INTELLIGENT ROD LIFT SYSTEM: FAULT DETECTION AND ACCOMMODATION

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ABSTRACT

Unplanned rod lift system outages often lead to long and costly repairs in addition to direct production loss. A recent study executed by Welling & Company on artificial lift systems [1] shows that the average downtime is 14 days at a total cost of $42,790/day. Leveraging design knowledge of the rod lift system combined with real-time condition monitoring represents a promising avenue to mitigate this problem. This study will demonstrate an application of advanced monitoring and diagnostic analytics on data from vibration, current and voltage sensors installed in critical locations of a beam pumping unit.

When pumping conditions deviate from the norm, the operators are alerted with regard to pending failures, and a supervisory control layer takes immediate action to adjust the operational pumping speed profile to maintain production at a safe operational level or shut down the equipment in the event of imminent catastrophic failure.

This paper will review the sensor installations and data acquisition approach. Experimental field test results is presented and discussed.

Key words

Sucker rod pump, fault detection, Condition monitoring, fault accommodation

INTRODUCTION

This paper presents a condition monitoring and fault detection approach for Rod Pumping systems. This study addresses the prime mover (electrical motor), the gearbox, and the bearings, as shown in the Figure 1. The motivation for this study is to improve pumping unit system availability by minimizing, or completely eliminating if possible, unscheduled maintenance outages. In this paper we will illustrate the successful application of a condition monitoring solution on a GE wind turbine and how this solution can be leveraged to address rod pump monitoring.

PUMPING UNIT FAILURE MODE ANALYSIS

In order to identify the appropriate health monitoring architecture, a pre-study of failure modes and effect analysis (FMEA) was conducted regarding the motor, gearbox, and all of the bearings (crank bearing, equalizer bearing, center bearing). Even though various failure modes were identified through the FMEA, it is the effect of those failures on the availability of the pumping system that would be of pertinent interest to the operator. This means that the sensing solution does not necessarily need to distinguish the various failure modes impacting the components. It is noteworthy that the main failures for these elements, as described in the FMEA, have a direct impact on vibration levels of the parts and also their temperature. For this reason, the best suited sensing technologies for health monitoring falls into two domains:

- Vibration sensors for bearings and gears
- Electrical signals analysis for motor monitoring.

ELECTRICAL MOTOR CONDITION MONITORING

Faults in Electrical Motors

Operating electrical motors can develop several faults such as stator insulation faults, bearing faults, eccentricity (static, dynamic, and mixed) faults, broken rotor faults, foundation looseness, shaft misalignment, etc. The faults in operating electrical motors below a 4kV voltage are shown in Figure 2 [Ref. Allianz survey report 2001]. Bearing and stator insulation faults represent ~75% of the total observed faults.

Online Condition Monitoring of Electrical Motors

Several technologies can be employed to monitor the health condition of operating electrical motors such as

- Electrical signature analysis (ESA)
- Vibration analysis
- Thermal analysis
- Acoustic analysis, etc.

In the next section more details on electrical signature analysis (ESA) will be discussed.

Electrical Signature Analysis Based Online Motor Monitoring

Electrical signature analysis (ESA) involves a spectral analysis of motor line currents and voltages to detect faults in operating motors. The spectrum of motor line current will exhibit a large magnitude of current at the fundamental operating frequency. Several other harmonic currents exist due to the non-sinusoidal distribution of stator windings, space harmonics of the air-gap, supply time harmonics, and operating faults. Several advancements have been brought by both industry and academia to improve fault detection in operating motors with less ambiguity to minimize false alarms.

Table **1** summarizes the various mechanical and electrical faults that can be detected using electrical or current signature analysis. Motors are often coupled to mechanical loads and gears. Several faults can occur in this mechanical arrangement. Some of the faults in a rod pump system driven by these motors are in the drive belts, rod string, gearbox, and crankshaft. The single largest cause of mechanical failures in induction motors are faults in the bearings. Continued stress on the bearings can result in fatigue on the inner and outer race of the bearings, which leads to motor failure over time. Another common mechanical fault observed in three phase induction motors is air gap eccentricity, which results when the rotor in not center aligned. This generates unbalanced radial forces that can cause the stator and the rotor to rub and results in damage.

