Gear fault diagnosis by motor current analysis – application to industrial cases

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Abstract

The use of motor current signature analysis (MCSA) for motor fault detection such as broken rotor bar is now well established, however the detection of mechanical faults related to the driven system is a more challenging task. Recently there has been a growing interest for the detection of gear faults by MCSA. Even if well adopted, the use of traditional vibration measurements can present several drawbacks: technical difficulties of access to the machine in some cases, influence of the transmission path and sensitivity to the sensor position. The motor supply current, being an image of the load torque, seems to be a relevant tool for the detection of local tooth faults, which will induce sharp variations of the mesh stiffness and consequently of the instantaneous torque. The use of one-phase stator current (1I) may be sufficient for some applications in case of a low rotation speed of the faulty gear. However in other cases the three-phase stator currents (3I) will be necessary in order to compute the Park's vector components, whose advantage is to bypass the demodulation step and the Bedrosian's conditions. The 1I current amplitude modulation function or the 3I Park's vector modulus may also be averaged on the gear rotation period in order to enhance the local tooth faults. Advantages and drawbacks of these techniques are presented and discussed on a few industrial cases.

1 Introduction

The use of motor current signature analysis (MCSA) for fault detection has received a growing attention in the recent past years. Electrical current analysis is a very useful tool for the diagnosis of faults inducing torque or speed fluctuations, and ideally completes vibration analysis [1]. First works were focussed on motor fault diagnosis such as broken rotor bars or eccentricity faults [2]. Recent works are considering more challenging faults such as bearing faults [3-4] or even gear faults in the driven gearbox [5-7]. This task is of great interest in applications where the mechanical system is not easily accessible for traditional vibration measurements, eg. in the nuclear industry.

In [5] authors propose a theoretical model based on Kron's transform, which leads to an equivalent two-phase machine from the initial three-phase motor (also known as Park's transform). 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 varying because the number of meshing teeth is periodically varying. Moreover when a faulty tooth is coming into mesh the stiffness is dropping suddenly, thus inducing a sudden reduction of the load torque and consequently of the current space-vector amplitude. The resulting theoretical current spectrum should then display harmonic components spaced buy the rotation speed of the faulty gear on the whole frequency range [3].

In [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 benchs with low power motors and low inertia. This is relatively far from industrial systems, which are mostly of higher power and with higher inertia. So far there has been very few works, to our knowledge, which showed the application of the MCSA-based techniques to large induction motors, and these studies are concerned with motor faults only [2]. Moreover, no work really mentioned what are the limitations 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. Moreover in practice the current spectral signature is polluted by high frequency components (rotor slots components and harmonics of the supply frequency) which add a difficulty in the diagnosis.

In this paper we will attempt to apply the MCSA-based techniques for the detection of gear faults based on industrial case studies. The use of one-phase stator current (1I) may be sufficient in case of a low rotation speed of the faulty gear. However in other cases the three-phase stator currents (3I) 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.

2 Effect of a small torque variation on the stator current

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

$$J\, d\Omega/dt = \Gamma e - \Gamma load \qquad (1)$$

with J the total moment of inertia of the system, Ω the rotational speed of the motor (we will consider here only one shaft for simplicity), Γe the electro-mechanical torque of the motor and $\Gamma load$ the 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 can be linearized as

$$\Gamma e = Km*s = Km*(\Omega s-\Omega)/\Omega s \qquad (2)$$

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, we obtain from (1) and (2)

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

so:

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

Therefore the effect on the speed variation $\delta\Omega$ will be reduced when :

- the moment of inertia J of the system is important,
- the time interval δt of the torque variation is small, i.e. the torque variation is high frequency,
- the constant Km of the motor is high (note that this constant depends on the motor supply voltage and will be higher for a high voltage motor).

The stator current of the motor being directly linked to the motor torque Γe, which is itself dependent on the speed from equation (2), the induced current variation δI will follow that of $\delta\Omega$. Moreover other parameters will also have an effect on the motor torque variations : the type of gears which will influence the mesh stiffness due to the variation of the number of teeth in contact, the type of the mechanical coupling of the motor which 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 behaviours depending on the system under analysis.

