Comparative investigation of electric signal analyses methods for mechanical fault detection in induction motors

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Abstract: This paper present a comparative investigation of various media for non invasive diagnosis of mechanical abnormalities in induction motors. Stator voltages and stator currents as well as noises on these signals are simulated first for a fault free motor then for a motor with mechanical abnormalities. These signals are subsequently employed to compute the instantaneous powers $P_{ab}$, $P_{cb}$, $P_{abc}$ and last the current park vector modulus known as the Extended Park Vector Approach “EPVA” method. Waveforms of these simulated signals were analyzed using the power spectral density transformation. Commercially available diagnostics systems uses the fact that the amplitude of some components known as fault characteristic frequencies in these electrical signals, increase when mechanical abnormalities occur. The amplitude increase of these characteristic frequencies is employed as a criterion in order to investigate noise immunity of the five diagnosis methods thus making possible their classification. Simulation and experimental results show that the extended park vector approach “EPVA” reveal the highest noise immunity. Utilization of the “EPVA” is thus enhancing the reliability of diagnostics of induction motor drives.

I- INTRODUCTION

Mechanical faults in electrical drive systems can shut down an entire process. Those unexpected shut downs have a cost, which result in loss production and financial income. During the past fifteen years there has been a substantial amount of research into the creation of new condition monitoring techniques for induction motor drives. This has reduced unexpected failures, increased the time between planned shutdowns for standard maintenance and reduced operational costs. However the machine’s operator must treat each induction motor drive as a unique entity. The potential failure modes, fundamental causes, mechanical load characteristics, and operational conditions have all to be taken into consideration when a condition monitoring system is being selected. In some cases there are several signals which may contain information on the failure mechanism. Generally we select a condition monitoring system based on evidence of its reliability to diagnose problems in industrial drives and on its applicability to the particular industrial installation. Vibration monitoring techniques are only usually installed on expensive and sensitive machines where the cost of such systems can be justified. Moreover, the environmental sensitivity of the sensors can provide unreliable indications. In some situation, such as for electrical submersible pumps, sensor installation is not practical or prohibitively costly. Motor current signal analyses methods “MCSA” are obtained using only non-invasive sensors as current and voltages sensors. These methods are based on spectral analyses of electrical signals as stator currents or the instantaneous power.
This paper reports results of research on noise sensitivity of five non-invasive diagnostic methods and specifically, their spectral response to mechanical abnormalities. The diagnostic media studied included the following:

1- The spectral analyses of the simple current, one of the three supply lines [1] to [4].
2- The spectral analyses of the partial instantaneous powers: $P_{ab}$, $P_{cb}$ and $P_{abc}$ [6] to [8].
3- The spectral analyses of the current park vector modulus, the EPVA method [5].

A theoretical discussion of the diagnostic potential of these media is presented briefly in section II, the simulation setup and the discussion results are presented in section III and finally experimental results are shown in section IV.

II- THEORETICAL BACKGROUND

Considering a healthy induction motor, supplied from a balanced three-phase source of sinusoidal voltages and driving a constant load, the following waveforms of selected stator voltages and currents may be assumed:

\begin{align*}
V_{ab}(t) &= U_m \cos(\omega t) \\
V_{cb}(t) &= U_m \cos(\omega t + \frac{\pi}{3}) \\
i_{a0}(t) &= I_f \cos(\omega t - \alpha - \frac{\pi}{6}) \\
i_{b0}(t) &= I_f \cos(\omega t - \alpha - \frac{2\pi}{3}) \\
i_{c0}(t) &= I_f \cos(\omega t - \alpha + \frac{2\pi}{3})
\end{align*}

where “$U_m$”, “$I_f$”, “$\omega$”, and “$\alpha$” are respectively the maximum value of the line to line voltage, the maximum value of line currents, the supply frequency in radians per second, and finally the power factor angle, see Fig.1.

