Fault Detection of Gearbox from Inverter Signals Using Advanced Signal Processing Techniques

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Abstract. The gear faults are time-localized transient events so time-frequency analysis techniques (such as the Short-Time Fourier Transform, Wavelet Transform, motor current signature analysis) are widely used to deal with non-stationary and nonlinear signals. Newly developed signal processing techniques (such as empirical mode decomposition and Teager Kaiser Energy Operator) enabled the recognition of the vibration modes that coexist in the system, and to have a better understanding of the nature of the fault information contained in the vibration signal. However these methods require a lot of computational power so this paper presents a novel approach of gearbox fault detection using the inverter signals to monitor the load, rather than the motor current. The proposed technique could be used for continuous monitoring as well as on-line damage detection systems for gearbox maintenance.

1. Introduction

Gears are important elements in a variety of industrial applications and unexpected failures of the gear may cause significant economic losses. Many methods based on vibration signal analysis have been widely used in the fault detection of rotation machinery such as power spectrum estimation, FFT, cepstrum analysis and envelope spectrum analysis, etc. However, these methods are based on the assumption of stationarity and linearity of the vibration signal while gear faults are time-localized transient events. To deal with non-stationary and nonlinear signals, time-frequency analysis techniques such as the Short-Time Fourier Transform [1], Wavelet Transform [2], motor current signature analysis (MCSA) [3] are widely used.

Treetrong [4] developed a new technique of parameter estimation using Genetic Algorithms so the MCSA signals can be used for the condition monitoring of electric motor drives without being necessary to be physically measured. This parameter identification method would have to work from available data (such as stator voltages, currents and the rotor speed) collected easily from the motor’s power supply. Induction motor parameter estimation using the GA technique minimised the difference between the measured and predicted state variables for the motor. The results from testing concluded that the new scheme can estimate the parameters and predict motor condition with sufficient accuracy for motor fault diagnosis. It was found that the method can not only detect the faults, but can also quantify how many faults are occurring in the induction motor.

Chinmaya et al. [5] applied MCSA method for fault diagnosis in a multistage gearbox under with simultaneous presence of transient loads and defects. The test rig had an induction motor driving the multistage gearbox and a DC generator for loading purposes. The gearbox vibration transients and the induction motor current transients were studied using advanced signal processing techniques such as discrete wavelet transform (DWT). The vibration transients showed that the load removal was a high-frequency phenomenon (the defective gear mesh frequency gains energy and large impact energy appears in low-frequency regions when the defect severity increased). The current transients showed that the load removal was a low-frequency phenomenon (a very small transient occurred at high-frequency regions for defective gears and the energy was distributed to the sidebands of the gear mesh frequency across supply line frequency when the defect severity increased). A corrected multiresolution Fourier transform (MFT) was applied to both vibration and current transients, mapping the energy level of different frequencies at a particular frequency bandwidth, in order to distinguish various faults in gears undergoing fluctuation in loads.

Günal et al [6] performed the condition monitoring of the induction motor using the Notch-Filtered Motor Current Analysis (NFMCSA) method. The main motor fundamental frequency of 50Hz (Europe) was notch-filtered out before being fed into the fault detection process. The reasoning behind this method was that the spectral components of motor current (other than the fundamental component) carry required information for fault detection and it is easier to interpret this data once the fundamental component had been removed. The experimental verification of the proposed features and classifiers revealed that NFMCSA approach is a promising analysis especially considering the fact that high classification accuracy can be achieved even in case of structurally different machines with numerous different faults under varying motor load conditions.

Research undertaken by F. Gu et al [7] involved the use of induction motor current feedback signals to identify and quantify common faults within a two-stage reciprocating compressor based on bispectrum analysis. This theoretical basis is developed to understand the non-linear characteristics of current signals when the motor is driving a varying load under different faulty conditions. This work provides a novel approach to the analysis of stator current for the diagnosis of motor drive faults from downstream driving equipment and it was proved that the bispectrum feature gives rise to reliable fault classification results using non-intrusive methods.

