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SUBMERSIBLE PUMPS CONDITION MONITORING, USING MOTOR CURRENT SIGNATURE ANALYSIS AND VIBRATION ANALYSIS COMPARISON

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Nicolas Péton joined GE in 2006 in the Machinery Diagnostic Services group. Previously he worked for two different manufacturers (Alstom Steam turbine and Cryostar expander/compressor) where he was in charge on site startup activities worldwide. He also worked as an operation and maintenance engineer in the chemical industry (PPG industry, USA) and as Free Lance for startup activities worldwide. He has been also a mechanical/acoustical research engineer in research institutes (Technion, Haifa and TU Berlin). He is currently Global Director for the Bently Nevada Machinery Diagnostics Services. He has a Diplome d'ingénieur from the Université de Technologie de Compiègne, France.

ABSTRACT

The article discusses how Submersible Pumps mechanical and electrical malfunctions are reflected in the dynamic current spectrum using Motor Current Signature Analysis and vibration spectrum using Vibration Analysis. The article contrasts the similarities vs. differences and advantages vs. disadvantages of both methods and may be of value for field engineers to understand the pros and cons. of each technology.

Vibration Analysis is widely used to detect faults on the Submersible Pumps. Vibration Analysis has been implemented for the detection of malfunction mainly of mechanical and process origin. The recommended practice on the Submersible Pumps is to take the vibration measurement at each bearing of the Submersible Pump, which is challenging.

Motor Current Signature Analysis (MCSA) is a suitable alternative as the method does not require any sensor installation on the Submersible Pumps itself and the measurement is carried out remotely in the motor control unit. Improved MCSA, Model-Based Voltage and Current Analysis (MBVI) uses a mathematical model of the relationship between dynamic current and voltage to identify electrical, mechanical or process problems. MBVI is especially attractive for inaccessible driven equipment and well suited for the monitoring of Submersible Pumps.

The paper further shows case studies on Submersible Pumps, such as Sea Water Lift Pumps and submerged Cryogenic Pumps. The presented results prove the potential of both techniques and the advantage of their combined use for reaching a more reliable Condition Monitoring of Submersible Pumps.

INTRODUCTION

The Submersible Pumps referenced in this paper are vertical pumps, with motors submerged in the pumped liquid, such as Sea Water Lift Pumps or LNG Cryogenic Pumps (In-Tank and Ex-Tank LNG Pumps).

Submersible Pumps condition monitoring is typically based on vibration measurements. Installation of the vibration sensors is quite difficult for Submersible Pumps, especially for the Cryogenic Pumps, where the sensors must be designed for cryogenic environment. Correct transducer installation is critical and can help pinpoint the bearing or pump problems. Otherwise, if the installation is designed or done incorrectly, the measurements will provide readings of limited use that may contain random spikes and false alarms or limit detectability of faults.

Improved Motor Current Signature Analysis (MCSA), Model-Based Voltage and Current Analysis (MBVI) can be an alternative or complementary method to the Vibration Analysis.

There are many similarities between the Vibration Analysis and improved MCSA, MBVI. Both are sensing the magnitude and frequency of signals being generated by the equipment to identify malfunctions and their severity. MBVI is using the motor as the sensor, where Vibration Analysis can use eddy current proximity probes, electromagnetic velocity sensors or piezo-electric accelerometers. The difference between these two techniques is that vibration sensors detect mainly radial (or axial) forces, whereas using the motor as a sensor is more sensitive to torsional forces. This means they can be complementary and the use of MBVI systems can give new insights to situations that have previously been assessed only by conventional Vibration Monitoring.

A significant advantage of the Model-Based Voltage and Current System is the built-in Expert System, which automatically detects the faults, assign the severity and send the notification to the user. There are existing Vibration Expert Systems as well, but usually not available for Cryogenic pumps due to very low temperatures and often false alarms from the vibration sensors.

VIBRATION ANALYSIS

The vibration analysis is the most common method of condition monitoring in the industry and has been used for decades.

The main advantages of the vibration Analysis are:

- It's well proven method, with reliable results and good overall understanding in the industry.
- The international standards exist with the recommended alarm values to compare across the fleet.
- The overall vibration can be trended and compared against the alarm values.
- The condition monitoring mainly depends on spectrum and waveform based analysis, which are widely understood.
- Individual spectrum band alarms can be set and trended.