As a function of the three phases currents (“$i_{a0}$”, “$i_{b0}$”, “$i_{c0}$”), the motor current Park’s Vector components (“$i_{d0}$”, “$i_{q0}$”) presented in a “d-q” plan are:

\begin{align*}
i_{d0}(t) &= \frac{\sqrt{2}}{\sqrt{3}} (i_{a0} - \frac{1}{2} i_{b0} - \frac{1}{2} i_{c0}) \\
i_{q0}(t) &= \frac{1}{\sqrt{2}} (i_{b0} - i_{c0})
\end{align*}

Considering a total balanced three-phase source, the current Park vector modulus can be computed as follows:

\[
|i_{p0}| = \sqrt{i_{d0}^2 + i_{q0}^2} = \frac{\sqrt{6}}{2} I_f
\]
Multiplying “$V_{ab}$” by “$i_{a0}$” and “$V_{cb}$” by “$i_{c0}$” yields partial instantaneous input powers “$P_{ab0}$”, “$P_{cb0}$” then adding the two partial powers will lead to the total instantaneous input power “$P_{abc0}$”:

\[
P_{ab0}(t) = \frac{U_m I_f}{2} (\cos(\alpha + \frac{\pi}{6}) + \cos(2wt - \alpha - \frac{\pi}{6}))
\]

\[
P_{cb0}(t) = \frac{U_m I_f}{2} (\cos(\alpha - \frac{\pi}{6}) + \cos(2wt - \alpha + \frac{5\pi}{6}))
\]

\[
P_{abc0} = P_{ab0}(t) + P_{cb0}(t) = \frac{\sqrt{3}}{2} U_m I_f \cos(\alpha)
\]

if a mechanical abnormality develops in a drive system, such as rotor cage fault, motor-load shaft misalignment, broken teeth in the load gearbox, or vibration, harmonic torques are generated in the motor, accompanied by speed oscillation, and modulation of the stator currents, typically in a periodic manner. In the case of periodic disturbances, all three line currents “$i_a$”, “$i_b$”, and “$i_c$” are simultaneously modulated with the fundamental frequency “$f_0$” of the fault-induced oscillation of motor variables. For simplicity, it is assumed that a mechanical fault in the drive system causes sinusoidal modulation of amplitude of the stator current, while the phase modulation of the current is negligible. Thus, the three currents of the supply line may now be expressed as:

\[
i_a(t) = i_{a0}(t) * (1 + M \cos(w_{osc} t))
\]

\[
i_b(t) = i_{b0}(t) * (1 + M \cos(w_{osc} t))
\]

\[
i_c(t) = i_{c0}(t) * (1 + M \cos(w_{osc} t))
\]
where “$M$” is the modulation index and “$w_{osc}$” is the modulating radian frequency (\(w_{osc}=2\pi f_{osc}\)). The value of the modulation index depends on the severity of the abnormalities substituting (3) in (12) we get:

\[
i_a(t) = i_{a0}(t) + \frac{M_i f}{2} (\cos([w + w_{osc}])t - \alpha - \frac{\pi}{6}) + \cos([w - w_{osc}])t - \alpha - \frac{\pi}{6})
\]

Clearly, in the power spectrum of current, two sideband components will appear about the fundamental, at frequencies \(f_1=(w+w_{osc})/2\pi\) and \(f_2=(w-w_{osc})/2\pi\).

With these assumptions, motor with a mechanical fault, the Park’s vector components \((i_d, i_q)\) are shown below:

\[
i_d(t) = \frac{\sqrt{2}}{\sqrt{3}} (i_a - \frac{1}{2}i_b - \frac{1}{2}i_c)
\]

\[
i_q(t) = \frac{1}{\sqrt{2}} (i_b - i_c)
\]

Substituting the values of \((i_a, i_b, i_c)\) of equations (12, 13, 14) in equations (16) and (17) yields:

\[
i_d(t) = i_{d0} * (1 + M \cos(w_{osc} t))
\]

\[
i_q(t) = i_{q0} * (1 + M \cos(w_{osc} t))
\]

\[
|p| = \sqrt{i_d^2 + i_q^2} = \frac{\sqrt{6}}{2} I_f * (1 + M \cos(w_{osc} t))
\]

The expressions for the modulated instantaneous power, obtained by multiplying the voltages by they corresponding currents are:

\[
P_{ab}(t) = V_{ab}(t) * i_q(t)
\]

\[
P_{ab}(t)=P_{ab0}(t)+\frac{1}{4} M U_{i} I_{f} (\cos([\omega \pm w_{osc}]) t - \alpha - \frac{\pi}{6}) + \cos([\omega \pm w_{osc}]) t - \alpha - \frac{\pi}{6} + 2 \cos(\alpha + \frac{\pi}{6}) \cos(w_{osc} t))
\]

\[
P_{cb}(t) = V_{cb}(t) * i_c(t)
\]

\[
P_{cb}(t)=P_{cb0}(t)+\frac{1}{4} M V_{i} I_{c} (\cos([\omega \pm w_{osc}]) t - \alpha + \frac{5\pi}{6}) + \cos([\omega \pm w_{osc}]) t - \alpha + \frac{5\pi}{6} + 2 \cos(\alpha - \frac{\pi}{6}) \cos(w_{osc} t))
\]