Electrical faults on the other hand are essentially caused by winding insulation problems. Rotor faults can happen due to several reasons, such as a rotor bar unable to move in the slot it occupies due to thermal stresses. A large portion of the stator winding related issues are initiated by insulation failures causing stator turn faults that generate excessive heat in these shorted turns, and if the heat, which is proportional to the square of the circulating current, exceeds the limiting value, a complete motor failure may occur[2]. A ground fault is a fault that creates a path for current to flow from one of the phases directly to the neutral through the earth bypassing the load. This occurs when the motor phase conductor’s insulation is damaged due to voltage stress, moisture, or an internal fault between the conductor and ground.

Recommended Current/voltage Sensors

Electric signature analysis involves essentially the measurement and analysis of electric current along with voltage. Current is measured around any one phase or all three phases, either through clamp on meters or using current transducers. Voltage is typically measured from phase to phase or from phase to ground of the motor. Table 2 lists the different types of current transducers in use today for industrial applications.

The most popular current sensors in motor applications are Hall effect closed loop current transducers because they provide a non-intrusive measurement and are available as a combined sensor and signal-conditioning circuit. Hall effect sensors are also used to monitor voltage where the magnetic flux created by the primary current is balanced by a complementary flux produced by driving a current through the secondary windings. A hall device and associated electronic circuit are then used to generate the secondary current that is an exact representation of the primary voltage.

Sensors Installation

For correct measurements, the transducers must be installed on the phase conductor that corresponds to the voltage input connection. They can be installed in electrical control panels – thus avoiding complex wiring. If the motor is controlled using a variable frequency drive (VFD), then the transducers should be connected at the output of the VFD that is driving the motor as shown in Figure **3** (the motor is a star motor in a 3-wire configuration).

Both voltage and current sensors can be installed either at the motor terminals or at the power supply. The method of measurement involves measurement of the electric current around any one phase or all three phases. The current signal is conditioned, and the analog to digital (A/D) board digitizes the signal to produce the time and frequency spectra for analysis. Figure **4** shows an example of a HTA 1000S current transducer connection diagram, and Figure **5** shows a CV3 1000 voltage transducer connection from LEM that can be used for monitoring 3 phase current and phase to phase voltage or phase to ground voltage for a 3 phase induction motor, respectively.

Experimental Results

To enable analysis of motor faults, a high frequency response is typically required to cover the frequency range of components that can be induced due to different fault mechanisms found in a wide range of designs. Mechanical faults related to belts, coupling etc. can be discerned through the use of the current spectrum. Figure 6 indicates a frequency spectrum of a healthy motor comprising the pumping unit’s mechanical oscillations like pump stroke, belt frequency etc.

An example of the current spectrum that occurs with a broken rotor bar in the motor that is caused due to heavy duty cycles is shown in Figure **8**. For comparison, the current spectrum of a healthy motor is shown in Figure 7. A broken rotor bar if not detected early can cause serious mechanical damage to the motor insulation resulting in a winding failure. These broken bars result in current components being induced in the stator winding at frequencies given by $+/-2sf_s$ around the supply frequency component (where fs is the supply frequency and s is the slip frequency)

A spread spectrum Fast Fourier Transform (FFT) may show sinusoid frequencies as continuously varying when a VFD is controlling the motor speed. Hence it may be necessary adjust the signal processing based on the VFD operating mode.

GEARBOX AND BEARING CONDITION MONITORING

Vibration measurement

Vibration measurement is widely recognized and used for gearbox and bearings condition monitoring. The variation of the vibration parameters compared to reference signals could provide early indication of the state of mechanical parts.

Using vibration accelerometers along with a data acquisition system, one can obtain the vibration signal from the structure. The spectral content (both frequency as well as magnitude) of the signal could then be compared with a reference signal obtained from a good mechanical component. This measurement technology could provide an early indication of abnormal operation of the pumping unit.

Technology choice

For gearbox elements and bearing, the vibration measurement can be implemented through different methods. The main vibration measurement instruments used to obtain the vibration parameters are accelerometers. Considering the working environment, working frequency, and working temperature, there are three major accelerometers which would be suitable for condition monitoring. One type of accelerometer is a wireless accelerometer, which can be applied when the wire connection is not convenient or the power connection is unavailable. The second type of accelerometer is a uniaxial accelerometer which measures vibration in the axial direction only. In some cases, the gearbox has both axial and torsional movement. In this case a triaxial accelerometer, which measures vibration signals in three directions, including axial, radial, and circumferential, would be suitable.