The main disadvantages of the vibration Analysis are:

- The vibration transducer is not easy to install in the case for submersible pumps. Please see the challenges with vibration transducers described below.
- The vibration transducer must be suitable for submersible application and in case of cryogenic pumps able to operate in cryogenic temperatures ranges below -162°C.

Vibration Transducers

According *Bently Nevada (2016),* in order to detect Rolling Element Bearing (REB) problems in the early phase, an accelerometer - casing vibration transducer is recommended ideally mounted near each bearing. Use of high frequency techniques, either high pass filtered acceleration peak value or enveloping (demodulation), will give the required indications of REB deterioration. The challenge is to get the accelerometers installed on a place where reliable vibration from the REBs can be observed. The sensors designed for cryogenic environment should be installed on the casing of a cryogenic pump, as near to the bearings as possible. For REB condition monitoring purposes, the high frequency acceleration signal is the most important measurement, but other vibration readings also should be considered. A direct overall velocity measurement may be used for protection and to acquire dynamic data, if available, to help manage the machine. If only velocity measurements are available, the recommended best practice is to configure the maximum frequency of the velocity spectra at 2000 Hz. This is a good compromise for detection of the components related to unbalance, misalignment, blade pass and bearing fault frequencies at an acceptable resolution.

It is very important to know that in many cases the sensors do not behave perfectly and produce several high amplitude spikes in the direct trends (this phenomenon is especially evident at some particular conditions, such as low flow rate and/or low level in the tank). When an excessively high amplitude event occurs, the corresponding spectra may show the “ski slope” pattern, which is clearly indicative of a bad reading. The “ski-slope” signal is an artefact normally caused by overloading or saturation of the accelerometer sensor or monitor channel. The first spectral line reported in the spectral graph is very large and is unrelated to any physical vibration. This artifact can invalidate other frequency content in the graph. Common reasons for the overload are incorrect mounting of the sensor, intermittent wiring, electrical interference, a large rapid temperature change or a very high vibration at a particular frequency exceeding the transducer’s vibration range.

Thus, the pump sensors must be properly qualified for the application, properly installed and properly maintained and monitored. An analysis tool for the sensor health is monitoring the bias voltage of an IEPE (integrated electronic piezoelectric) accelerometer. An accelerometer bias voltage that is unstable or contains spikes is a clear indication of a malfunctioning accelerometer sensor, so the data taken under those circumstances is of limited or no value for diagnosing pump problems. The cause of the unstable bias voltage needs to be determined and corrected to reestablish proper monitoring and protection.

MOTOR CURRENT SIGNATURE ANALYSIS

Motor Current Signature Analysis (MCSA) is based on capturing the current demanded by the machine at steady-state and applying the Fast Fourier Transform (FFT). The current spectrum, obtained with the FFT, provides the harmonic content of the captured current signal and indicates the frequencies [Hz] and amplitudes [dB] of the different harmonics. When a certain fault is present, several components are amplified in the current spectrum, similarly as in vibration spectrum.

Based on *Walker (2017),* conventional MCSA is limited in its analysis capability because the motor current is not only affected by phenomena within the motor and driven equipment system, it is also affected by the voltage applied. This is not only a question of the scalar magnitude of the voltage (as measured by an RMS Figure), it is also a question of the shape of the dynamic waveform. A voltage waveform that is not a pure sinusoid, but may be distorted, will result in a current waveform that will likely be distorted in some way from being a pure sinusoid. Such distortions are very common, particularly when dealing with equipment driven by an inverter. These distortions may not indicate any problem with the electric motor or the equipment, they are purely caused by the distorted voltage input. Conventional MCSA is unable to distinguish between these distortions caused by the voltage waveform and faults that are a genuine indication of developing equipment problems.

The new solution is Model Based MCSA, known in the literature as Model-Based Voltage and Current Analysis (MBVI), which effectively uses the electric motor driving the equipment as a sensor, and makes use of the fact that the current drawn by an electric motor depends on two main factors:

- the voltage applied to the motor, and
- the behavior of the motor and driven equipment system.

MBVI Systems are able to separate out the impact of distortions coming from the voltage supply, by making a mathematical model of the relationship between current and voltage and using this to identify those components that are coming from the internal behavior of the system. The approach used is represented in Figure 1.

