

## A Real Time Condition Monitoring System for Gears Operating under Variable Load Conditions

Alwadie. A

Faculty of Engineering, Electrical Engineering Department, Najran University,  
King Abdulaziz Road, State Najran, Saudi Arabia

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### ABSTRACT

Gears are important component of the rotational power transmission system and are largely used in variable load and speed applications. The faults on the gear generate excessive vibration which leads to breakdown of the machine. Sensor based methods could diagnose gear faults but proved to be expensive and have limited applications due to heavy cost and need of access of gear box for sensor installation. The motor stator current analysis has been reported to overcome the drawbacks of the sensor based fault detection methods. However, motor stator current analysis has a limited capability for reliable detection of small gear fault signatures typically for low load conditions. This paper presents an alternative non-invasive approach based on instantaneous power analysis of the motor to reliably diagnose gear faults for variable load applications. The theoretical and experimental results indicates that the instantaneous power analysis offers three fault related harmonics and amplitude variations on these harmonics could give the indication of health status of the gear. The superiority of the proposed instantaneous power analysis technique has been confirmed through experiments performed on three operating points of the motor. The comparison of the amplitude sensitivity of the motor stator current and instantaneous power at three operating points has been performed to validate the superiority of the proposed technique.

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### Corresponding Author:

Alwadie. A,

Faculty of Engineering, Electrical Engineering Department, Najran University

King Abdulaziz Road, State Najran, Saudi Arabia

Email: alwadie@hotmail.com

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## 1. INTRODUCTION

The gears are the important component of the industrial facilities and are used in the machines for the rotational power transmission. The reliability and cost effective operation of industrial machines could be ensured through adoption of the proper condition monitoring technique [1-5]. The unexpected machine shutdowns and catastrophic failures could be avoided through continuous condition monitoring and fault diagnosis process. Many condition monitoring techniques such as vibration analysis, temperature analysis, sound analysis, acoustic emission, non-invasive motor stator current analysis have been reported in the literature [6-9]. Measurement method, cost of the sensors, installation of the sensors and reliability of the measured data are the important parameters in the selection of the proper condition monitoring technique [10-12].

Several studies have been conducted in the past to monitor the condition of the gear through vibration analysis technique [13-17]. Although vibration analysis have been shown to successfully diagnose the gear faults but it involves the huge cost of the accelerometers used for data collection and its use is limited where access to the gearbox is not possible for sensor installation [18-24]. The non-invasive motor stator current analysis has been proposed by few researchers to overcome the drawbacks associated with the

vibration analysis technique [25-27]. The stator current could be measured from the motor supply line and thus it does not require access to the gearbox. Although, motor stator current analysis technique is best alternative to vibration analysis technique for the development of an economical and versatile condition monitoring system, however, most of the researchers have used this method only on full load condition [28-30]. Hence, there is a need to explore the effectiveness of motor stator current analysis method to diagnose gear faults for variable loading points of the motor. Furthermore, the two fault related components produced by stator current spectrum appear near to fundamental component and amplitude of these fault components is suppressed by the large amplitude of the fundamental component [31-33]. Thus, the reliable fault detection through motor stator current analysis is still a challenging issue in on-line condition monitoring applications.

Recently, some of the researchers have reported the use of instantaneous power signal (which takes the information from both the stator current and voltage) for the diagnosis of bearing faults. The experimental results have shown a better capability of detecting bearing faults through reported technique. However, theoretical and experimental investigations of instantaneous power for gear fault detection have never been performed in earlier research work [34, 35]. The main contributions of this paper are 1) Derivation of gear fault frequency model in variable loading conditions for instantaneous power spectra 2) Experimental confirmation of the derived gear fault frequency model 3) Comparison of the motor stator current analysis technique and instantaneous power analysis technique for reliable condition monitoring of gear faults specifically under variable load conditions.

The rest of the paper has been organized as follows: Section II derives the gear fault frequency model for instantaneous power spectra for variable load operations of the motor. Section III provides the design of the experimental test rig and data acquisition system. Section IV provides the spectra of the instantaneous power and motor stator current for healthy and faulty gear operating in variable load conditions. The comparison of the gear fault detection capabilities of the motor stator current analysis technique and instantaneous power analysis technique has also been given in this section. Finally, Section V presents the conclusion of this paper.

