Gear Fault Diagnosis by Motor Current Analysis: Application to Industrial Cases

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The use of motor current signature analysis (MCSA) for motor fault detection — such as a broken rotor bar — is now well established. However, detection of mechanical faults related to the driven system remains a more challenging task. Recently there has been a growing interest for detection of gear faults by MCSA. Advantages and drawbacks of these MCSA-type techniques are presented and discussed on a few industrial cases.

Introduction

Reliance upon motor current signature analysis (MCSA) for fault detection has received growing attention in recent years. Electrical current analysis is a very useful tool for the diagnosis of faults inducing torque or speed fluctuations, and provides ideal vibration analysis (Ref.1). First works were focused on motor fault diagnosis, such as broken rotor bars or eccentricity faults (Ref. 2). Recent works are considering more challenging faults such as bearing faults (Refs. 3-4), or even gear faults in the driven gearbox (Refs. 5-7). This work is of great interest in applications where the mechanical system is not easily accessible for traditional vibration measurements; e.g., in the nuclear industry.

In Reference 5 the authors propose a theoretical model based on Kron's transform — a close form to Park's transform — that leads to an equivalent, two-phase machine from the initial three-phase motor. The resulting vector is called the current space-vector and rotates with the stator magnetic field. When considering the meshing of gears, the tooth mesh stiffness is normally varying because the number of teeth in mesh is periodically varying in time. Moreover, when a faulty tooth is coming into mesh the stiffness is dropping suddenly, thus inducing a reduction of the load torque and consequently of the current space-vector amplitude. The resulting theoretical current spectrum should then display harmonic components spaced by the rotation speed of the faulty gear on the entire frequency range (Ref. 3).

In Reference 6 it was proposed to synchronously average the stator current space-vector amplitude with the rotation of each gear in the driven gearbox. The method was applied to a test bench with a two-stage reduction gearbox where a fault was created on one tooth of the output gear. Results were very promising when compared with the averaged vibration signal.

It should be noted, however, that most of these studies are concerned with test benches of low power and low inertia. This is relatively far from industrial systems, which may be constituted of high-power motors driving a high-inertia load. So far, there have been very few works to our knowledge that show the application of the MCSA-based techniques and large induction motors; and we only found a few studies that focus on motor faults exclusively (Ref. 2). No work really addressed what the limitations are of the MCSA-based techniques for the detection of gear or bearing faults, and whether these techniques are applicable or not to large, industrial systems. In addition, in practice the current spectral signature is polluted by high-frequency components (rotor slots components and harmonics of the supply frequency) that add difficulty in making a diagnosis.

In this paper we will attempt to apply the MCSA-based techniques for the detection of gear faults based on industrial-environment case studies. The use of one-phase (1I) stator current may be sufficient in the case of low-rotation speed of the faulty gear. However, in other cases the three-phase (3I) stator currents will be necessary in order to compute the current space-vector or Park's vector, whose advantage is to bypass the Bedrosian's conditions associated with the Hilbert transform. We will then apply the synchronous averaging techniques in order to detect and enhance the local tooth faults. Possibilities and limitations of these techniques are discussed.

Effect of Small Torque Variation On Stator Current

Let us consider a small torque variation applied to a mechanical system constituted of the elements from the driving AC motor to the mechanical element submitted to a load variation (due, for example, to a cracked tooth on one gear). By neglecting the frictional forces, it writes:

$$J\,d\Omega/dt = \Gamma e - \Gamma load \tag{1}$$

With

J Total moment of inertia of the system

Ω Rotational speed of the motor (we consider here only one shaft for simplicity)

Γe Electro-mechanical torque of the motor

$\Gamma load$ Loading torque applied to the system.