Bently Nevada (2012), Model Based Motor Anomaly Detection Monitor uses MBVI, a combination of voltage and current dynamic waveforms, together with learned models for motor anomaly detection. Motor fault detection is based on a learned, physics-based motor model, where constants in the model are calculated from real-time data. Automated diagnostics (Expert System) is based on the Power Spectral Density (PSD) amplitudes in particular frequency bands, in relation to learned values and alarm thresholds. The spectrum-based fault detection in MBVI Monitor is similar to MCSA, but with several important differences. The MBVI Monitor takes the input voltage waveform and passes it through the model transfer function to obtain a theoretical current waveform. The theoretical current waveform is subtracted from the measured current waveform to produce a residual current waveform (Fig.1). The residual waveform contains the “errors” between theory and reality. The Fast Fourier Transform (FFT) is applied on residual waveform to obtain residual PSD Spectrum. Power Spectral Density (PSD) shows the strength of the variation (energy) as a function of frequency. PSD is Auto Spectrum divided by its frequency resolution (the increment between frequency lines). If the units of an Auto spectrum are (g^2), the units of its corresponding PSD are (g^2 / Hz). The Auto Spectrum is calculated by multiplying the Fourier spectrum of a signal by its complex conjugate. The Auto Spectrum has magnitude only and its phase is zero.

The significant advantage of MBVI systems over conventional MCSA is that by being based on measurements of all three phases, phase unbalance can be identified, and this itself can be of significance, both as an indicator of problems with the motor windings, and as a cause of torque oscillation that can put additional stresses on components such as couplings.

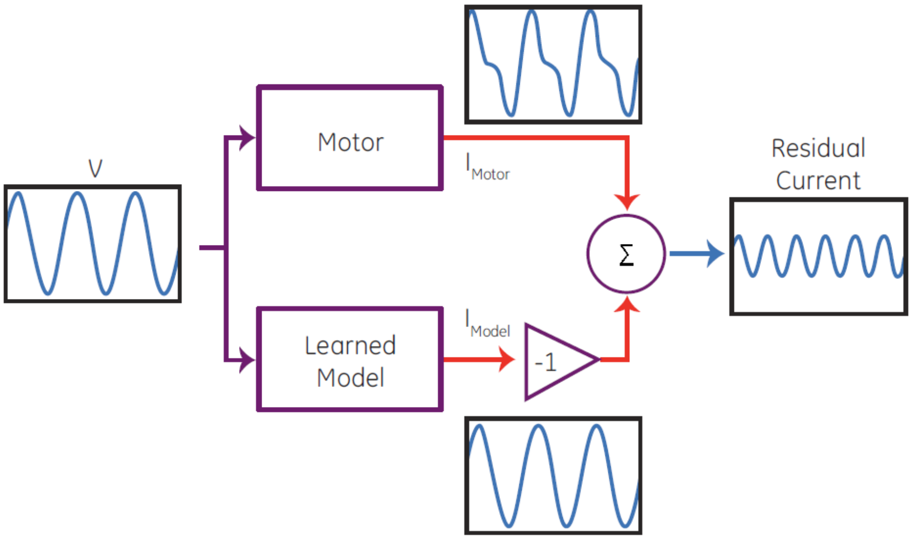


Figure 1: Model Based Motor Anomaly Detection (Courtesy of Bently Nevada)

Based on *Walker (2017)*, the practical deployment of MBVI systems involves measuring current and voltage on the lines supplying the motor. Generally, the best place to measure this is in the motor starter cabinet, which is typically in a switch room, which is generally a dry location with no flammable atmosphere hazards. The MBVI units are typically installed in the motor cabinet itself, or in a separate cabinet mounted nearby. The current signal can either be provided by installing a fixed Current Transformer (CT), or in some cases by making use of existing CTs that are often already installed for metering or motor protection purposes. Since these are all inside the motor starter cabinet, they are not vulnerable to accidental damage during normal operation or maintenance work.

The information from the MBVI monitors needs to be communicated out to the appropriate place where it can be made use of, i.e. to a plant operator's control panel to give indication of a problem, or to a maintenance planner or reliability engineer's screen to provide information for planning appropriate intervention. This is normally achieved via Intranet or via the Internet.

Model-Based Voltage and Current Systems offer the ability to identify and give advance warning of a wide range of commonly occurring failure modes, across a wide range of mechanical, electrical and operational areas. This is the essential information required to support the adoption of a Condition Based Maintenance (CBM) regime. They are simple to install, robust against accidental damage, and inexpensive.