3 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 analysed 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 be applied in order to enhance the local tooth faults [6,7].

3.1 Gear fault detection in a paper making machine

This application deals with the diagnosis of local gear faults in a drying roll section of a paper making machine, by means of electrical current analysis. The system is composed of a low voltage AC motor (30kW, 1480rpm) 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 4 stronger peaks (Fig. 1) which seem to indicate local tooth faults on the main geared roll. Indeed, when dismantling the gear at the inspection the operator literally observed 'several falling teeth'.

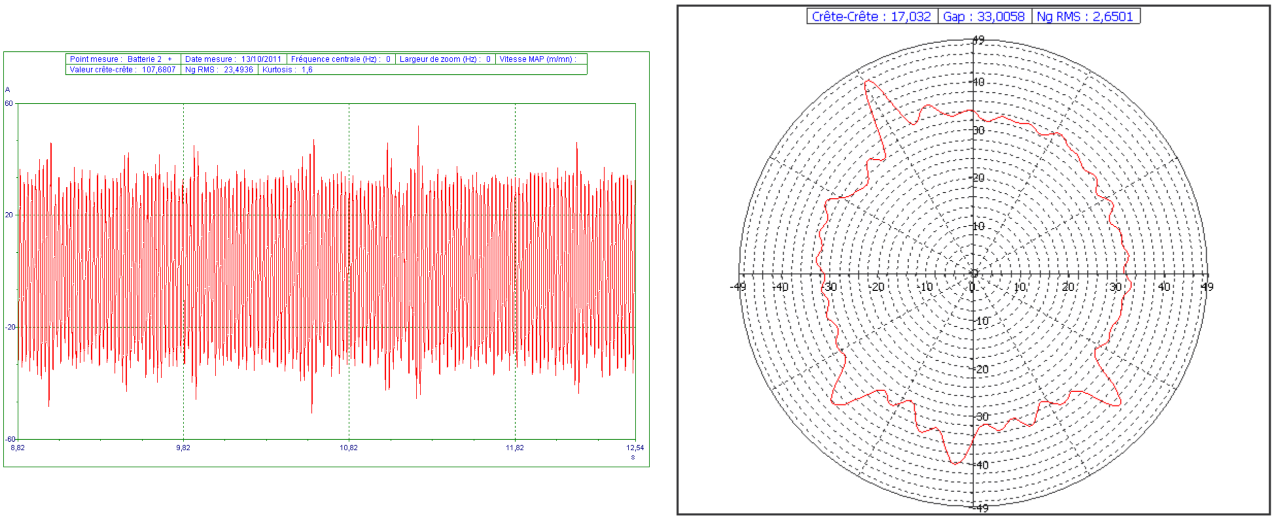

Fig. 1 : stator current signal (left) and AMF profile averaged over the rotation period of the geared roll (right)

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). The moment of inertia of the rolls is relatively high, however that of the driving system (medium size motor, small reduction gearbox and output pinion) is relatively small. Thus we satisfy here the above conditions for the detection of torque fluctuations via stator current analysis.

3.2 Gear fault in a ball mill machine

This application deals with a ball mill machine driven by two AC motors, each through a 2-stage reduction gearbox. Motors are 2MW power, 5kV voltage and 1000rpm speed. The gears are chevron type.