In normal operating conditions, i.e., when Ω is close to the synchronous speed Ωs of the motor, the torque characteristic may be linearized as:

$$\Gamma e = Km^{*}s = Km^{*}(\Omega s - \Omega)/\Omega s \tag{2}$$

with Km a constant depending of the motor characteristics and s the motor slip. Now by considering a small variation of the load torque $\delta\Gamma$ load occurring during the time interval δt, by applying these small perturbations to (Eq. 1) and (Eq. 2) we obtain:

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$$J\,\delta\Omega/\delta t = \delta\Gamma e - \delta\Gamma load = Km\,\delta\Omega/\Omega s - \delta\Gamma load \quad (3)$$

so:

$$\delta\Omega = -\delta\Gamma load / [J/\delta t + Km/\Omega s] \quad (4)$$

It appears that the effect on the induced speed variation δΩ will be reduced when:

Moment of inertia *J* of the system is important

Time interval δt of the torque variation is small; i.e. the torque variation is of high-frequency nature

Constant *Km* of the motor is high (note that this constant is related to the motor supply voltage and will be higher for a high-voltage motor)

With the stator current of the motor being directly linked to the motor torque Γ*e* — which is itself related to the speed from Equation 2 — the induced current variation δI will follow that of δΩ. As well, other parameters will impact motor torque variations, e.g.: the type of gears (spur, helical), the type of the mechanical coupling of the motor that will add a filtering effect between the load torque and the motor torque, etc.

From this simple analysis it is clear that the effect of small load torque variations in the driven mechanical system on the stator current of the driving motor is strongly dependent on a few parameters: moment of inertia, frequency of the torque variation, type of the motor and of the gears. Therefore we can expect different behaviors depending on the system under analysis.

Application to Industrial Cases

We will consider here two case studies where a gear fault was present in the reduction gearbox driven by an induction motor. In the first case only one phase current (1I) will be analyzed due to a low rotation speed. On the second study the three-phase current (3I) will be necessary in order to compute the Park's vector. Synchronous averaging will also be applied in order to enhance the local tooth faults (Refs. 6-7).

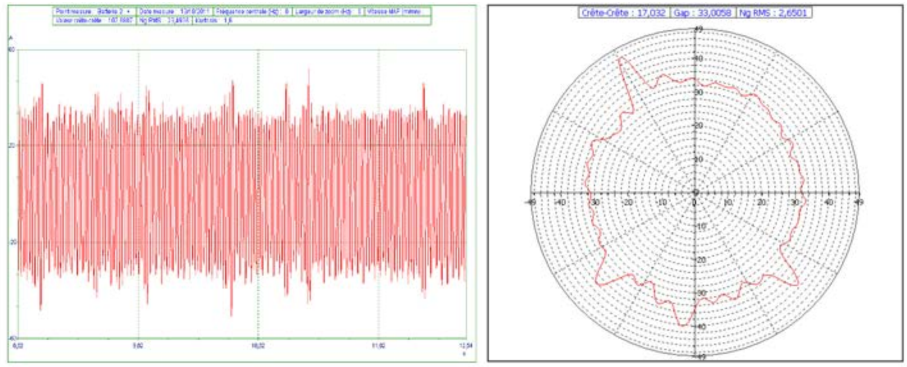

Figure 1 Stator current signal (left) and AMF profile averaged over the rotation period of the geared roll (right).

Gear fault detection in a paper making machine. This application deals with the diagnosis — by means of electrical current analysis — of local gear faults in a drying roll section of a paper making machine. The system is composed of a low-voltage AC motor (30kW/1,480 rpm) running a pinion through a 6.1 reduction gearbox. The pinion has 32 teeth and is meshing with a 178-tooth ring gear attached to the driving roll of the section. The rotation of the rolls is rather slow (0.63Hz), which gives a gear mesh frequency at 112Hz.

The operator observed on the current indicator abnormal and apparently random variations of the instantaneous current absorbed by the motor (Fig. 1). The stator phase current was measured and the amplitude modulation function (AMF) of the current 50Hz fundamental component was computed and then averaged synchronously with the rotation period of the rolls. The AMF average profile shows four stronger peaks (Fig. 1) that seem to indicate local tooth faults on the main geared roll. Indeed, when dismantling the gear at inspection, the operator literally observed "several falling teeth."