Example from wind turbine application

In this section, we will illustrate an example of condition monitoring techniques that were successfully applied for GE wind turbine bearing monitoring. The technologies developed in this case are being leveraged and optimized to address the rod pump application where similar operating conditions are observed, such as pumping speed below 20 SPM (wind turbine rotation 20 rpm), typical motor shaft speed for rod pumps of 1200 rpm (generator shaft speed of 1500 rpm in the wind case). This study published in [3] shows how envelope spectrum analysis provides a powerful tool for bearing monitoring. Technical details about envelope analysis will be given in the analytics section.

Figure 9 shows the raw acceleration signal spectrum and the envelope spectrum of the output shaft accelerometer data from a wind turbine with a damaged bearing. The data demonstrates a much higher sensitivity of enveloping to bearing defect frequencies. In the envelope spectrum, the lowest prominent frequency near 8 Hz corresponds to the rotation speed of the gearbox intermediate shaft. The next feature (66 Hz) is the inner race ball pass (IRBP) frequency of one of the intermediate shaft bearings. It has two sidebands that are located at 8 Hz to either side of the 66 Hz frequency. The next cluster of frequency lines centered near 132 Hz represents harmonics of the group around 66 Hz. These harmonics are an artifact of the enveloping algorithm and have no physical meaning.

The bearing was removed and inspected, and substantial damage was found on the inner race. Figure **11** shows one of several large spalls that were found on this race. The bearing was replaced, and the wind turbine was returned to service.

Data was collected again and processed as before. Figure 10 compares the raw acceleration signal spectrum with the envelope spectrum from the same accelerometer as in Figure 9. The spectrum of the raw accelerometer data shows some gear mesh frequencies, but the envelope spectrum is completely clean.

This illustrated technique can be applied similarly for the rod pump bearing monitoring by taking into consideration the bearings design information in order to adjust the faults frequencies.

Installation

For rod pump bearings and gearbox, accelerometers can be installed on the surface of the housing either through adhesive bonding between the structure and a steel pad, or through screws to mount the accelerometer to the bearing case surface structure. For the long term condition monitoring application screw mounting is the preferred option.

Analytics

Reliability and availability of the pumping unit can be improved if monitoring techniques are developed, which can detect when a faulty bearing requires maintenance. Defects in general rolling element bearings can be generated by fatigue, wear, installation and improper lubrication. A few critical things to consider while analyzing the vibration signatures for gearbox and bearings are:

- The bearing components have a number of vibration modes that generate resonance at various frequencies throughout the spectrum.
- The vibration signatures will contain a number of high-energy frequencies from shaft and gear harmonics, which would mask analysis at lower bearing frequencies.
- There are a number of accelerometers with natural resonance at frequencies that are similar to the bearing modes. Using a higher frequency window close to the accelerometer resonance can amplify the bearing fault signal, increasing the probability of fault detection.

Whenever the bearing spins, any defect in the raceway surfaces or in the roundness of the rolling element excites periodic frequencies called fundamental defect frequencies. These are indicated in Figure **13**.

Fundamental defect frequencies depend upon the bearing geometry and shaft speed. Once the type of bearing installed is identified, the defect frequencies can be calculated, and faulty bearings can be detected using the bearing envelope analysis. Bearing envelope analysis is a very powerful technique to detect bearing faults [6]. The objective of this technique is to extract the fault frequency from the high frequency carrier signal as described in Figure **14**.

Experimental results

When the rolling elements strike a local fault on the inner or outer race, or a fault on a rolling element strikes the inner or outer race, an impact is produced. These impacts modulate the accelerometer signal at the associated bearing pass frequencies, such as: Cage Pass Frequency (CPF), Ball Pass Frequency Outer Race (BPFO), Ball Pass Frequency Inner Race (BPFI), and Ball Fault Frequency (BFF). Figure **15** shows a healthy wrist pin bearing and equalizer bearing where only harmonics of the rotational speed are observed while Figure **16** shows an example of an inner race simulated fault in a rolling element bearing.

FAULT ACCOMODATION

The outputs of the condition monitoring and diagnostic analytics are used primarily to inform the user about failure patterns. This triggers different levels of actions ranging from speeds and peak loads reduction to prolong parts life in order to allow time for maintenance; or a complete shutdown of the rod pump in case of imminent failures. The controls action associated with these alarms can be classified into two categories:

Local controls action

The local controls actions are managed at the rod pump controller based on sensor data failure analysis. When first patterns of the failure are detected, the controller reacts by reducing the operating speed and reducing the peak load on the bearings. Then, it sends an alarm to the operator to who can perform first level diagnosis remotely or schedule a diagnosis of the system by a field engineer.