Benbouzid et al [8] proposed to use advanced signal processing techniques on the stator motor current signals instead. In their investigations, the frequency signature of some asymmetrical motor faults was identified using advanced signal processing techniques such as high-resolution spectral analysis. Initial experimental results clearly illustrated that stator current high-resolution spectral analysis is very sensitive to induction motor faults that modify the main spectral components, such as voltage unbalance and single-phasing effects. Experimental results demonstrated that the stator current high-resolution spectral analysis – proposed as a medium for induction motors faults detection – has definite advantages over the traditionally used FFT spectral analysis. Generally, this technique will be useful in detecting other fault conditions that modify the main spectral component signals.

Newly developed signal processing techniques such as empirical mode decomposition and Teager Kaiser Energy Operator [9] enabled the recognition of the vibration modes that coexist in the system, and to have a better understanding of the nature of the fault information contained in vibration signals.

However these methods require a lot of computational power so this paper presents a novel approach of gearbox fault detection using the inverter signals to monitor the load, rather than the motor current. Faults were implemented on the motor gearbox fitted to the test rig and the experimental data was compared between healthy and faulty gearboxes so this is a model-based approach. A data acquisition system was used to measure the armature current in DC motor (load), speed and torque feedback signals for AC motor (actuator) and speed demand for the inverter. The comparison between measured signals for healthy and faulty gearboxes showed that the actuator can be used as a transducer for detecting electrical and electromechanical faults on an inverter-driven motor system. Several MATLAB programs implementing algorithms for advanced data analysis have been produced by the authors. Time Synchronous Average technique and normalised data analysis method were used for the comparison of measured torque and actual current feedback signals for healthy and faulty gear sets and evident differences were visible.

2. Fault diagnosis of experimental inverter-driven motor system

A fault is implemented on the motor gearbox fitted to the test rig (see Figure 1) and the experimental data is compared between healthy and faulty gearbox. These tests take the form of a model-based approach, whereby a healthy system is first tested and used as a baseline for the results. Testing on faulty system is hoped to reveal differences in the model data compared to the actual faulty data.