The main advantages of the MCSA/MBVI are:

- Non-invasive method as no mounted sensor is required on the pump casing.
- The current transducer/transformer is easy to install, usually clamp on.
- The current transducer/transformer is usually installed in airconditioned motor control cabinet and there are no problems with the outside temperature or in case of cryogenic pumps with cryogenic temperatures.
- No environmental problems with the transducer installation as it's installed inside, in dry location with no flammable atmosphere hazards.
- The built-in Expert System, with automated advisory, reporting and notification.
- The condition monitoring mainly depends on Power Spectral Density analysis, similar to the vibration spectrum analysis.
- Individual spectrum bands for typical machine malfunctions can be trended.

The main disadvantages of the MCSA/MBVI are:

- Conventional MCSA is limited and affected by network loads and power supply harmonics. Model-Based Voltage and Current Analysis (MBVI) needs to be used to compensate for distortions coming from the voltage supply.
- It's not that widely used and understood method in the industry.
- There are limited international standards with the recommended alarm values to compare across the fleet.
- There is not one overall current value, which can be trended and compared against the alarm values or standards.
- There are only individual spectrum band values, which can be trended and compared against the alarms, usually defined and limited to experience with given machine types and fleet.

MODEL-BASED VOLTAGE AND CURRENT (MBVI) EXPERT SYSTEM

Based on *Bently Nevada (2012)*, the Model-Based Voltage and Current Analysis (MBVI) Expert System uses 12 mechanical parameters, obtained from the Power Spectral Density (PSD) plot, sensitive to mechanical faults like unbalance, misalignment, looseness, transmission or bearing problems. The Expert System uses also 8 electrical parameters to feed the model, further classified in two groups: *Internal and External.* Based on created electrical model internal and external electrical faults are diagnosed, while other mechanical faults are diagnosed based on PSD plot. *Internal electrical parameters* indicate problems associated with rotor, stator, winding etc. *External electrical parameters* indicate electrical supply problems such as voltage unbalance, isolation problem of cabling, capacitor, motor connector, terminal slackness, defective contacts etc.

An example of Expert System results and automated advisory is shown in bar graph (Fig.2). Bar graph compares the signal of an equipment, collected during the analyzed period, with the closest fitting healthy baseline database. The bar graph represents the fault severities under different categories. Green dotted line represents the healthy average level of the closest fitting healthy baseline. There is "Caution" yellow region, which suggests attention and closer monitoring the fault parameters. The "High" red region suggests, that values within this zone are normally considered to be of sufficient severity to cause damage to the machine. The example of Expert System results (Fig.2) suggests an elevated severity of the Transmission Elements fault, based on mechanical parameters and PSD Plot (Fig.4). The Expert System on bar graph (Fig.2) further suggests increased severity of the Internal and External Electrical fault, based on electrical parameters (Fig.3) and the physics-based motor model.