In these operating conditions, if the condition of the bearing deteriorates based a predefined threshold level, the controller shuts down the pumping system to insure the safety on the asset until the diagnosis is performed.

Remote controls action

The remote controls actions are based on supervised decisions made by the operator. Typically the non-catastrophic alarm failures are sent to the central station with suggested controls actions such as reducing the pumping speed. The operator can analyze the alarm root cause and make a decision from a remote center. This decision is sent back to the rod pump controller and applied to the pumping unit. This route allows the user to continue the production while preparing the appropriate maintenance steps.

CONCLUSION

In this study, fault detection and accommodation solutions for rod pumping systems have been evaluated. An FMEA analysis highlighted that, failures in the bearings, the gearbox and the electrical motors represent the most critical component faults in the surface unit that result in downtime. Two major technologies have been explored to capture early failures patterns of these components. The first technology is based on Electrical Signal Analysis for motor failure monitoring and the second technology is the vibration analysis of bearings and the gearbox rotating elements. Preliminary experimental tests have been conducted on a healthy beam pump where six accelerometers, three current transducers and three voltage transducers have been installed. These tests demonstrated the feasibility of the sensing solution and the data collection. Signal processing techniques have been applied on the captured signal to detect fault signatures. In addition, the study confirmed the minimum number of sensors for beam pump monitoring as well as the optimal location for these sensors.

Additionally, a fault accommodation strategy has been developed to address different failure levels and how the rod pump controller will handle these failures. Two types of actions have been considered. Local fault accommodation aims to reduce failure rates based on early fault detection or shut down of the system in case of imminent catastrophic failure. The second level of action is remote fault accommodation that consists of human based decisions to either remotely derate the system or order a complete shutdown to provide the operator time to plan maintenance and repair.

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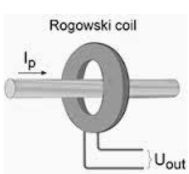
Table 1: Mechanical and electrical faults in a 3 phase induction motor

Fault location	**Fault**	**Voltage/ Current**	**Shaft speed**	**Analysis technique**
Mechanical systems faults	Belt	Required		Shaft torque estimation Looking for abnormalities in frequencies corresponding to these faults in the torque
	Rod string	Required		
	Gear-box	Required	Required	
	Crank-shaft	Required	Required	
	Bearings	Required	Required	
Electrical faults	Broken rotor	Required	Required	Detecting 2 x slip frequency side bands
	Turn fault	Required		Calculating negative sequence current from three phase currents
	Ground fault	Required		

Table 2: Types of current transducers in use today

Type	AC/DC	Range	Bandwidth	Pros and Cons	Applications
Iron core Clamp 	AC	5kA	10kHz	Cheap, but not flexible, DC and low AC currents are difficult to measure	Motor current measurement, grid monitoring
Ragowsky coil 	AC	10kA	20kHz	Rugged and flexible, overload withstand capability. Can measurey small currents (some 100mA) up to very high currents (>100 kA)	Short circuit testing in electric generators Sensors in protection systems Shaft current measuremets Grid monitoring
Hall Effect 	AC and DC	300A	100Khz	Consists of both open loop and closed loop. High accuracy and high bandwidth. Low measurement range	Grid monitoring
Zero flux transducers	AC and DC	1000A	Upto 300kHz	Highest accuracy and high bandwidth	Power analyser and Grid monitoring