Last we can show that the latest expressions can be expressed as below:

\[
P_{ab}(t) = P_{ab0}(t) * (1 + M \cos(w_{osc} t))
\]

\[
P_{cb}(t) = P_{cb0}(t) * (1 + M \cos(w_{osc} t))
\]

\[
P_{ab}(t) = P_{ab0}(t) * (1 + M \cos(w_{osc} t))
\]

\[
|p| = |p_0| * (1 + M \cos(w_{osc} t))
\]

Our first interested result can be expressed as below:

With the assumptions that a mechanical fault in the drive system causes only sinusoidal modulation of amplitude of the stator currents, the simple currents, the instantaneous partial and
total powers, the current vector components and finally the current Park vector modulus are modulated with the same modulation index, in other words these signals are affected by the same manner.

III- SIMULATION SETUP

This article treats a comparison investigation between methods that use only the electric signals of the induction motors. Signals are simulated according to a model of the electric signals for a fault free motor and a motor with mechanical abnormalities.

III-a Simulation setup

In the simulation, equations (1) to (5) are generated to model the electric signals for a fault free model and equations (12) to (14) are utilized to model the electric signals for a motor with mechanical abnormalities. A simulated motor of 3 KW, 380 V, 50 Hz two pole induction motor is used. The nominal current of the motor is 5 Amp as an rms value and the power factor angle is given by his cosine “\( \cos(\alpha)=0.89 \)”. Concerning the mechanical abnormalities the modulation index “\( M \)” is taken 1% and the fault characteristic frequency is taken 2Hz. Additive noise is added to the simulated currents and motor voltages, these noises are assumed to be white noises, zero mean noises and with a variance of one. Therefore these noises are multiplied by two gains the “\( K_{nc} \)” and the “\( K_{nv} \)” in order to amplify respectively the currents and the voltages noises. These noises determine the severity of the additive noises and take the values in the ranges: [0-2.5]Amp for the current noise gain and [0-50]Volts for the voltage noise gain. Finally for each generated electric signals a 4995 values were recorded, with the sampling frequency of 1 Khz.

III-b Signals presentation

Spectral analyses of these signals can lead to better monitoring and diagnosis of the induction motors. First, with the assumptions taken to model mechanical abnormalities, (12, 13, 14) we can clearly notice that in the case of mechanical abnormalities the spectrum of the simple current will contain, apart from the fundamental frequency “\( f_1=50Hz \)”, two sideband components at frequencies “\( f_0 \pm f_{osc} \)” while in the case of a fault free motor the spectrum contains only the fundamental frequency “\( f_1 \)”.

Second, in the case of a fault free motor the electric signals “\( P_{abc0} \)” and current Park’s modulus are constant that why the spectrum of these signals in the case of a mechanical faults contain only a spectral component directly at “\( f_{osc} \)”. This component is characteristic of the abnormality, not of the motor.

Finally, concerning the instantaneous partial powers “\( P_{ab} \)” and “\( P_{cb} \)” we can see from equations (9, 10, 22, 24) that in the case of a fault free motor the spectral analyses of these signals reveals the presence of only a fundamental component at twice the power supply fundamental “\( f_2=100 \) Hz”. In another hand when mechanical abnormalities appear, the spectrum of these signals contains the component at “\( f_2 \)” , two sidebands components at “\( f_2 \pm f_{osc} \)” and a fourth spectral component directly at “\( f_{osc} \)”.