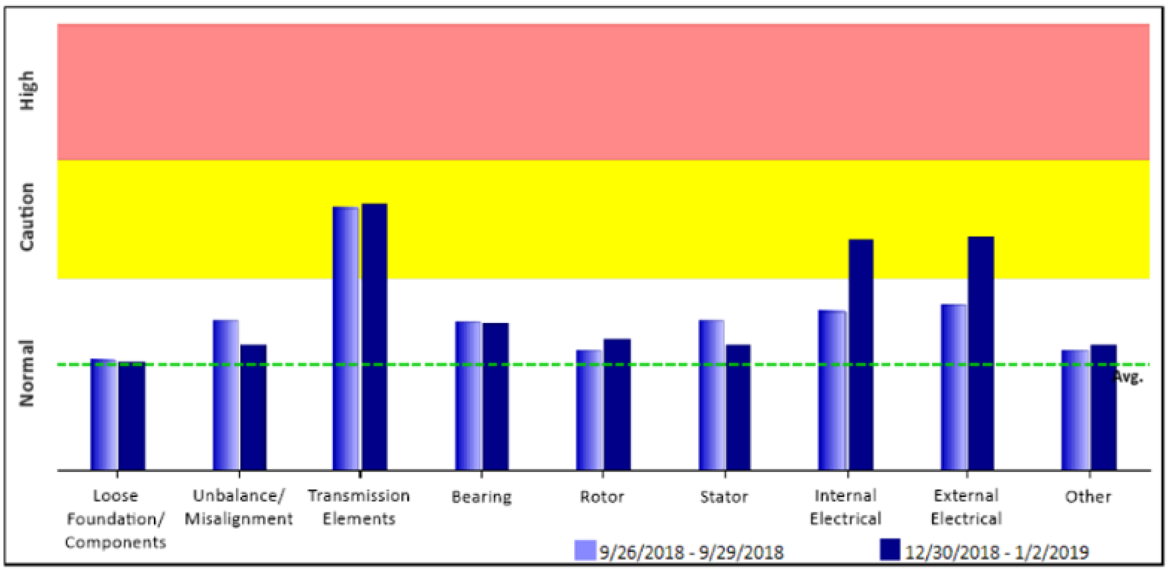


Figure 2: Expert System Bar Graphs

Table of average electrical parameters (Fig.3) shows measured and calculated electrical values compared with reference thresholds, used for additional advisory of Expert System. The example of Expert System results suggests that all electrical values are within their expected range.

Status	Name	Value	Reference
OK	Power Factor	0.84	
OK	Active Power [kW]	249	
OK	Reactive Power [kVAr]	142	
OK	Vrms(L-N) [V]	3565	Vn ± 10%
OK	Irms [A]	28	≤ In + 10%
OK	V Unbalance [%]	0.13	≤ 2.0
OK	I Unbalance [%]	0.32	≤ 5.0
OK	Frequency [Hz]	50	
OK	THD [%]	0.82	≤ 5.0
OK	3th Harmonic [%]	0.17	≤ 5.0
OK	5th Harmonic [%]	0.31	≤ 5.0
OK	7th Harmonic [%]	0.31	≤ 5.0
OK	9th Harmonic [%]	0.10	≤ 5.0
OK	11th Harmonic [%]	0.21	≤ 5.0
OK	13th Harmonic [%]	0.39	≤ 5.0
OK	Electrical values are within their expected range.		

Figure 3: Avg. Electrical Parameters

The example of Expert System automated report further contains Power Spectral Density (PSD) (Fig.4), used for detailed explanations of the findings. Recall that the PSD is calculated from the model residuals.

The motor waveform and the learned model of MBVI output waveform are subtracted, producing a residual current waveform. The residual waveform represents the error between theory and reality. There is two step model building process: model learning and model improving. During the learn period, the reference model is established. This reference model basically consists of model parameters, their mean values and their standard deviations. During the improve period, while monitoring varying load conditions, the model is being improved, and model parameters updated. When learn and improve modes are completed, the model is compared with the fleet data (healthy baseline) from similar motors and similar driven equipment. If the learned model values exceed the threshold values, then an alarm is given. The final residual current curve is obtained (represented as blue line in the Figure 4 below), known as "Learned PSD" or "Equipment PSD". The residual current displayed in the frequency domain as shown below where x-axis is frequency (Hz) and y-axis is the standard deviation amplitude.

The monitor classifies PSD energy into 12 typical spectral frequency bands associated with particular fault classes: Loose foundation, Transmission elements, Rotor problems, Bearing parameters 1, Unbalance, Misalignment, Loose windings, Stator problems, Bearing parameters 2, Bearing parameters 3, Bearing parameters 4, Other problems.

The Energies (higher amplitudes, peaks) in the bands are automatically reflected to the associated faults and represented in the bar graph. "Normal" and "High" regions represent the deviation limits/thresholds from the healthy baseline (fleet data). If the equipment signal exceeds the "High" threshold for a particular frequency range, the monitor will trigger the associated alarm.

There are 18 mechanical and electrical parameters, which can be trended individually: Loose foundations, Unbalance/Misalignment, Transmission/Driven Equipment, Bearing, Rotor, Loose windings/Stator, Internal Electrical fault, External electrical fault, Other, Voltage, Current, Voltage unbalance, Current unbalance, Power factor, Active power, Signal Frequency, Motor status, Total Harmonic Distortion and all the harmonics. Trending these individual parameters displays the faults progressing over the time and interpolates when equipment will likely require action.

The Example of Power Spectral Density (PSD) plot (Fig.4) shows increased amplitude in the Transmission Element band (no.3) and confirms Expert System "Caution" advisory (Fig.2). Further, detail Analysis of PSD, reveals that increased frequency component is 0.22x times the rotating speed frequency, suggesting the flow turbulence, possibly normal for this In-Tank LNG Pump.