Fig.2 : reduction gearbox and motor driving a ball mill

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

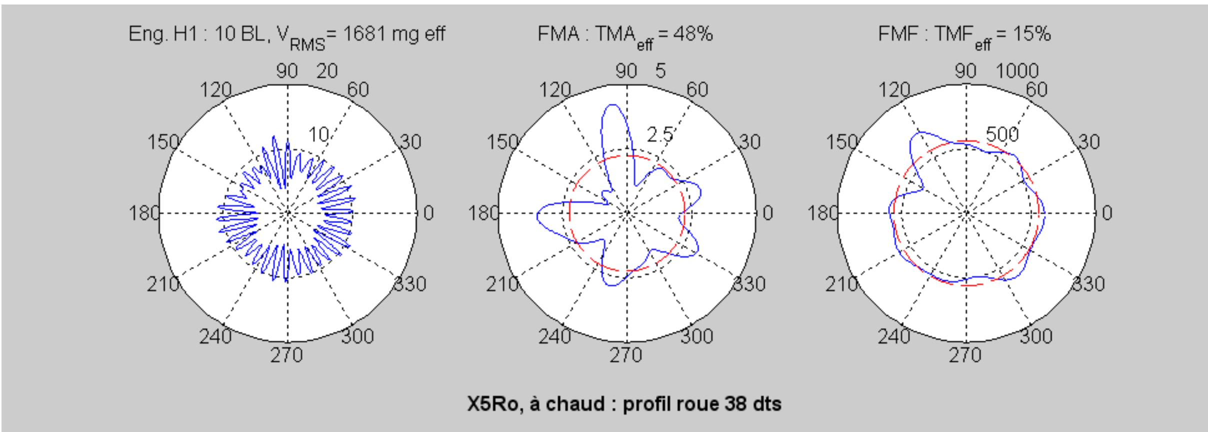

Fig. 3 : synchronous averaged vibration profile of the high speed gear with a cracked tooth

The 3 phase stator current of the motor were also recorded. The rotation frequency of the faulty gear being higher here (16.5Hz) the classic 50Hz demodulation technique will only give information on the 1X torque fluctuation but not on the rapid torque variations within the rotation period. Therefore in this case the Park's vector approach may 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:

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

It can be shown that the modulus and the phase of the Park's vector correspond respectively to the instantaneous amplitude and phase modulations of each of the three-phase currents, whatever the modulation and carrier frequencies [4]. Thus, by taking advantage of the three-phase current measurements, the Park's vector analysis allows to perform the demodulation process in case of a fast modulated signal and to bypass the Bedrosian's conditions associated with the Hilbert transform.

Fig. 4 shows the frequency spectrum of the Park's vector modulus. A few strong components can already be observed at 18X the motor speed and at 72X (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, however the mesh frequency at 38X (623.3Hz) is hardly visible here.