III-c Noise immunity and comparison

Previous studies like in [9], have made a comparative investigation of some electric signals methods for the detection of mechanical abnormalities. This comparative approach treated only the instantaneous total and partial powers using the amplitude of fault characteristic frequency
as a criterion to classify these detection methods. In fact from equations (15), (20), (22), (24), and 27 we can extract respectively the amplitudes \( A_c, A_{cp}, A_{ab}, A_{cb}, A_{abc} \) of the fault characteristic frequency \( f_d \). This frequency takes the value \( f_{osc} \) for the simple current detection method and the value of \( f_{osc} \) for instantaneous powers and the “EPVA” detection methods.

\[
A_c = \frac{1}{2} M I_f \tag{29}
\]
\[
A_{cp} = \frac{\sqrt{6}}{2} M I_f \tag{30}
\]
\[
A_{ab} = \frac{1}{2} M U_m I_f \cos(\alpha + \frac{\pi}{6}) \tag{31}
\]
\[
A_{cb} = \frac{1}{2} M U_m I_f \cos(\alpha - \frac{\pi}{6}) \tag{32}
\]
\[
A_{abc} = \frac{\sqrt{3}}{2} M U_m I_f \cos(\alpha) \tag{33}
\]

Fig. 2 shows the values of the fault characteristic frequency amplitudes function of the power factor angle. The range of the power factor angle is taken between 0 and 180 degree but generally practical motors are designed that within a wide range of load torque, the power factor angle does not change significantly, staying at a low level to maintain a high power factor. However comparison between these amplitudes doesn’t have a physical meaning if they aren’t referred to a reference. Normally the amplitude values of spectral components at the fault characteristic frequency in case of a motor with no mechanical abnormalities, is the reference. We define a criterion \( \Delta A \) which denotes the increase in amplitude, when mechanical abnormalities occur, of the spectral component at the fault characteristic frequency from its value when there are no faults.

![Fig.2. Simulated fault characteristic component Amplitude function of the power factor angle and the detection method for a motor with mechanical abnormalities.](image-url)
Theoretically the equations (25) to (28) reveal that the increase in amplitude for all electric signals at the fault characteristic frequency is perfectly the same. Simulation results in Fig.7 show clearly the fact. Therefore noisy signals perturb the diagnosis analysis. The spectrums of the electrical signals are very affected by noise coming from measurement procedures done to the currents and the voltages. In general noises increase the low level of the spectrums so why our criterion “ΔA” is affected. Figs. (3, 4, 5, 6) present the spectrums of the simulated electric signals in the spectral range where the fault characteristic frequencies may occur. All the figures show that when mechanical abnormalities occur, the amplitude of the spectral components at the fault characteristic frequencies increase. This increase of amplitude “ΔA” is directly linked to the severity of the fault so why it is used as a criterion in order to classify the non invasive diagnostic procedures. Finally high amplitude of spectral components indicative of the fault is not the only quality expected for a good diagnostic method but the increase in amplitude from the fault free situation under noisy environmental is the criterion that seems more adequate to make a comparative investigation for the electric signal diagnostic methods.

This paper investigates the noise immunity of each electric signal that can be used to elaborate mechanical abnormalities detection and diagnostic method in induction machine. The electric signals treated below are the simple current, the current Park vector modulus, the instantaneous partial powers “P_{ab}”, “P_{cb}”, and last the instantaneous total power “P_{abc}”. To accomplish this work we calculated the criterion average value “ΔA” over 500 simulated sample noisy electric signals for all the methods. The amplitude of the injected noise to currents and voltages is controlled by a gain “K_{nc}”, “K_{nv}” respectively for currents and voltages amplitude noises see Fig.8. The effect of the current noise amplitude is investigated into the range [0.1 , 2.5] Amp using a step of 0.1 Amp while the voltage noise amplitude is investigated into the range of [0.5 , 50] Volts using a step of 1 Volt. For each step of the noise current and voltage amplitude five values of the classification criterion “ΔA” is calculated and saved corresponding to the five diagnostic methods.
Fig. 3. Spectrum of the simple current for a fault free motor (dashed line) and a motor with mechanical abnormalities (straight line)

Fig. 4. Spectrum of the partial instantaneous powers for a fault free motor (dashed line) and a motor with mechanical abnormalities (straight line)

Fig. 5. Spectrum of the total instantaneous power for a fault free motor (dashed line) and a motor with mechanical abnormalities (straight line)

Fig. 6. Spectrum of the current Park vector modulus for a fault free motor (dashed line) and a motor with mechanical abnormalities (straight line)

Fig. 7. Spectrums of five electric signals at the range of the fault characteristic frequency for a fault free motor (dashed line) and a motor with mechanical abnormalities (straight line)
Voltages generation for a fault-free motor \((V_{ab0}, V_{cb0})\) and for a motor with a mechanical fault \((V_{ab}, V_{cb})\).