## 2. THE MATHEMATICAL MODEL OF THE STATOR CURRENT AND INSTANTANEOUS POWER FOR GEAR CONDITION MONITORING

Stator current of the motor with healthy gear connected on the shaft does not contain side bands of the gear defect frequencies. However, during the faulty gear, lower side band and upper side band harmonics are appeared around the fundamental frequency of the current, as described in Equation (1). The gear fault frequencies have been calculated using Equation (2) and are shown in Table 1.

$$I(t) = I_0(t) + ml_0(t) \cos[2\pi(f_s \pm f_g)t - \alpha_0] \quad (1)$$

$$f_{es} = |f_s \pm f_g|, \begin{cases} f_e - f_g & \text{Lower Side Band} \\ f_s + f_g & \text{Upper Side Band} \end{cases} \quad (2)$$

where:

- $f_g$ , is the gear characteristic defect frequency
- $I_0(t)$ , is the current in the motor for healthy gear.
- $I(t)$ , is the current in the motor for faulty gear.
- $f_s$ , is the frequency of the supply current.
- $\alpha_0$ , is the load angle.

Table 1. Calculated Gear Fault Harmonics in Stator Current Spectra

Load Conditions	Motor Speed (rpm)	Lower Side Band (Hz)	Upper Side Band (Hz)
No Load	1485	25.2	74.8
Medium Load	1432	26.2	73.8
Full Load	1392	26.8	73.2

Whereas, for healthy gear, the instantaneous power of the motor could be described using Equation (3).

$$P_o(t) = V_0(t)I_0(t) \quad (3)$$

where:

- $P_o(t)$ , is the ideal instantaneous Power

$V_0(t)$ , is the instantaneous supply voltage  
 $I_0(t)$ , is the instantaneous supply current

When we replace the healthy gear with the defected gear, the motor shaft fluctuated due to effect of defected teeth. The symmetry of the electromagnetic flux between stator and rotor is disturbed due to these fluctuations of the shaft. The disturbed symmetry eventually creates side band harmonics around the fundamental frequency. These sideband harmonics are calculated using Equation (4) and (5) and are shown in Table 2.

$$P(t) = P_o(t) + mV_0(t)I(t)[\cos\{4\pi(f_s - f_g)t - \alpha_0 - \frac{\pi}{6}\} + \cos\{4\pi(f_s + f_g)t - \alpha_0 - \frac{\pi}{6}\} + 2\cos(\alpha_0 - \frac{\pi}{6})\cos(2\pi f_g t)] \quad (4)$$

$$f_{es} = |2f_s \pm f_g| \quad \left\{ \begin{array}{l} 2f_s - f_g \text{ Lower Side Band} \\ 2f_s + f_g \text{ Upper Side Band} \end{array} \right. \quad (5)$$

Table 2. Calculated Gear Fault Harmonics In Instantaneous Power Spectra

Load Conditions	Motor Speed (rpm)	$f_g$ (Hz)	Lower Side Band (Hz)	Upper Side Band (Hz)
No Load	1485	24.8	75.2	124.8
Medium Load	1432	23.8	76.2	123.8
Full Load	1392	23.2	76.8	123.2

It has been observed from Table I and II that the defect in gear causes motor current analysis produce two harmonics at lower sideband and upper sideband frequencies. While three harmonics are induced in instantaneous power spectrum at gear fault frequency ( $f_g$ ), lower sideband and upper sideband frequencies. Thus, the instantaneous power spectrum provides more harmonic components related to gear defect as compared to stator current analysis. This is the distinguish feature of the instantaneous power analysis for reliable fault diagnosis applications. These mathematical derivations are confirmed through experiments in the next section.

### 3. EXPERIMENTAL DESIGN

A test rig was designed to conduct the experiments of the healthy and faulty gears. The schematic diagram of the designed test rig has been shown in Figure 1. It consists of a current sensor (i5SPQ3), a voltage sensor (EVCC), a tachometer (R7050), LabVIEW, Data acquisition board (NI 6281), healthy gear assembly, faulty gear assembly and a three phase 1HP, 50 Hz, induction motor. Sampling rate was 10 kHz and frequency resolution of 0.2 Hz.