Note that here the rotation period of the rolls is low enough so that only one stator phase measurement is necessary for the demodulation of the 50Hz carrier frequency (the 25Hz span of the AMF spectrum contains about 40 harmonics of the gear rotation frequency). While the moment of inertia of the rolls is relatively high, that of the driving system (medium-size motor, small reduction gearbox and output pinion) is relatively small. Thus we seem to satisfy here the abovementioned conditions for the detection of torque fluctuations via stator current analysis.

Gear fault in a ball mill. This application deals with a ball mill machine driven by two AC motors — each through a two-stage reduction gearbox. The motors are 2MW power, 5kV voltage and 1,000 rpm speed; the gears are chevron-type.

During one experiment it was known from the operator that the high-speed pinion of one gearbox had one cracked

Figure 2 Two-stage reduction gearbox.

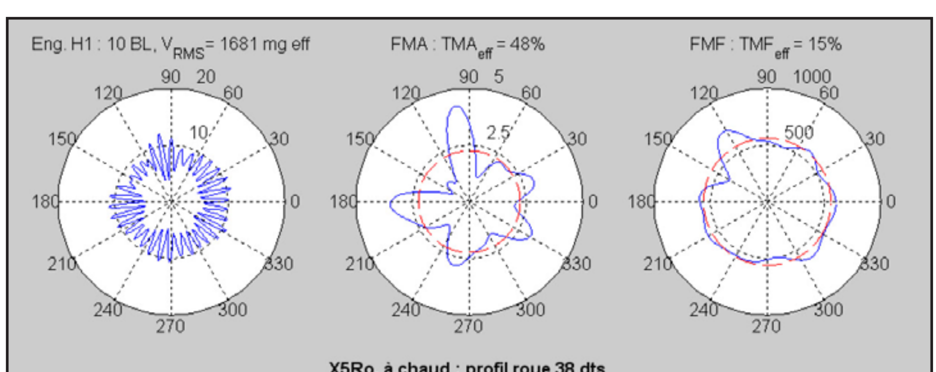

Figure 3 Synchronous averaged vibration profile of the high-speed gear with a cracked tooth.

tooth (the gearbox was to be replaced one month later). The synchronous time averaging technique applied to a vibration measurement performed on the gearbox clearly shows a strong, localized modulation of the associated profile of the 38-tooth, high-speed pinion (Fig. 3).

The three-phase stator current of the motor was also recorded. With the rotation frequency of the faulty gear being higher here (16.5Hz), the classic 50Hz demodulation technique will only give information on the 1× torque fluctuation, and not on the rapid torque variations within the rotation period. Therefore in this case the Park's vector approach will be used.

The three-phase stator currents i1-3(t) can be represented by a complex vector, also known as "space-vector" or Park's vector, defined as:

$$Ipark(t) = 2/3\,[i1(t) + a.i2(t) + a^2.i3(t)], \text{ with } a = \exp(j2\pi/3) \quad (5)$$

It can be shown that the modulus and phase of Park's vector correspond respectively to the instantaneous amplitude and phase modulations of each of the three-phase currents — regardless of modulation and carrier frequencies (Ref. 4). Thus by taking advantage of the three-phase current measurements, the Park's vector analysis allows quick implementation of the demodulation process in the event of a fast-modulated signal and thus to bypass the Bedrosian's conditions associated with the Hilbert transform.

Figure 4 shows the frequency spectrum of the Park's vector modulus. A few strong components can already be observed at 18× the motor speed and at 72× (this one probably corresponds to the slot frequency of the motor). The crosses positioned on the motor rotation harmonics indicate a few harmonics in the low-frequency range; yet note that the mesh frequency at 38× (623.3Hz) is barely visible here.