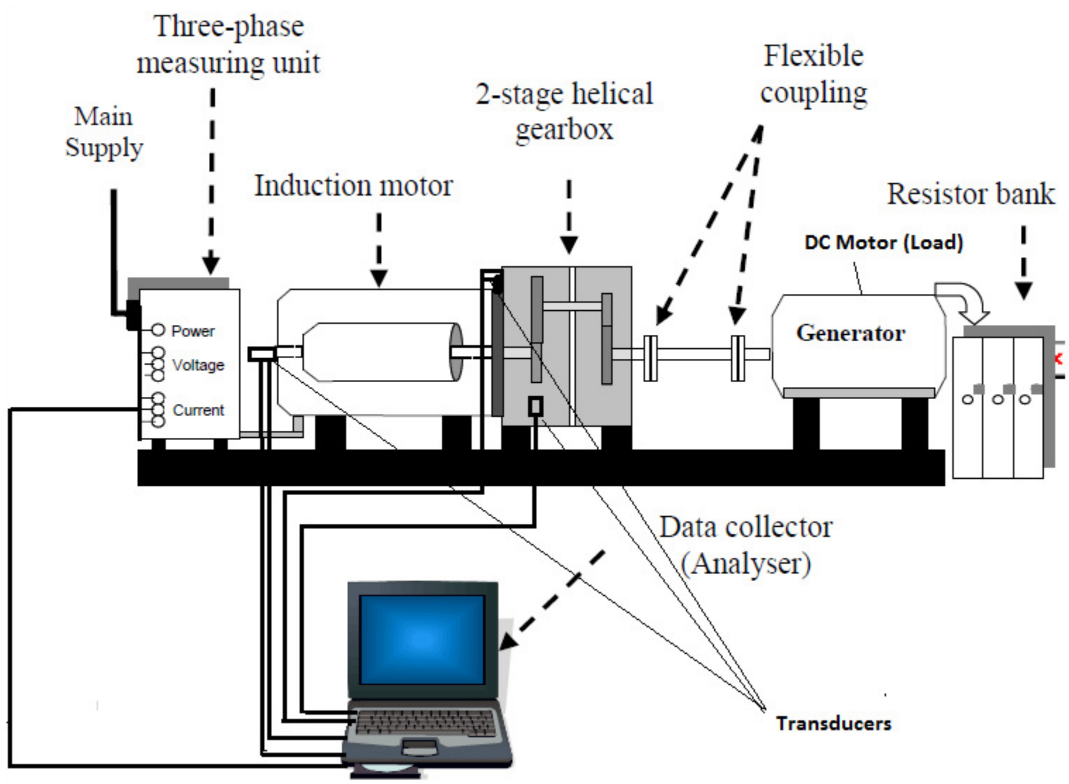


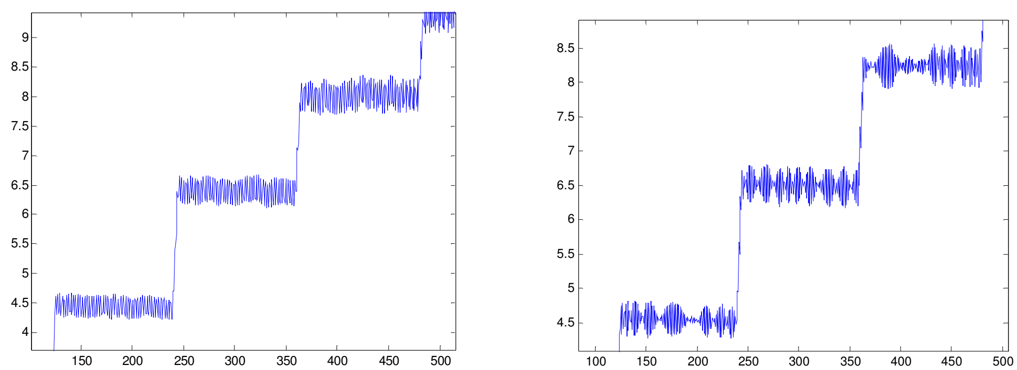
Figure 1. Experimental gearbox test rig.

The motor current and voltage in each phase are measured using a PCB-mounted hall-effect current transformer. A measured value for the current in each line is fed into the DAQ unit, which converts this into a voltage measurement, provides appropriate filtering and anti-aliasing, and feeds the signals to the data collection channel of a data collector / analyser. Thus, this unit can be used to measure the instantaneous current in each of the three phases, the instantaneous voltage of each of the three phases and the instantaneous electrical power supplied by each of the three phases.

Two sets of tests are performed for the healthy gearbox and another two sets of tests are done for faulty gearbox in order to check the repeatability and reliability of the measurement procedures.

The following variables are measured for the healthy gearbox: DC motor armature current; load set; AC motor speed feedback; AC motor torque feedback; AC motor current; AC motor speed demand. The same variables are measured after the fault (introducing a break in tooth number 47 from the gearbox primary drive set) and the results are included in [10]. The experimental data show that the torque feedback from the drive with the faulty gear is higher than the torque feedback of the healthy set which it is expected because it is necessary to produce more work to overcome this defect. Also the torque demand and the motor current value are higher once the load setpoint has changed, gradually dropping off as the test rig stabilises. The motor speed feedback remains constant throughout the range of loads applied.

Figure 2 shows the comparison between the actual AC motor phase currents for the healthy gearbox and faulty gearbox. Torque pulsations from Figure 2b have a different pattern than those from Figure 2a as expected. These pulses can last between 20 and 5 second periods and there are no such oscillations observed on the healthy gear set. One suggestion is that these pulses can occur on a system that is 'under-damped' in terms of gain values applied to the speed or current loop. As the faulty gear rotates, there is potential for greater backlash in the gearbox and this will reduce the damping effect of the load that the motor is driving, the result being an oscillation in the drive speed loop and therefore the current demand to the motor.



(a) healthy gearbox **(b)** faulty gearbox

Figure 2. Comparison between the actual AC motor phase currents.

The sampling rate of the DAQ system limits the examination to a time-domain analysis – the rate is too low to allow FFT to be performed and a frequency analysis to be performed.

The comparison between measured current signals for healthy and faulty gearbox is showing that the AC motor (actuator) can be used as a transducer for detecting electrical and electromechanical faults on an inverter-driven motor system. The next step was to analyse in more depth the differences between the two sets of measured data and the next section is explaining this approach.