Single stage bevel gear assembly coupled with motor shaft was used in this study. The conically shaped rack and pinion gears are mounted on shafts that are 90 degrees apart. The pitch surface of bevel gears is a cone shape. The teeth of the gears are cut straight and are all parallel to the line pointing to the apex of the cone on which the teeth are based. In this work, the number of teeth of the pinion gear ( $T_1$ ) is 20 and number of teeth on the wheel gear ( $T_2$ ) is 30. The experiments were conducted on the healthy pinion gear, tooth damaged pinion gear, under three different loading conditions. The fault on gear tooth was created artificially using electric discharge machine (EDM). The healthy and defected gears are shown in Figure 2.

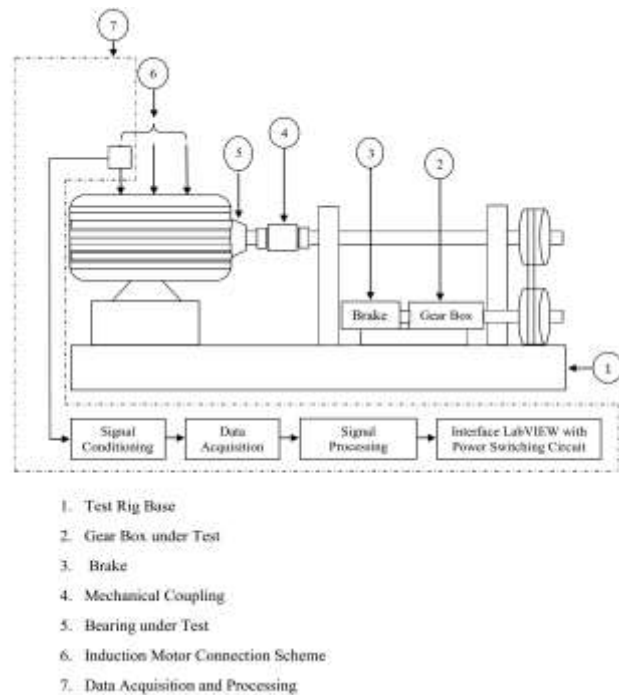


Figure 1. The Schematic Diagram of the Developed Set-Up



(a)



(b)

Figure 2. Gear Under Test (a) Healthy Gear (b) Fault Gear

## 4. RESULTS AND DISCUSSIONS

### 4.1 Case Study 1: Fault diagnosis of the gear through instantaneous power analysis

The normalized spectra of the instantaneous power for the healthy and faulty gear operating in variable load condition has been shown in in Figure 3 and 4 respectively. The instantaneous power spectra provides three fault related frequencies and the amplitude values on these fault frequencies are monitored and recorded. For example, the amplitude values are -71.98, -64.6 and -59.04 dB for healthy gear and -68.98, -61.55 and -56.1 dB for defected gear operating under no-load condition. Thus, a 3 dB change in amplitude values at gear fault frequencies occur due to fault in the gear. Similarly, a change of 6 dB and 13 dB has been observed at medium load and full-load condition. The summary of the amplitude variations at gear defect frequencies has been given in Table 3.

Table 3. Summary of the Amplitude Variations for Helthy and Faulty Gear in Instantaneous Power Spectra

Operating Point	Amplitude Values for Healthy Gear (dB)	Amplitude Values for Faulty Gear (dB)	Difference in Amplitude (dB)
No Load	-71.98	-68.98	3
Medium Load	-87.54	-81.01	6
Full Load	-72.48	-59.2	13.28