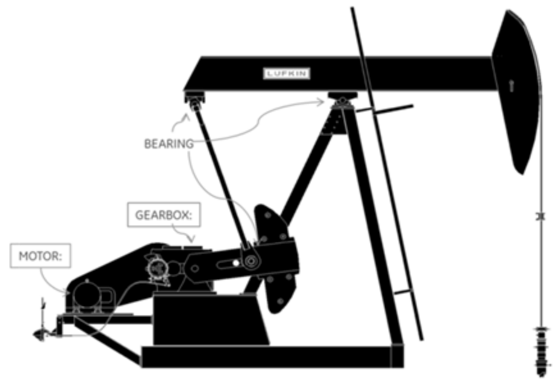


Figure 1: Components of the Bean Pump Unit for Health Monitoring

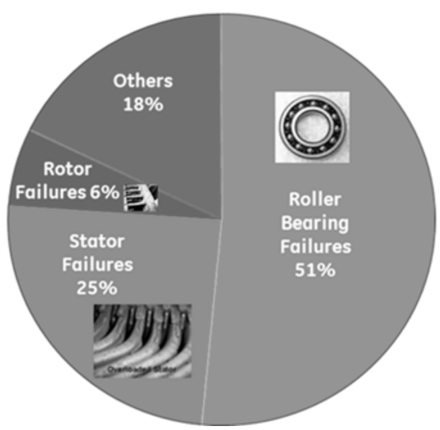


Figure 2: Faults in electrical motors [Ref. Allianz survey report 2001][2]

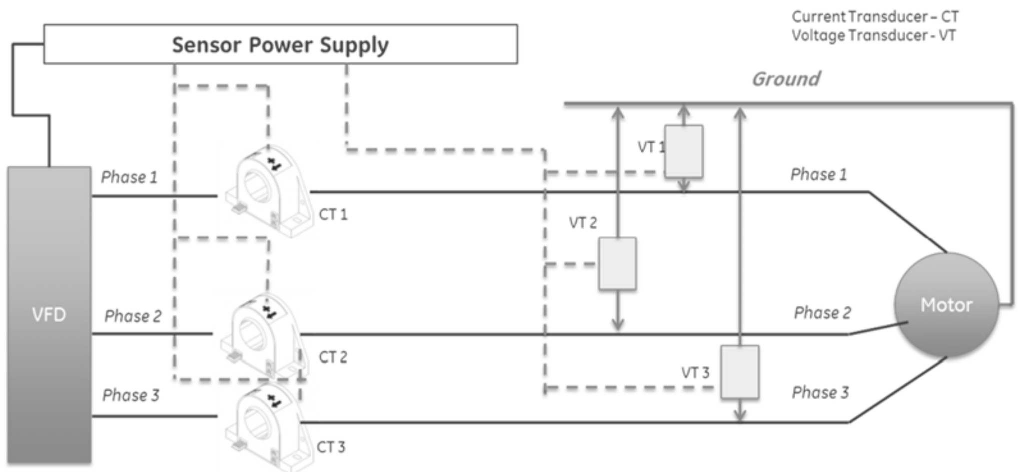


Figure 3: Motor current and voltage sensor installation

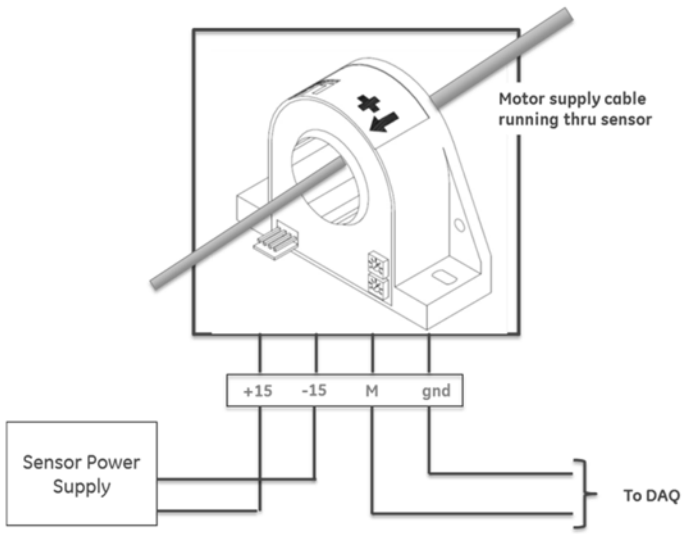


Figure 4: Wiring schematic of a current transducer (LEM HTA 1000S)