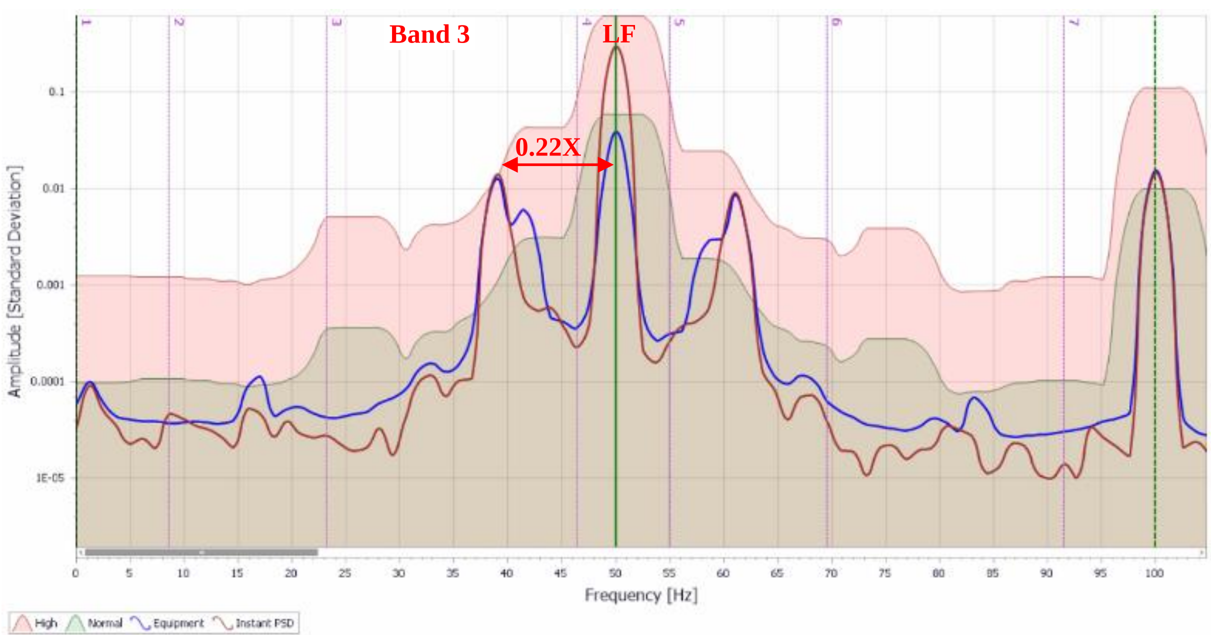


Figure 4: Power Spectral Density (PSD)

The Power Spectral Density (PSD) plot, uses Standard Deviation (SD) as y-axes.
The Expert System uses the Alarm threshold as 6Sigma (6 Standard Deviation) from the mean/central tendency.
The Standard Deviation (also known as Sigma or σ) is explained in the reference *Sixsigma Institute (2019).*

MOTOR CURRENT SIGNATURE ANALYSIS AND VIBRATION ANALYSIS, COMPARISON

Ideally, the residual current waveform signal and residual PSD spectrum (with MBVI systems) should be based only on a single harmonic located at the supply frequency (50 or 60 Hz) (terminology in MCSA/MBVI: Fundamental Supply Frequency (f) aka. Fundamental Component (FC), in Vibration Analysis: Line Frequency (LF)). However, in practice, the current of any induction motor contains two other additional harmonic families: Winding Harmonics (WH) and Principal Slot Harmonics (PSH). Basically, WH are caused by two factors: the presence of harmonics in the supply voltage and the fact that the distribution of the conductors in the stator is not continuous in its perimeter, but they are installed in a finite number of slots, so that the resulting airgap field is not purely sinusoidal. On the other hand, PSH are due to the rotor slotting which causes that the permeability of the magnetic circuit changes in the different radial positions.

When a certain fault is present, several components are amplified in the current and/or vibration spectra. Many works have studied the components amplified by each specific failure: *Cameron et al. (1986), Thomson et al. (2017), Popaleny et al. (2010-2019)*

Table 1 shows the main formulae that give the components amplified by each fault. Please see the list of variables at the end of the paper in NOMENCLATURE.

