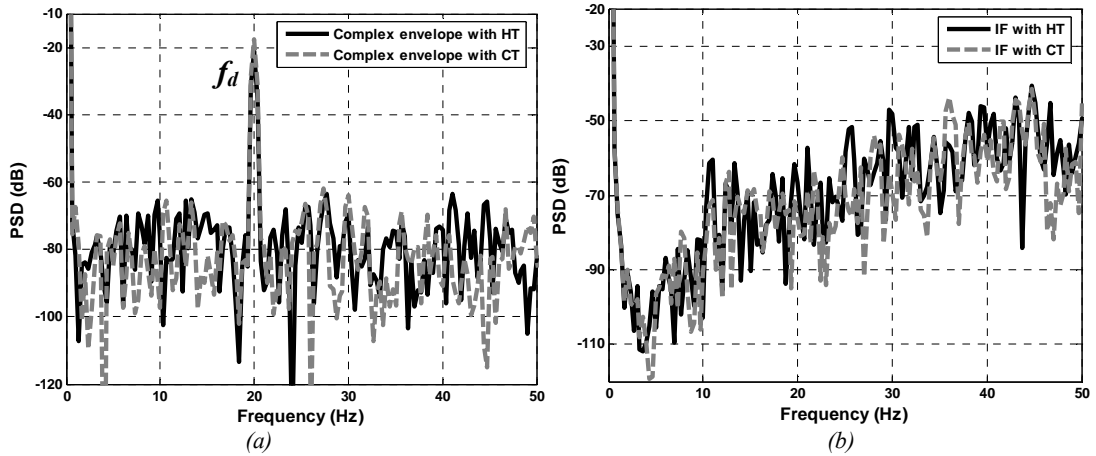


Figure 2 – Spectrum of complex envelope and instantaneous frequency computed through the Hilbert and the Concordia Transforms in case of low frequency AM

B. High Frequency Modulations

In case of high frequency modulations, the Bedrosian theorem conditions are not valid. The stator current model presented in (1) is used to simulate fault currents. Only a PM is considered in this example, the following parameters are used: $I_1=I_2=10$, $\alpha=0.03$, $\beta=0$, $\varphi_{d1}=\pi/7$, $\omega_{d2}=2\pi/70$, $\omega_s=2\pi/50$. An additive white and Gaussian noise with a controlled variance of 0.003 is also simulated. Fig. 3(a)-(b) show respectively spectrum of the complex envelope and IF of simulated currents estimated by the HT and the CT

As Bedrosian theorem hypothesis are not valid, extra harmonics exist in the complex envelope and IF spectrum. The HT leads to fault harmonics at pulsations ω_{d2} and $2\omega_s-\omega_{d2}$ on complex envelope and IF, as expected according to the results in Table 1. Only the Concordia Transform allows to get a unique harmonic on the IF spectra at pulsations ω_{d2} and thus clearly demonstrates the presence of a high frequency PM. Note that similar results can be observed in case of high frequency AM according to Table 1.

To conclude, in case of high frequency modulations, results from the CT allow to clearly diagnose the modulation type and frequency while simulated stator currents are analysed.

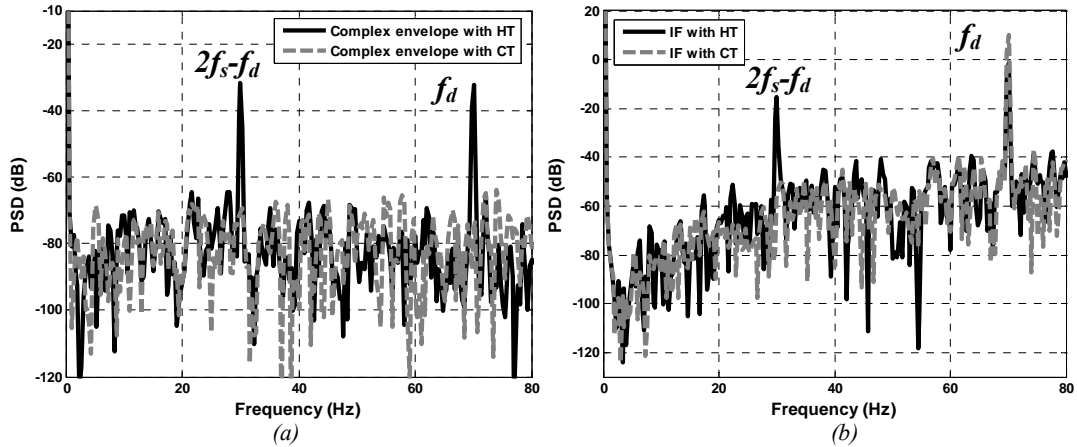


Figure 3 – Spectrum of simulated complex envelope and instantaneous frequency computed through the Hilbert and the Concordia Transforms in case of high frequency PM