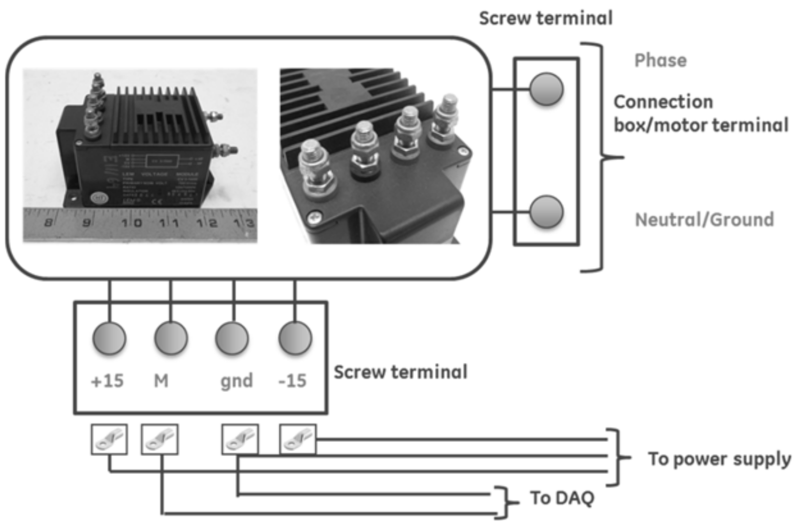


Figure 5: Wiring schematic of a voltage transducer (LEM CV3 1000)

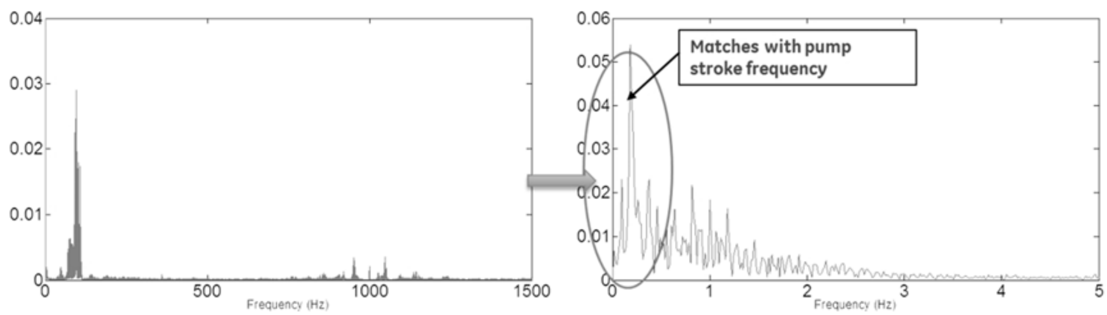


Figure 6: Frequencies corresponding to pumping unit's mechanical oscillations

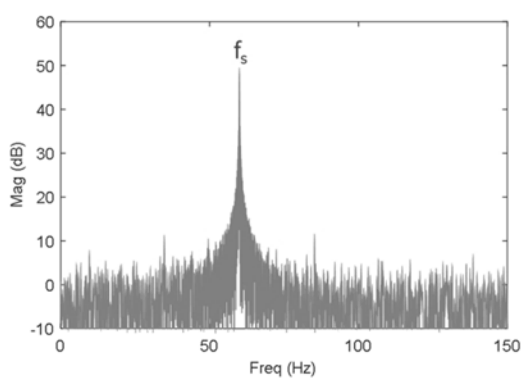


Figure 7: Current spectrum of a healthy motor

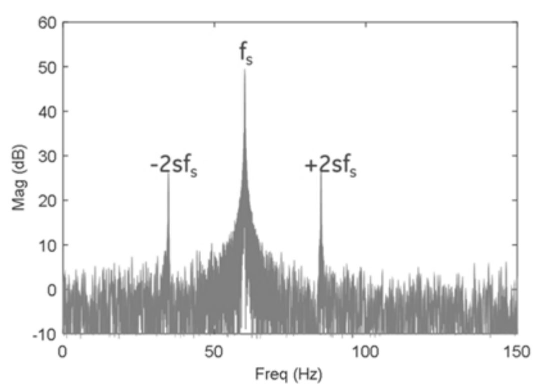


Figure 8: Current Spectrum with broken bars

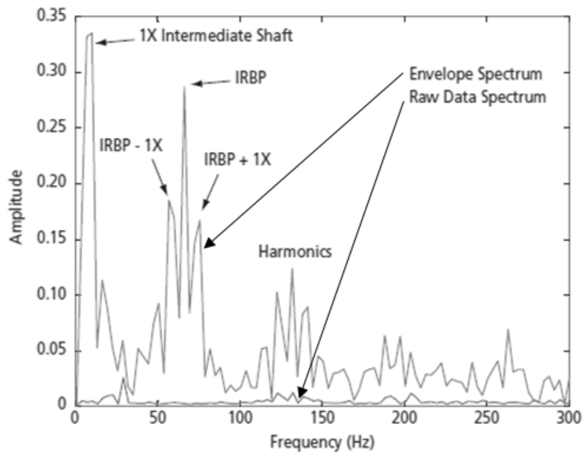


Figure 9: Wind turbine data with damaged bearing[5]