3. Advanced data analysis of the experimental results

Several Matlab programs implementing algorithms for advanced data analysis have been produced by the researchers from Diagnostic Engineering Research Centre within the University of Huddersfield. Time Synchronous Average technique and normalised data analysis method are used for the comparison of measured torque and actual current feedback signals. Figure 3 shows the results for the comparison of measured torque feedback values between the healthy and faulty gear set. The following steps have been taken:

1. A simple subtraction of torque feedback is taken between the values from each set over time;
2. The root-mean-squared value of differences in the % torque feedback is calculated at each data points to measure the difference;
3. The difference is normalised by nominal current to remove the effect of load settings

It is visible in Figure 3 that the normalised data set (bottom) shows that the error percentage stays the same at each load level, whilst the non-normalised data (middle) naturally gives a higher % difference at higher values of torque, as this is where the greatest difference in values occurs. RMS (Root-Mean-Squared) values are used for the non-normalised data because the peak deviation between the measured signals is so high.

For a monitoring system that is to trigger faults from a percentage value difference being greater than a set threshold, then the normalised data analysis method is preferred. There will be no requirement to modify the threshold value as the value of torque feedback increases because the data is normalised dynamically to the healthy data set. If both data sets were from healthy gearboxes, one would expect the points at each load setting to be grouped closer together to form a circle pattern, rather than a line.

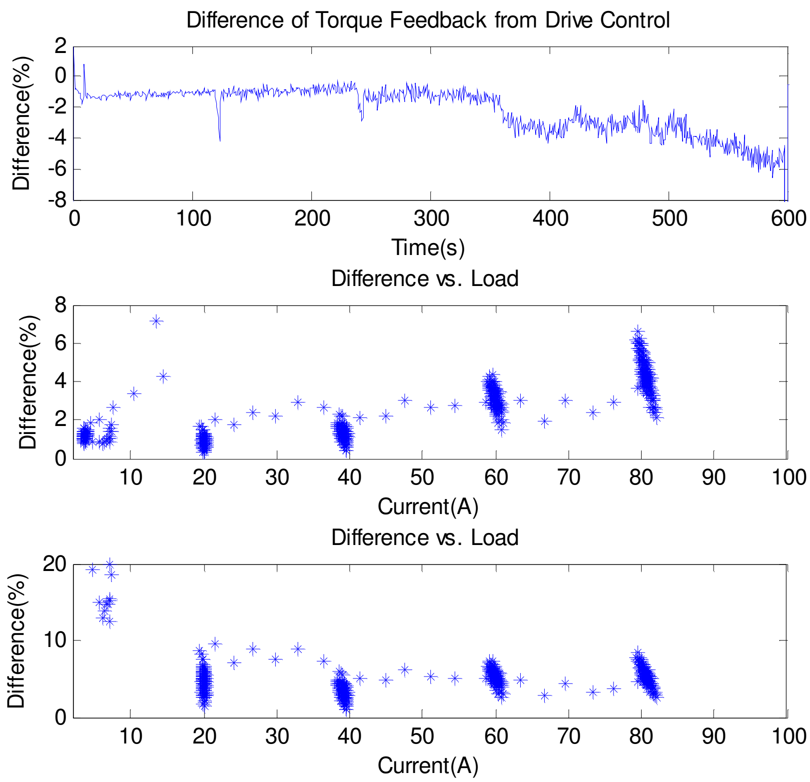


Figure 3. Comparison of torque feedback values for the healthy and faulty gear sets.

Figure 4 shows the comparison of measured actual current feedback between the healthy and faulty gear sets after following the three steps mentioned above. The grouping of this data is more spread-out at each load, but it must be considered that the actual current value is non-sinusoidal coming from the PWM drive and the X-axis data spread is due to the fluctuations in currents measured as the drive switches and these fluctuations are not 'in-phase' from one test run to the next. If one tries and subtracts one current signal directly from the other, it becomes impossible to overlay the peaks of each signal exactly and that is where the wide data spread on the x-axis occurs.

However, by comparing the two results from Figure 3 and Figure 4 it can be seen that the drive torque output gives a sufficiently detailed signal to allow a comparison to be made between healthy and faulty gear sets from the torque signal obtained. This is important, as it may be possible to perform additional data analysis on the signals output from a standard inverter drive. The inverter drive uses a 32-bit microprocessor which relies on accurate current and voltage signals being measured by the drives own instruments. These signals may lose some resolution before being fed out to the drive analogue outputs, but sufficient resolution may be retained.