Current generation for a fault-free motor \((i_{a0}, i_{b0}, i_{c0})\) and for a motor with a mechanical fault \((i_a, i_b, i_c)\).

White noise zero mean, Variance = 1

Computation:
- 3- noisy voltages(fault + fault-free)
- 4- noisy currents

Computation:
- 1- Current Park vector modulus
- 2- Partial Powers

Electric signals spectral analyses.
Computation of the average value of “ΔA” for every method over “Nb=500” samples of 3 seconds each

\(K_{nc} = K_{nc} + S_c\)

\(K_{nv} = K_{nv} + S_v\)

\(Y\) if \(Nb \leq 500\)

Save all «ΔA»

\(Y\) if \(K_{nc} < K_{ncf}\)

\(Y\) if \(K_{nv} < K_{nvf}\)

\(N\) if \(K_{nc} \geq K_{ncf}\)

\(N\) if \(K_{nv} \geq K_{nvf}\)

END

Fig.8 Flow chart for computation of the amplitude increase average when mechanical abnormalities occur, of the fault characteristic frequency function of the detection method and the current and voltages noises.
Fig. 9 The amplitude increase in the simple current spectrum of the component at the fault characteristic frequency $50 - f_{osc}$ function of voltages and current noises.

Fig. 10 The amplitude increase in the current Park vector modulus spectrum of the component at the fault characteristic frequency $f_{osc}$ function of voltages and current noises.

Fig. 11 The amplitude increase in the Partial power “Pcb” spectrum of the component at the fault characteristic frequency $f_{osc}$ function of voltages and current noises.

Fig. 12 The amplitude increase in the Partial power “Pab” spectrum of the component at the fault characteristic frequency $f_{osc}$ function of voltages and current noises.

Fig. 13 The amplitude increase in the total power “Pabc” spectrum of the component at the fault characteristic frequency $f_{osc}$, function of voltages and current noises.
Fig. 14 The amplitude increase of the spectral component at the fault characteristic frequency, function of the detection methods and current noises, (voltage noise = 0.5 V)

Fig. 15 The amplitude increase of the spectral component at the fault characteristic frequency, function of the detection methods and current noises, (voltage noise = 9.5 V)

Fig. 16 The amplitude increase of the spectral component at the fault characteristic frequency, function of the detection methods and voltage noises, (current noise = 0.1 A)
Fig. 17: The amplitude increase of the spectral component at the fault characteristic frequency, function of the detection methods and voltage noises, (current noise = 1 A)

Fig. 18: Methods Classification by fixing a threshold value of 1.5 dB for the amplitude increase of the spectral component at the fault characteristic frequency.

Fig. 19: Methods Classification by fixing a threshold value of 10 dB for the amplitude increase of the spectral component at the fault characteristic frequency.
III-d Discussion of the results

Fig.9 presents the amplitude increase “\(\Delta A\)” in the simple current spectrum of the component at the fault characteristic frequency function of the voltages and currents noises. This characteristic frequency is found at “\(50-f_{osc}\)” which is in our case 48 HZ. We can see clearly that this criterion is normally not affected by the voltage noises. Starting with a current noise amplitude of 0.1 Amp the “\(\Delta A\)” criterion have a value of 24 dB then this value decreases to zero when the current noise amplitude increases. Fig.10 represents the “\(\Delta A\)” criterion applied to the “EPVA” detection method. Once more this criterion is not sensitive to voltages noises because the last method does not use the supply voltages. The increase of the current noises decreases the value of the comparative criterion. Fig.11 presents the amplitude of the comparative criterion “\(\Delta A\)” for the partial power “\(P_{cb}\)” . We can notice that this criterion is sensitive for both current and voltage noises. The criterion value will tend to zero either when voltage noises or current noises increase. Figs.(12, 13) show the comparative criterion value function of the currents and voltages noises respectively for the partial power “\(P_{ab}\)” and for the instantaneous total input power “\(P_{abc}\)”.