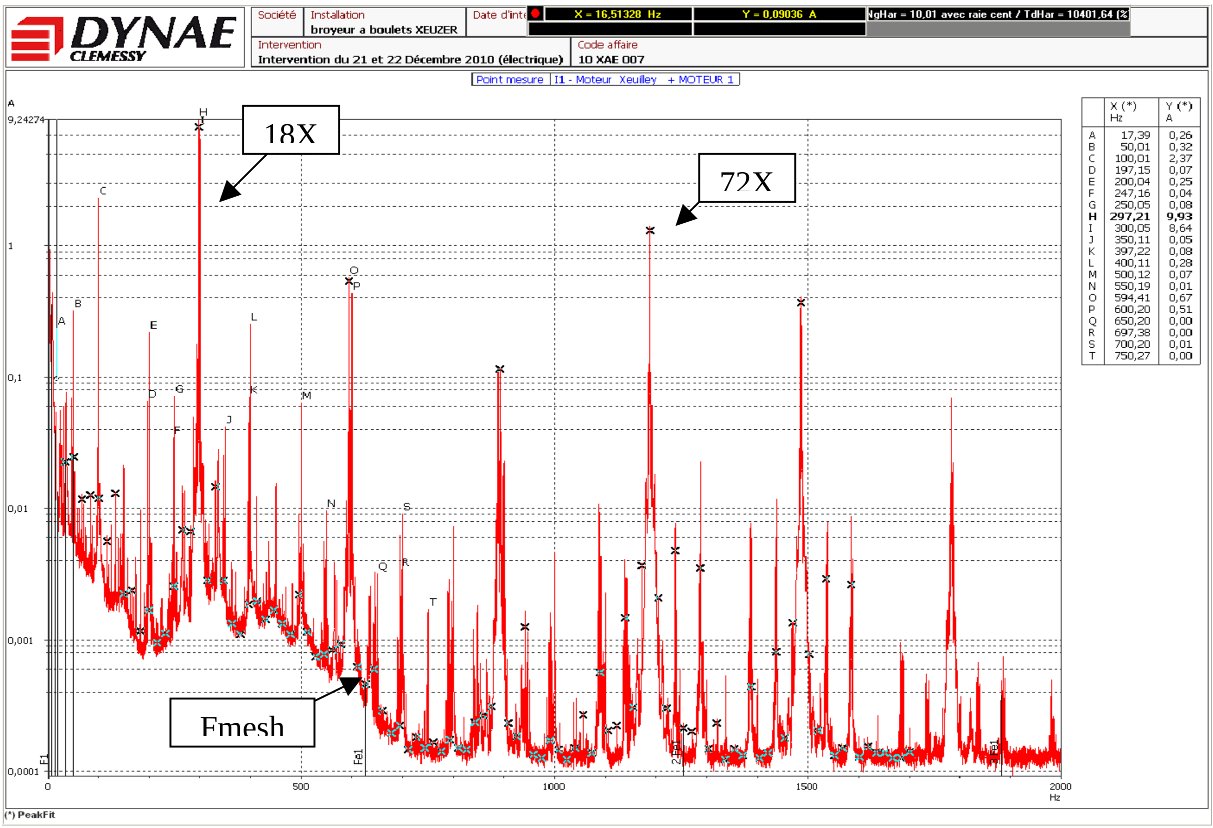

Fig. 4 : Spectrum of Park's vector modulus

The Park's vector modulus was then synchronously averaged with the rotation speed of the motor. The result is shown on fig. 5 (left) where the 18X fluctuation is clearly visible. Note that this effect is likely due to the motor construction: for a 72 slot rotor we have 72/6/3 = 4 slots per pole and per phase, which makes 18 groups of 4 slots. We also obtain exactly the same profile after the gearbox was changed. On fig.5 (right) the 18X 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.

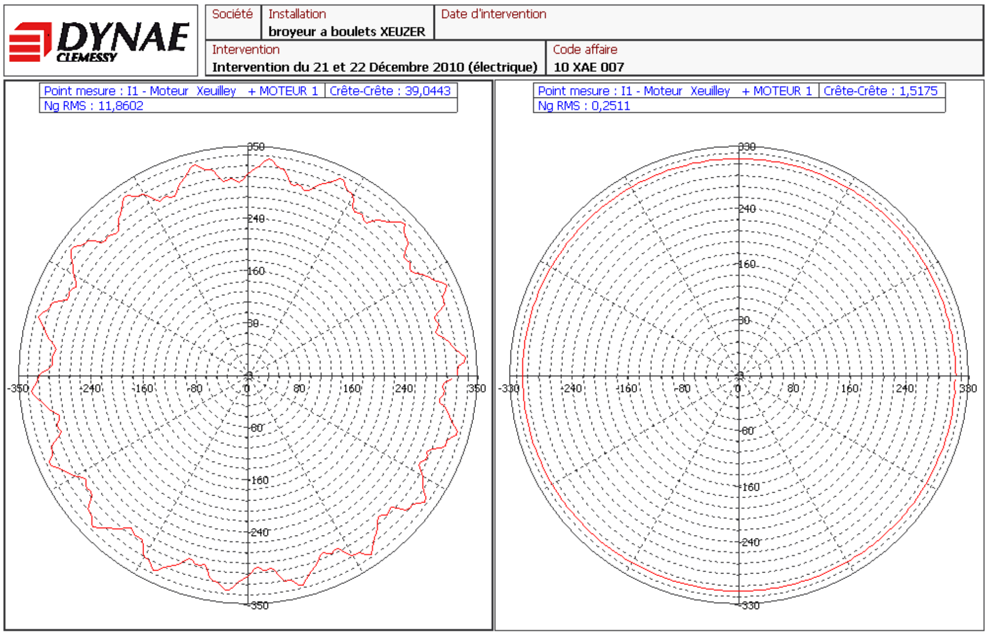

Fig. 5 : Averaged profile of Park's vector modulus (left), with 18X harmonics removed (right)

Nevertheless, the Park's vector can still 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 is shifted at a lower frequency (32.5Hz) after the change. Note that as the motor coupling was also change, this may correspond to the coupling torsional resonance (the new coupling seem to have a lower stiffness).