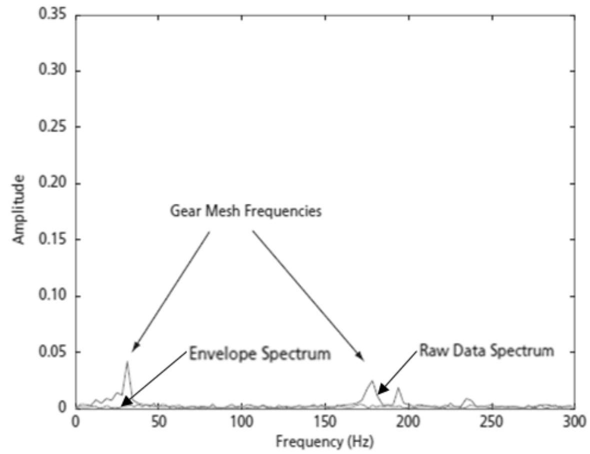


Figure 10: Wind turbine data after damaged bearing replacement[5]

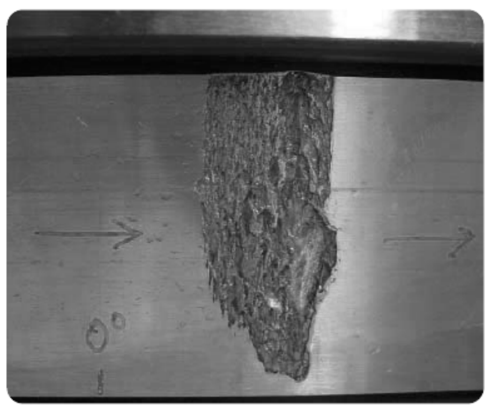


Figure 11 : Damage on the inner race of one of the intermediate shaft support bearings. This was one of several spalls in the bearing.