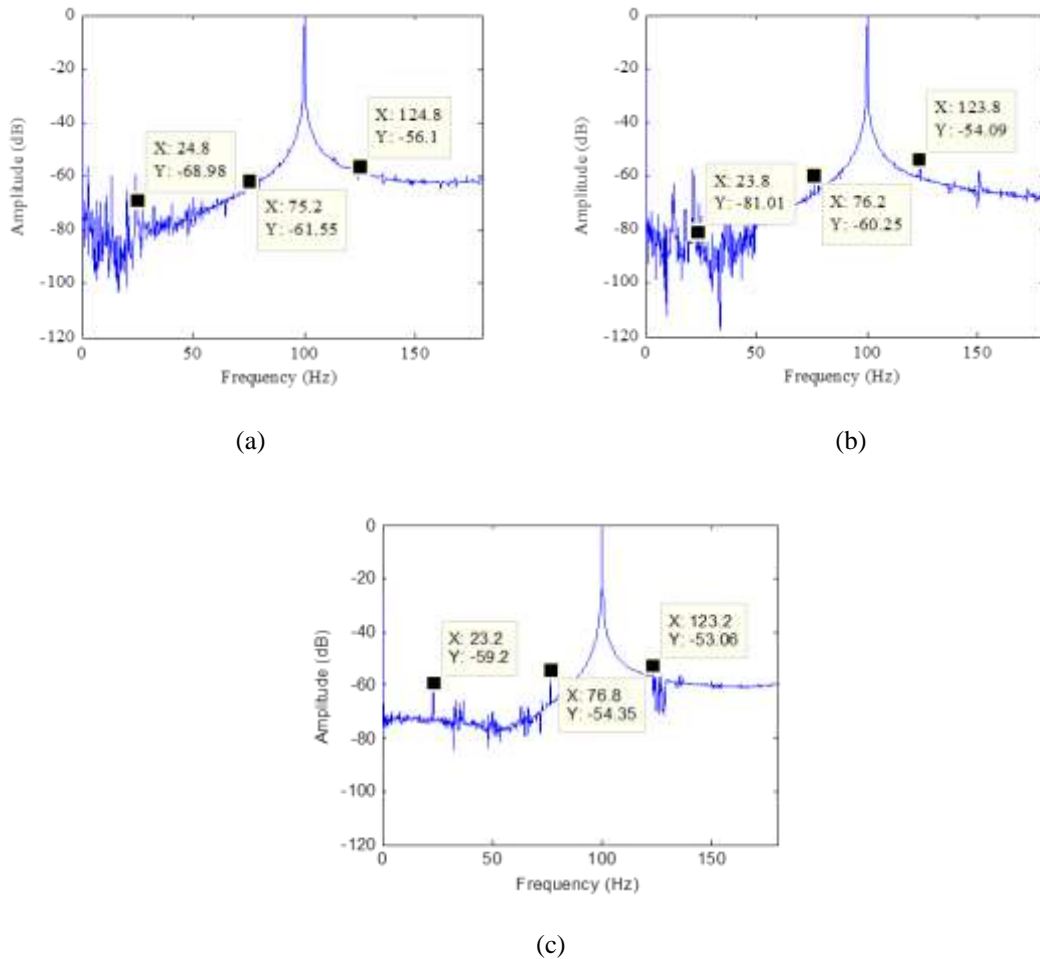


Figure 4. The Instantaneous Power Spectra of the Faulty Gear for Three Operating Points (a) No Load (b) Medium Load (c) Full Load

**4.2 Case study 2: Fault diagnosis of the gear through motor stator current analysis**

As described earlier, the gear faults has been investigated in various studies through motor stator current analysis under full load conditions. However, the use of motor stator current analysis for gear faults detection in variable loading conditions has never been investigated in previous studies. While this paper has considered three different loading conditions to investigate the gear faults via motor stator current analysis.