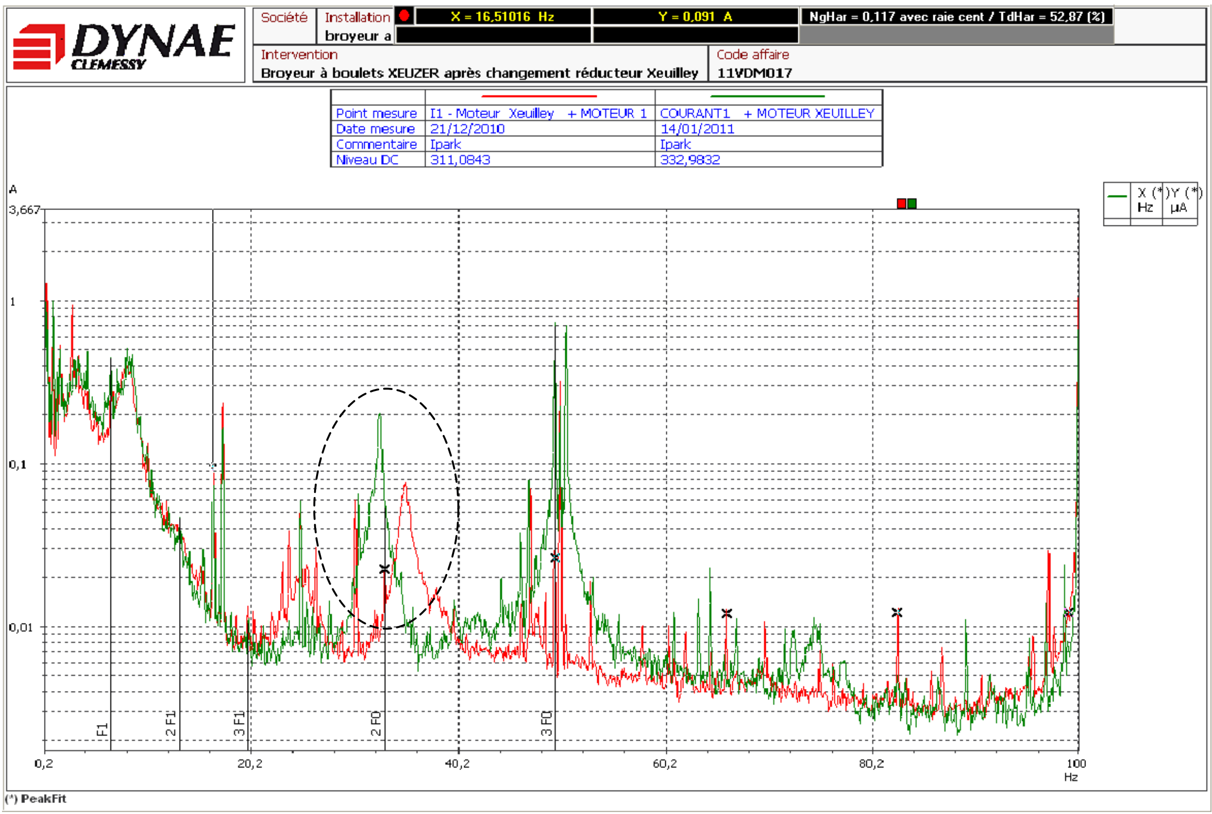

Fig. 6 : comparison of the Park's vector low frequency spectrum before (red) and after (green) the change of the gearbox and the motor coupling

This rather disappointing result can be explained as we are in quite a different configuration compared to the first case study: higher power and high voltage motor, higher mechanical inertia and higher frequency of the induced torque fluctuation. Moreover the chevron type of the 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.

4 Conclusion

This paper aimed to show on industrial applications 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 litterature on this subject report a successful detection, however without mentionning the limitations of the method in terms of mechanical parameters: moment of inertia, type of the motor and of the gears, effect of the coupling, frequency of the torque fluctuation (ie. the rotation speed of the faulty gear). We have shown on two examples that the influence on the stator current can be very different depending on the context. An interesting extension of this work would consist in predicting the detection capabilities of the stator current based techniques in each case based on a better knowledge of the influence of each of the mechanical parameters.

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