5. EXPERIMENTAL RESULTS

Tests have been performed on an experimental setup with a three phase, 50 Hz, 5.5 kW induction machine mechanically coupled to a load DC motor. The machine is supplied by an inverter. The DC motor armature current is controlled to produce a constant torque with an additional oscillation.

A. Low Frequency Modulation Analysis

The stator current signatures of the machine with load torque oscillations are compared in case of low frequency oscillations $\omega_{d2} < \omega_s$ ($\omega_{d2} = 2\pi 21 \text{ rad.s}^{-1}$, $\omega_s = 2\pi 50 \text{ rad.s}^{-1}$) through the complex envelope and IF spectrum estimated with HT and CT. The stator current spectra (see Fig. 4(a)) show fault signatures around the fundamental frequency i.e. an increasing amplitude of the peaks at $\omega_s \pm \omega_{d2}$ pulsations. Contributions of PM and AM to the peak amplitude cannot be done using the spectrum. An analysis of the complex envelope and the IF spectrum determines that the stator current is amplitude and phase modulated. However, with regard to the fault harmonic amplitude, the major modulation is a PM at ω_{d2} pulsation. Moreover, as shown on Fig. 4(b), the IF estimated with the Hilbert and Concordia Transforms are similar because the Bedrosian theorem is respected.

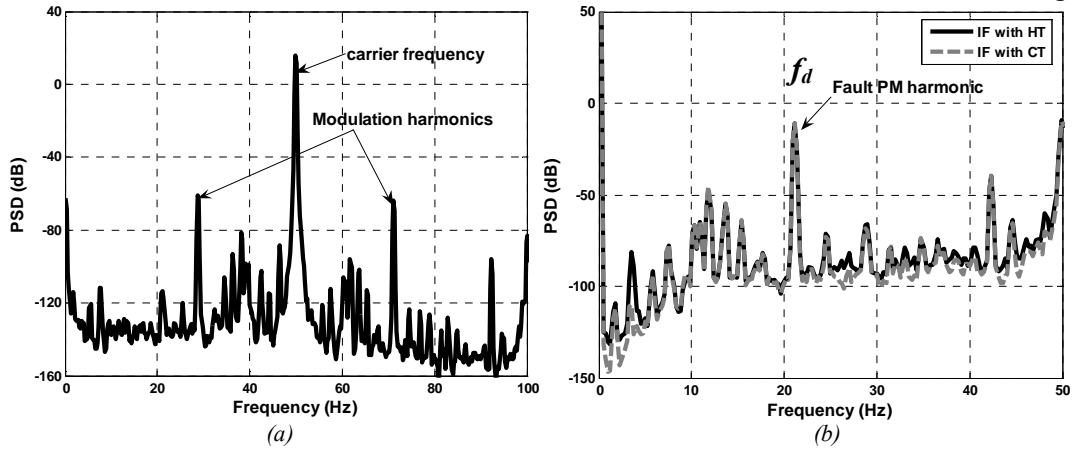


Figure 4 – Spectrum of stator current and associated instantaneous frequency computed through the Hilbert and the Concordia Transforms in case of low frequency load torque oscillations

B. High Frequency Modulation Analysis

The stator current signatures are compared in case of high frequency load torque oscillations $\omega_{d2} > \omega_s$ ($\omega_{d2} = 2\pi 81 \text{ rad.s}^{-1}$, $\omega_s = 2\pi 50 \text{ rad.s}^{-1}$) using the complex envelope and IF spectrum estimated with HT and CT. The stator current spectrum shows fault signatures around the fundamental frequency at $\omega_s \pm \omega_{d2}$ pulsations. As for simulated signals, the estimated IF with the HT creates an extra PM harmonic at $2\omega_s - \omega_{d2}$ pulsation as depicted in Fig. 5. The CT provides a unique harmonic related to the PM at ω_{d2} pulsation. Moreover, the analysis of the complex envelope and the instantaneous frequency determines that the major modulation is a PM at ω_{d2} pulsation.