In order to make a comparison between the diagnostic procedures we have group all the values of the comparison criterion for the different diagnostic methods. Figs.14, 15 shows the values of the comparison criterion for five non invasive diagnostic methods function of the current noises at respectively a voltage noise value of 0.5V and 9.5V which correspond to 0.13% and 13% of the nominal voltage. We can see that the “EPVA” method exhibit the highest values of the comparison criterion. This means that this method have more immunity against noises and therefore give better detection of the mechanical abnormalities. Next comes the total input power “\(P_{abc}\)” , “\(P_{cb}\)”, the simple current and last the partial power “\(P_{ab}\)” . Figs.16, 17 shows the values of the comparison criterion for five non invasive diagnostic methods function of the voltage noises at respectively a current noise value of 0.1Amp and 1 Amp which correspond to 4% and 40% of the nominal current. We notice in Fig.16 that only the instantaneous power detection criterion decreases when the voltage noises increase. The value of the detection criterion can be used to classify the methods. More the value of the criterion is pronounced more the method present noise immunities and thus is more effective. In Fig16 given that the current noises value is fixed to 0.1 Amp and supposing the voltage noises is less then 13 volts the order of the non invasive detection methods from the most effective to the less one is : “EPVA”, “\(P_{abc}\)” , “\(P_{cb}\)”, the simple current and last the “\(P_{ab}\)” method. This order change if the voltage noise is greater then 13 volts and in this case the simple current will be more important the all the instantaneous power detection methods. Fig.17 shows that in case of great values of current noises, here about 40% of the current nominal value the classification of the detection method is the same and do not change with the voltage noises, in this case the “EPVA” method show the most reliable values of the detection criterion, second comes the total input power, the instantaneous partial power “\(P_{cb}\)” , the simple current, and last the partial power “\(P_{ab}\)” . Figs.18 and 19 show the contour of the criterion “\(\Delta A\)” by fixing respectively two thresholds of 1.5 dB and 10 dB. The detection criterion contour of all the five detection methods function of both voltage and current noises is presented thus rendering very clear the classification. The Fig.18 invests the case of a threshold of 1.5 dB, in another words we have mechanical abnormalities detection when the amplitude increase of the fault characteristic frequency is more than 1.5 dB. We can see in this case that all the non invasive methods show their detection aptitude even with great values of amplitude noises. In fact the “EPVA” method shows little sensitivity to current noises. Mechanical abnormalities are detected even when current noises reach 2 Amp which correspond to 80 % of the nominal current. The instantaneous powers “\(P_{abc}\)” and “\(P_{cb}\)” can deal with current noises up to 1 Amp which correspond to 40% of the nominal current, the simple
current can give detection with current noise amplitude up to 0.6 Amp and finally the “$P_{ab}$” method can deal only with current noise amplitude of 0.4 Amp.

In order to invest the case of a great values of thresholds, Fig.19 show the contour of the criterion “$\Delta A$” for a threshold of 10 dB. In this Fig we can see that if the detection is fixed to a value of 10 dB all the treated methods shows critical situations for the detection of the mechanical abnormalities. The “EPVA” method gives detection only if current noises amplitudes are less then 0.6 Amp. The “$P_{abc}$” and the “$P_{cb}$” detection methods give detection if current noises amplitude is less then 0.35 Amp and less then 38 volts for voltage noises in the zone delimited by their contour. The simple current method will show no detection if current noises amplitudes are greater then 0.25 Amp and last the “$P_{ab}$” detection method is no usefulness if the current noises exceed 0.2 Amp or the voltage noises exceed 18 volts.

IV- Experimental Results

The experimental tests were carried out using data from the Laboratory of images and signals “LIS” (Laboratoire des Images et des Signaux) Grenoble-France. The purpose of our benchmark “GOTIX” is to detect mechanical abnormalities in rotating machinery and especially defects in a gear box using vibration, acoustical and / or electrical supply signals. The benchmark “GOTIX”, see Fig.20, is formed by a 55 kW “Leroy Somer” asynchronous motor, by a gear box with a multiplicative ratio of (57/15) see Fig.21, by a speed variable controller and by a DC motor in order to simulate variable loads. GOTIX is equipped with three voltage sensors, three current sensors, eight accelerometers, torque sensor, temperature probes and finally the benchmark is equipped with a speed sensor. The data acquisition system is used to acquire synchronously twenty instantaneous signals with 100 KHz maximum sampling frequency per channel.