The Park's vector modulus was then synchronously averaged with the rotation speed of the motor. The result is shown (Fig. 5, left) where the 18× fluctuation is clearly visible. Note that this effect is likely due to the motor construction; for a 72-slot rotor we have

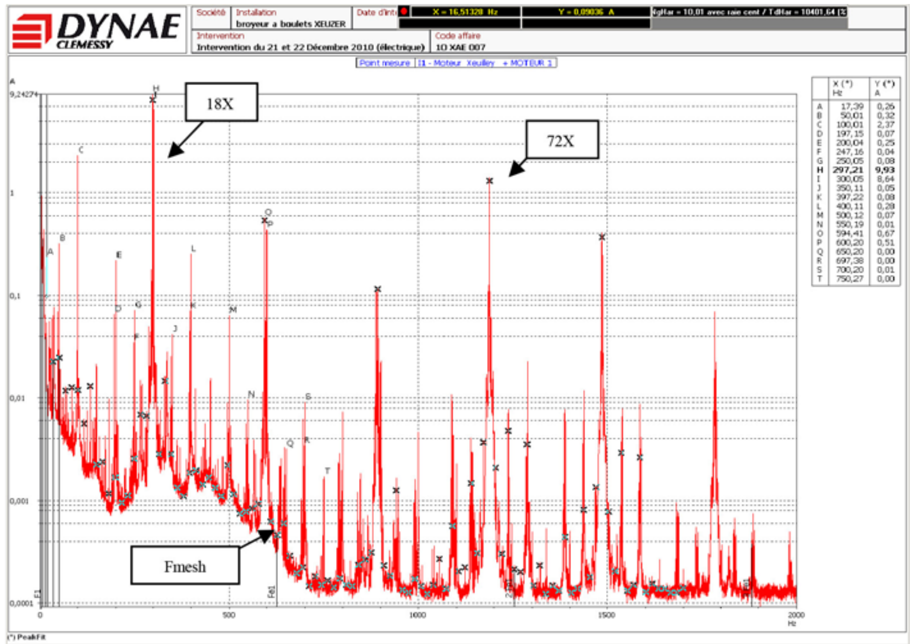

Figure 4 Spectrum of Park's vector modulus.

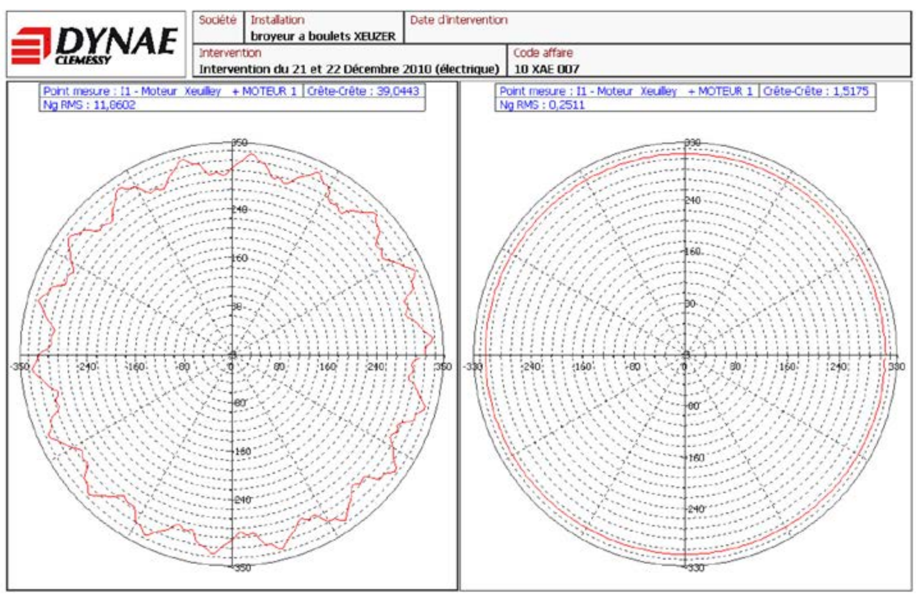

Figure 5 Averaged profile of Park's vector modulus (left); with 18× harmonics removed (right).