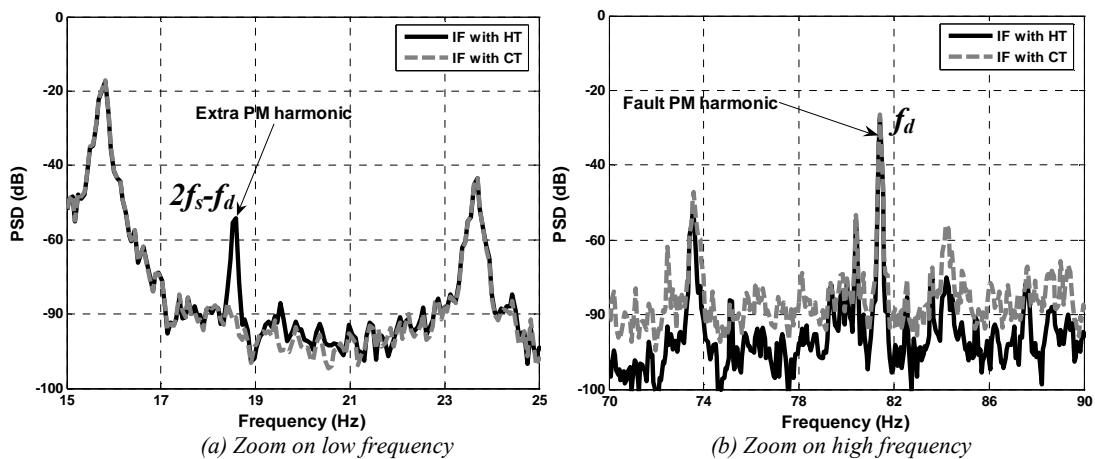


Figure 5 – Spectrum of instantaneous frequency computed through the Hilbert and the Concordia Transforms in case of high frequency load torque oscillations

6. CONCLUSION

A novel method for stator current monitoring of mechanical faults in induction motor has been proposed in this paper. Through simulated signals, differences between space vector obtained with the Hilbert and Concordia Transforms have been clearly shown in case of high frequency modulations. 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. Moreover, the Concordia Transform is by far less computationally expensive than the Hilbert Transform. As a consequence, when two stator current components are available, the Concordia Transform should be preferred to build the complex signal required for the time-frequency analysis.

References:

- [1] W. T. Thomson. *On-line current monitoring to detect electrical and mechanical faults in three-phase induction motor drives*. Proceedings International Conference on Life Management of Power Plants, Dec. 1994, pp. 66-73.
- [2] M. Chabert, M. Blödt, J. Regnier. *Diagnosis of Mechanical Failures in Induction Motors based on Stator Current Wigner Distribution*. World Congress in Engineering Asset Management and international conference on Condition Monitoring (CM2007), Harrogate, June 11-14, 2007
- [3] J.R. Cameron and W. T. Thomson. *Vibration and current monitoring for detecting airgap eccentricities in large induction motors*. IEE Proceedings, vol. 133, no.3, pp. 155--163, May 1986.
- [4] M. Blödt, M. Chabert, J. Faucher, and B. Dagues. *Mechanical load fault detection in induction motors by stator current time-frequency analysis*. Proceedings IEEE International Electric Machines and Drives Conference (IEMDC '05), San Antonio, Texas, May 2005.
- [5] P. Flandrin. *Time-Frequency/Time-Scale Analysis*. San Diego, Academic Press, 1999.
- [6] E. Bedrosian. *A product theorem for Hilbert Transforms*. Proceedings of the IEEE, vol. 51, n° 5, pp. 868-869, May 1963.
- [7] P. Granjon, S. Bacha, V. Ignatova. *Space Vector and Signal Processing for Voltage Dips Monitoring*. Condition Monitoring and Machinery Failure Prevention Technologies (CM2008/MFPT2008), Edinburgh, 15-18 July 2008.
- [8] D.C. White, H.H. Woodson. *Electromechanical energy conversion*. Wiley, New-York, 1959.
- [9] P. Vas. *Electrical Machines and Drives – A space-vector theory approach*. Oxford Science Publications, Oxford, 1992.