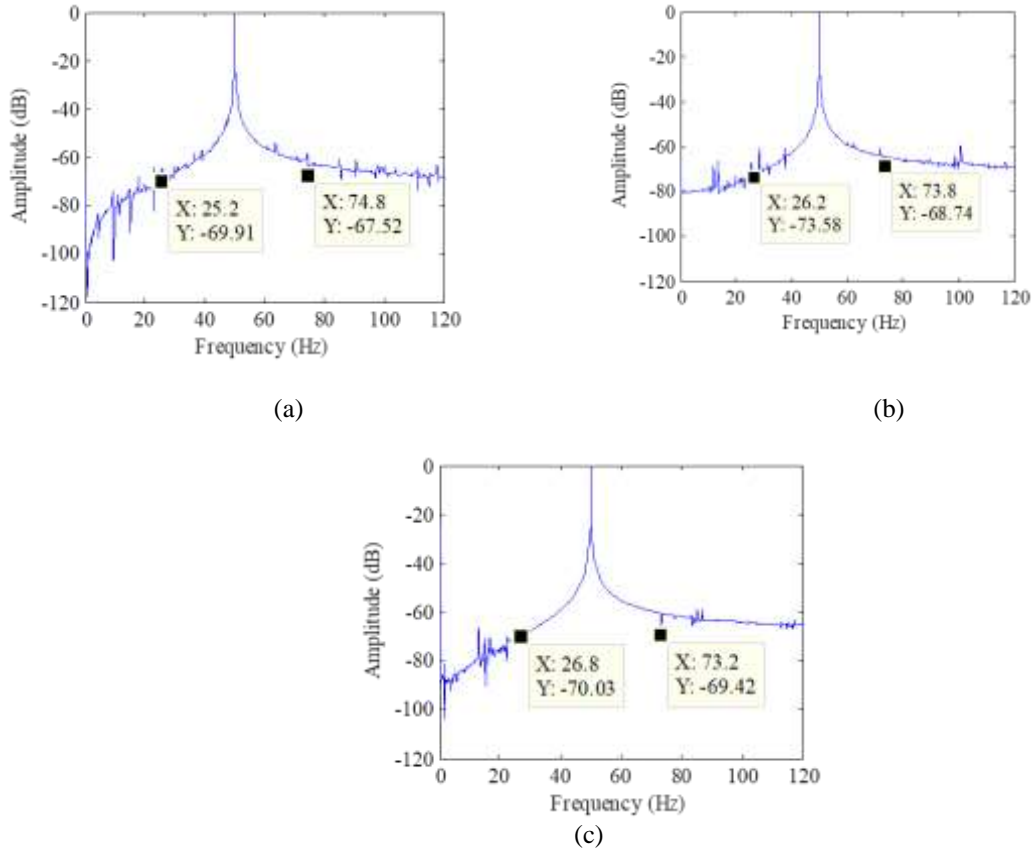


Figure 5. The Motor Stator Current Spectra of the Healthy Gear for Three Operating Points (a) No Load (b) Medium Load (c) Full Load

The normalized spectra of the motor stator current for the healthy and defected gear operating in variable load condition has been shown in in Figure 5 and 6 respectively. The motor stator current spectra provides two fault related frequencies and the amplitude values on these fault frequencies are monitored and recorded. For example, the amplitude values are -69.91 and -67.52 dB for healthy gear and -68.91, -66.53 dB for defected gear operating under no-load condition. Thus, a 1 dB change in amplitude values at gear fault frequencies occur due to fault in the gear. Similarly, a change of 3 dB and 7 dB has been observed at medium load and full-load condition. The summary of the amplitude variations at gear defect frequencies has been given in Table 4

Table 4. Summary Of The Amplitude Variations For Helthy And Faulty Gear In Stator Current Spectra

Operating Point	Amplitude Values for Healthy Gear (dB)	Amplitude Values for Faulty Gear (dB)	Difference in Amplitude (dB)
No Load	-69.91	-68.91	1
Medium Load	-73.58	-70.01	3
Full Load	-70.03	-63.04	7

It has been concluded from Table IV that the diagnosis of the gear faults through non-invasive motor stator current analysis is sensitive to the operating point of the motor and this technique gives better results only at full loading condition.