72/6/3 = 4 slots-per-pole and per-phase, which makes 18 groups of 4 slots. We also obtained exactly the same profile after the gearbox was changed. On Figure 5 (right) the 18× harmonics where removed: the profile does not indicate any fluctuation here. Therefore we may conclude that the motor does not "see" any torque fluctuation related to the cracked tooth on the high-speed pinion.

Nevertheless, the Park's vector may yet contain some valuable information; by comparing the spectrum low-frequency band before and after the change of the gearbox, we can see some changes, especially a torsional resonance located at 35Hz that has shifted at a lower frequency (32.5Hz) after the change. Note that as the motor coupling was also changed, this may correspond to the coupling torsional resonance (as the new coupling seems to have a lower stiffness).

This rather disappointing result can be explained by the fact that we are in a quite different configuration, as compared to the first case study — i.e., higher power and high-voltage motor, higher mechanical inertia, and higher

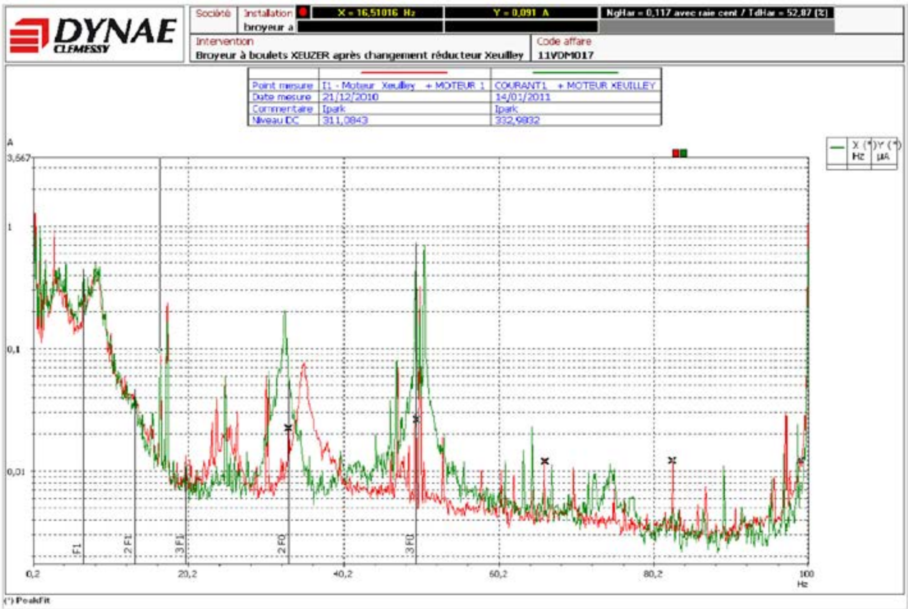

Figure 6 Comparison of the Park's vector low-frequency spectrum before (red), and after (green), the change of the gearbox and the motor coupling.

frequency of the induced torque fluctuation. Moreover, the chevron-type gears and the coupling may also have an influence by filtering out the torque fluctuations seen by the motor and reflected in the stator current.

Conclusions

It was the intent of this paper to demonstrate — with industrial applications as examples — the application of the stator current-based-techniques for the detection of small torque fluctuations such as those induced by gear faults in the driven gearbox.

Most of the literature on this subject reports successful detection, but fails to mention the limitations of the method in terms of mechanical parameters, which are:

- Moment of inertia
- Type of the motor and of the gears
- Effect of the coupling, frequency of the torque fluctuation (i.e. the rotation speed of the faulty gear)

We have shown in two examples that the influence on the stator current can be very different, depending on context. An interesting continuation of this work would consist of predicting the detection capabilities of the stator current-based techniques in each case, and based on better knowledge of the influence of each of the mechanical parameters. **PTE**

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François Combet completed his PhD thesis at Grenoble, France, on the subject of signal processing methods applied to cable transportation systems vibration modelling. He subsequently moved to the UK, taking a position as a Research Fellow at Cranfield University and working on various industrial projects related to gearbox fault diagnosis. Dr. Combet is currently working with DYNAE, a leading French company in the field of machinery diagnosis based on vibration and electrical measurements.