The detection tests were performed with the equipment described above, for a healthy mode without any mechanical or electrical abnormalities taken as the reference time (time=0), after 2800 hours of continuous work with a load of 172Nm (mode fault1) and finally after 3100 hours (mode fault2). Obviously after 2800 hours of continuous effort the gear box is exhausted and encloses defects. Fig.21 shows the gear box equipped by some vibration sensors.
For every of the three operation modes a number of eight signal of ten seconds each are acquired. These signals are re-sampled at frequency of 2.5 KHz. The spectrums of the simple current, the current Park vector modulus and the three instantaneous powers are computed then averaged over the eight experimental set of electrical signals for the three operation mode. The simple current spectrum is normalized with respect to the amplitude of the fundamental supply frequency. The spectrums of the current Park vector modulus and the three instantaneous powers are normalized with respect to their direct component (0 HZ).

Fig. 22 shows a comparison between the spectrum of the simple current for a fault free machine and for the two functioning modes “fault1” and “fault2”. The spectral analysis clearly shows that when a mechanical fault, gear fatigue, is present several components appear at the fault’s characteristic frequencies in the current spectrum \( f_r \pm f_{osc} \). These fault’s characteristic frequencies is directly related to shaft rotating frequency and its sub harmonics.

Fig. 23 shows a comparison between the spectrum of total instantaneous power for a fault free machine, and in case of fault1 and fault2 functioning modes. The spectral analysis clearly shows that when a mechanical fault is present a component appears at the fault’s characteristic frequencies \( f_{osc} \) which in our case are 3.2, 12.2 and 19.6 Hz.

Figures 24 and 25 show the spectrum of the partial power “Pcb” for the three different functioning modes respectively in the low band frequencies [0,50]Hz and for the band around twice the fundamental supply frequency [70,130]Hz.

The values of the comparison criterion \( \Delta A \) function of the diagnostic procedure and for two gear fault’s severity level are given by table and presented by Fig.26.
Fig. 22 The simple current spectrum for a fault free machine (dotted line) and for a machine with gear fault (straight lines).

Fig. 23 The total power spectrum for a fault free machine (dotted line) and for a machine with gear fault (straight lines).

Fig. 24 The partial power “Pcb” spectrum for a fault free machine (dotted line) and for a machine with gear fault (straight lines) in the frequency range [0, 50Hz].

Fig. 25 The partial power “Pcb” spectrum for a fault free machine (dotted line) and for a machine with gear fault (straight lines) in the frequency range [70, 130Hz].

Table 1: “\( \Delta A \)” criterion for the characteristic frequency 19.22 Hz, function of the detection methods and for two gear fault’s severity level

<table>
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<th></th>
<th>“EPVA”</th>
<th>Simple current “SC”</th>
<th>Partial power “Pcb”</th>
<th>Partial power “Pab”</th>
<th>Total power “Pabc”</th>
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Amplitude (dB)

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<th>Fault2</th>
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</tbody>
</table>

The results in Fig.26 show clearly that the “ΔA” criterion is directly linked to the gear fatigue severity. In fact the “ΔA” values increase in mode fault2 relatively to mode fault1 which correspond of an addition of 300 hours of use. We can also see that the “EPVA” method exhibits the highest values of the comparison criterion for the two functioning modes, which signifies that this method has more reliable detection capability of gear abnormalities. Next the total instantaneous power “Pabc” method comes. The instantaneous power “Pab” occupies the second position. Next the simple current diagnostic procedure comes. Finally we can notice that the instantaneous power method “Pcb” exhibits relatively low values of the detection criterion “ΔA”. These experimental results match very well the simulation results. However, we can see a degradation of the detection effectiveness of the instantaneous partial power “Pcb” that’s why more research must be provided to explain this phenomenon.

V- CONCLUSION

This paper had reported results of research on noise sensitivity of five non invasive diagnostic methods and specifically, their spectral response to mechanical abnormalities. Simulation results have investigated the noise immunity of the mechanical abnormalities detection methods thus making possible the classification of these diagnostic methods. Simulations results show the great noise immunity of the “EPVA” detection method over all the other non invasive methods. Then comes the instantaneous total input power “P_{abc}”, the partial power “P_{cb}”, the simple current, and last the instantaneous partial power “P_{ab}”. Experimental results were carried out using the “GOTIX” benchmark of the laboratory of Images and signals “LIS” Grenoble France, treating two severity gear box severity fatigue. The experimental results show a quite good agreement with the simulation results. Presently, we are concentrating on the study of the relationship between the angular displacements of the current sidebands components which it seems that this one is directly related to the type of the rotating machines faults. Finally, we
don’t fail to say that utilization of the “EPVA” is thus enhancing the reliability of diagnostics of induction motor drives.

REFERENCES