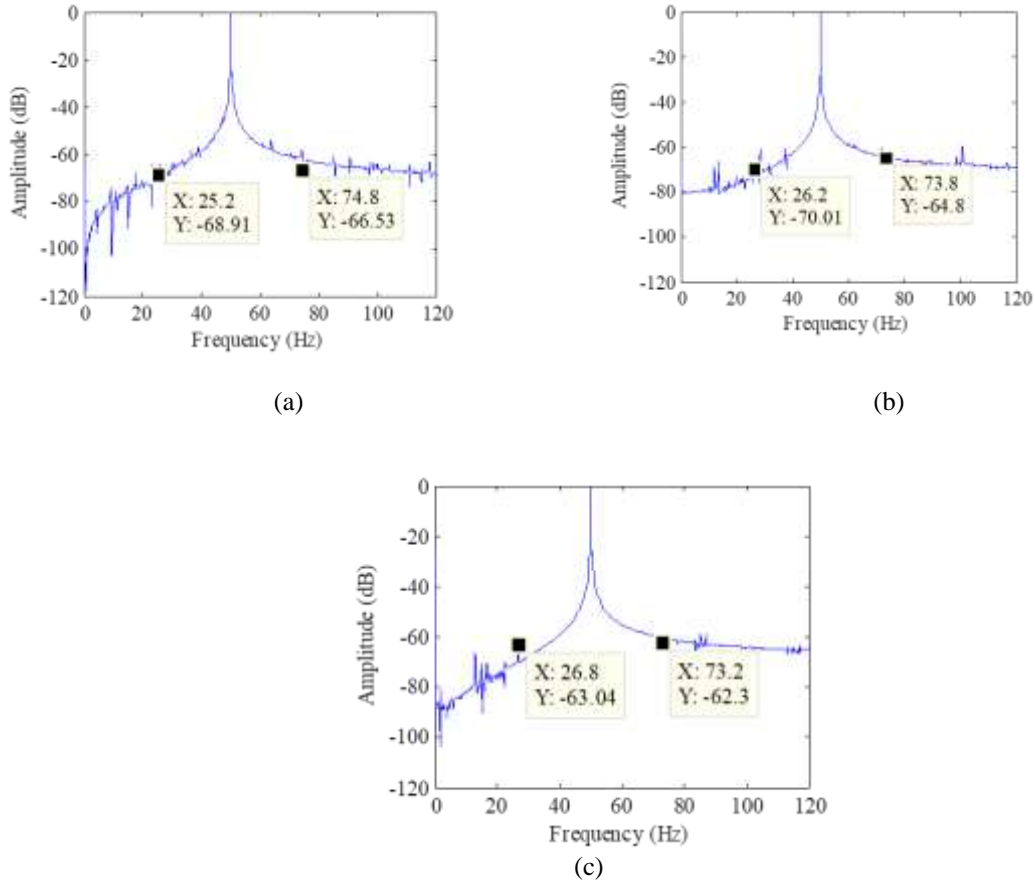


Figure 6. The Motor Stator Current Spectra of the Faulty Gear for Three Operating Points (a) No Load (b) Medium Load (c) Full Load

The Figure 7 presents the comparison of the amplitude variations on gear defect frequencies for instantaneous power spectra and motor stator current spectra. It has been observed that the change in the amplitude in motor stator current spectra is very small under low load operating points, hence, motor stator current analysis is not suitable for the diagnosis of gear faults under low load applications. However, observable amplitude variations of greater than 6 dB are found for full load operations of the motor. Comparatively, the larger changes in amplitude were detected in instantaneous power spectra even at low load operating conditions and even more prominent amplitude difference was found at full load condition of the motor. Another prominent feature of the instantaneous power analysis is that it provides three fault related components which enhances the reliability of fault detection in online condition monitoring system.

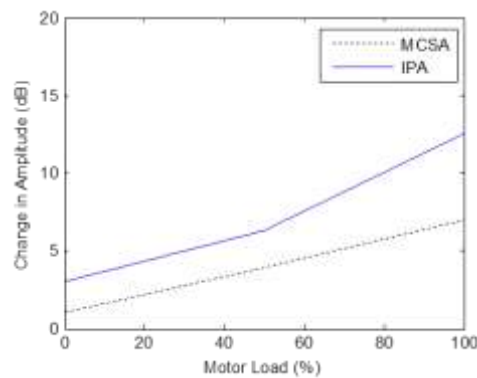


Figure 7. Comparison of the Amplitudes Variations of the Gear Fault Frequencies for the Instantaneous Power Spectrum and Motor Stator Current Spectrum

## 5. CONCLUSION

A reliable non-invasive fault diagnosis technique has been designed in this research for the condition monitoring of the gears coupled with induction motor specifically for variable load applications. The gear fault frequencies have been formulated theoretically and their sensitivity to fault levels under variable load conditions has been confirmed experimentally in the instantaneous power spectrum. The comparison of capabilities of the instantaneous power analysis method for the reliable fault diagnosis under variable load conditions has been done with the previously used stator current analysis method. It has been proved that the instantaneous power spectrum contains three fault related components and have high amplitude sensitivity as compared to motor current signature analysis which has only two fault related components.

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