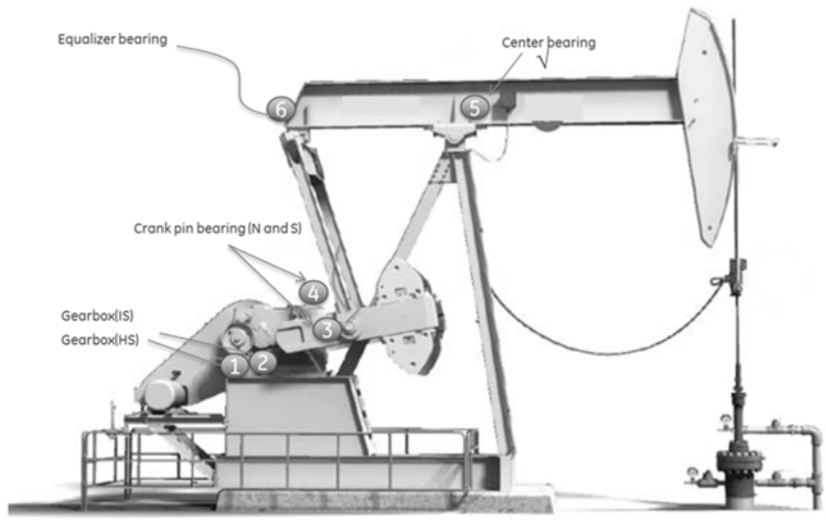


Figure 12: Locations for accelerometer installation

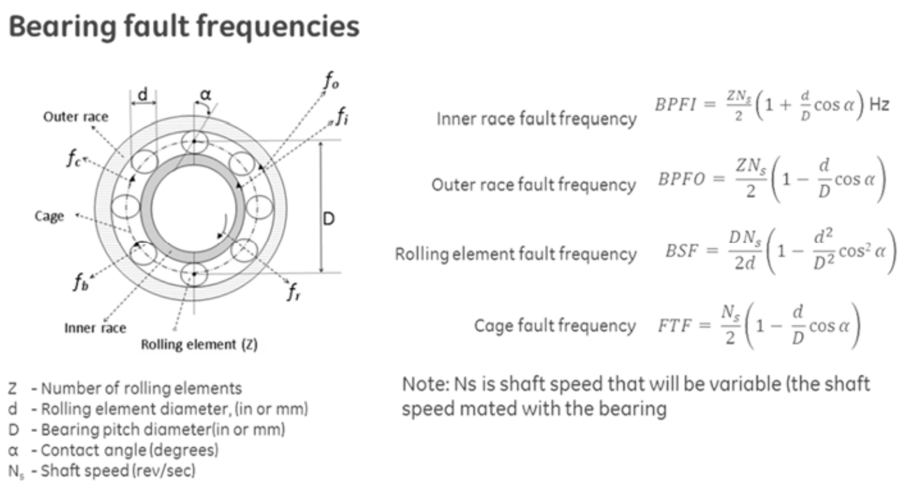


Figure 13: Bearing fault frequencies

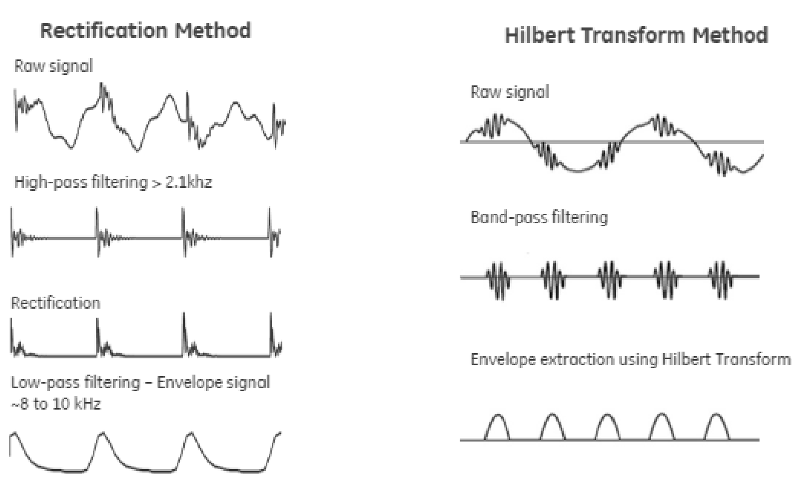


Figure 14: Envelope signal generation

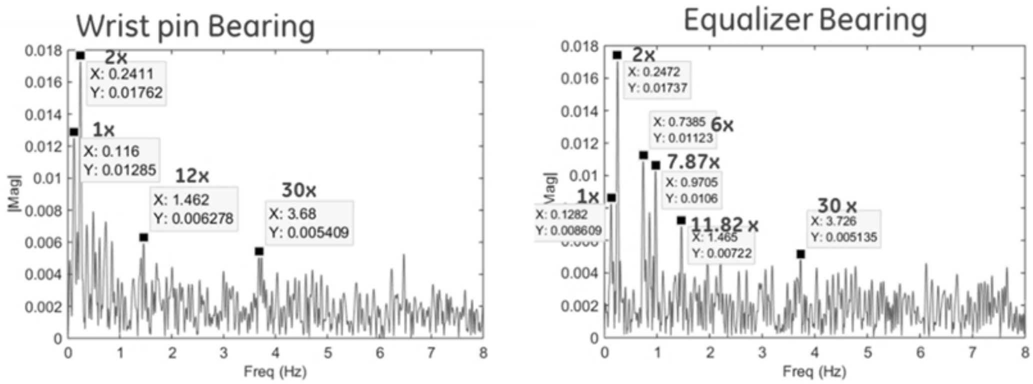


Figure 15: Signature of a healthy wrist pin and equalizer bearing

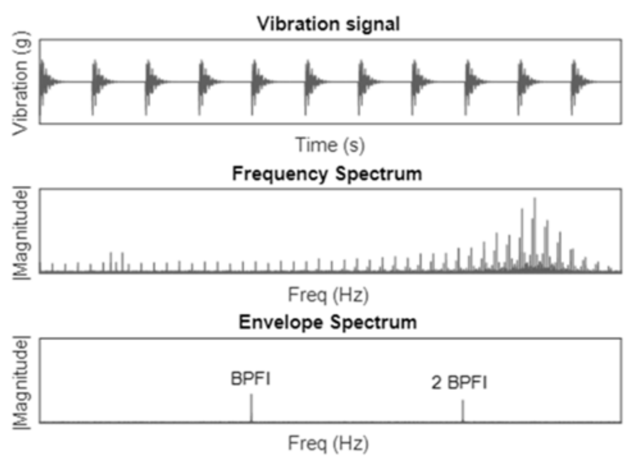


Figure 16: Example of a bearing inner race fault