The inverter drive signals have provided sufficient information to allow a difference between healthy and faulty gear sets to be observed so that there is good potential in using the inverter signals to detect downstream mechanical faults within electrical drives.

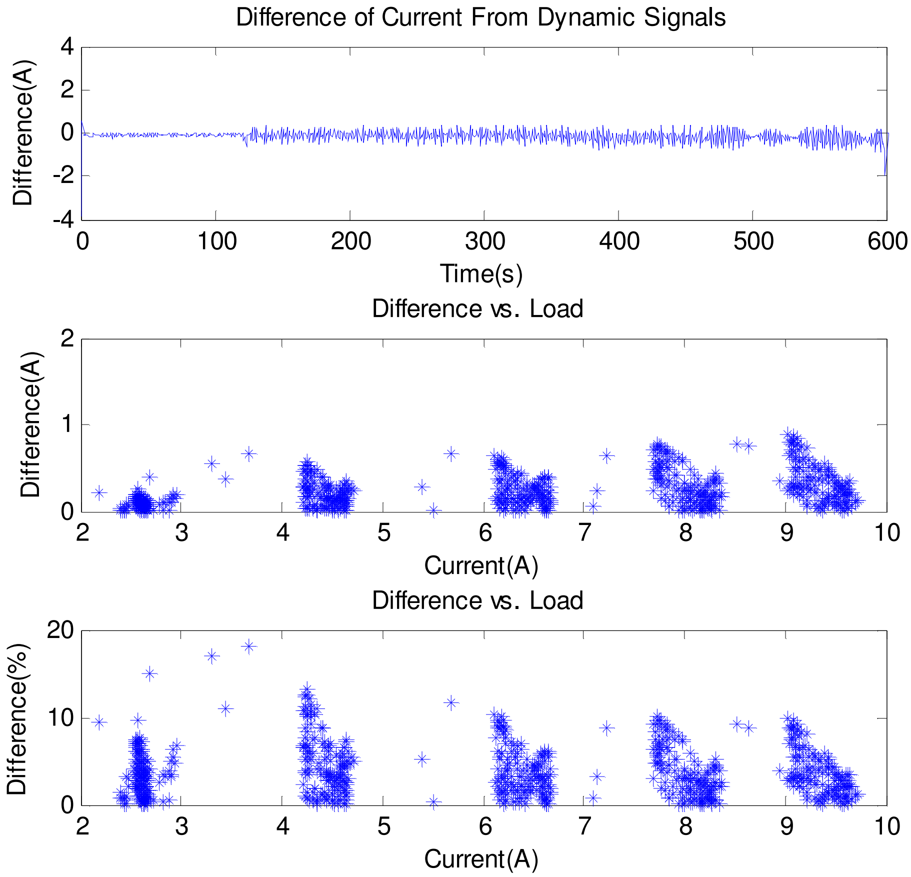


Figure 4. Comparison between actual motor current signals for healthy and faulty gears.

4. Conclusions

This paper presents a novel approach of gearbox fault detection using the inverter signals to monitor the load, rather than the motor current. More recent techniques for gear fault detection enable the recognition of the vibration modes that coexist in the drive system but require a lot of computational power. Therefore the authors of this paper focused their research on using the motor current signals and torque feedback to identify faults in gears.

A model-based approach was applied so faults were implemented on the motor gearbox fitted to the test rig and the experimental data was compared between healthy and faulty gearboxes. The following variables were measured: the armature current in DC motor (load), speed and torque feedback signals for AC motor (actuator) and speed demand for the inverter. The comparison between measured signals for healthy and faulty gearboxes showed that the actuator can be used as a transducer for detecting electrical and electromechanical faults on an inverter-driven motor system. Time Synchronous Average technique and normalised data analysis method were used for the comparison of measured torque and actual current feedback signals for healthy and faulty gear sets and evident differences were visible.

Experimental results validate the effectiveness of this novel method which could be used for efficient continuous monitoring as well as on-line damage detection systems for gearbox maintenance.

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