Fault	**Components amplified in the current spectrum (MCSA)**	**Components amplified in the vibration spectrum (VA)**
Broken rotor bars/end-rings	$f(1\pm2\cdot k\cdot s)$ k=1,2…	$k\cdot f_r\pm$PPF k=1,2…
Mixed eccentricity (static +dynamic eccentricity)	$f(1\pm m\cdot(1-s)/p)$ m=1,2,3…	please see below separated
Dynamic eccentricity (bent shaft, rotor bow, asymmetric thermal expansion or unbalanced magnetic pull…)	$[(R\pm n_d)\cdot k/p\cdot(1-s)\pm v]\cdot f$ n_d=1,2… v=1,3,5…	rotor bow: $1\cdot f_r$ or 1X rotor unbalance: $1\cdot f_r$ or 1X rotor eccentricity: $k\cdot f_r\pm$PPF k =1,2… or: $2\cdot f\ \pm$PPF
Static eccentricity (stator core ovality/eccentricity, misalignment, manufacturing tolerances in stator core/ incorrect installation of stator core/bearing	$[(R\pm n_d)\cdot k/p\cdot(1-s)\pm v]\cdot f$ n_d=0 v=1,3,5…	stator eccentricity: $2\cdot f$ or $2\cdot$LF misalignment: $k\cdot f_r\cdot$ k =1,2,3 structural looseness: $1\cdot f_r$ or 1X rotating looseness: $k\cdot f_r\cdot$ k =1 to 10
Bearing faults Outer race damage Inner race damage Ball damage Cage damage	 $\lvert f\pm m\cdot f_O\rvert$ m=1,2,3… $\lvert f\pm m\cdot f_I\rvert$ m=1,2,3… $\lvert f\pm m\cdot f_B\rvert$ m=1,2,3… $\lvert f\pm m\cdot f_C\rvert$ m=1,2,3…	 simplified: $f_O=(N_b/2)$ - 1.2 simplified: $f_I=(N_b/2)+1.2$ simplified: $f_B=(N_b/2)$ - 1.2/ N_b simplified: $f_C=(1/2)$ - 1.2/ N_b

Table 1: Components amplified in the current and vibration spectrum by different faults

In this table, s is the slip, p is the number of pole pairs, R is the number of rotor slots, N_b is number of rolling elements, f_r is mechanical rotor rotating frequency, f is Fundamental Supply Frequency

Based on Vibration Analysis (VA), rotor cage asymmetry due to a broken rotor bars produce the sidebands at Pole Pass Frequency (PPF) around the 1X aka. rotating frequency $f_r = N_r \cdot \frac{p}{60}$ [Hz]. The PPF is defined as SLIP FREQUENCY times NUMBER of POLES (n), where slip frequency is $f_s = \frac{N_s - N_r}{60}$ [Hz], where N_s [rpm] is Synchronous Speed and N_r [rpm] is Rotating Speed.

Let's compare the sidebands for MCSA/MBVI and VA for four pole induction motor, with $f = 50Hz$ and $fr = 24.5Hz$:
MCSA/MBVI sidebands at $2 \cdot s \cdot f\ =\ 2 \cdot 0.02 \cdot 50Hz = 2Hz$, where SLIP with MCSA/MBVI is: $s = \frac{N_s - N_r}{N_s}$ [1].
VA sidebands at $PPF\ =\ f_s \cdot n = (25Hz - 24.5Hz) \cdot 4 = 2Hz$, where n is number of poles

Despite different definitions in MCSA/MBVI vs. Vibration Analysis the sidebands frequency due to broken rotor bars is the same. The main difference is that, with VA the sidebands at Pole Pass Frequency (PPF) are displayed around rotating frequency 1X, where with MCSA/MBVI the twice slip frequency sidebands (2·s·f) are displayed around Supply Frequency aka. Line Frequency

COMPARATIVE TESTS

The following tests are based on authors *Popálený and Antonino-Daviu (2018)* and are shown in this Tutorial for its clear explanation of the most typical malfunctions using MCSA/MBVI current spectrum and vibration spectrum.

TEST 1: The Induction Motor with two broken rotor bars, coupled, misaligned, but unloaded.

Misalignment malfunction is presented in the Vibration Spectrum plot (Fig.5) measured on the Motor Drive End (DE) Bearing in horizontal direction as high amplitude peaks at 1X, 2X (rotating frequency harmonics) suggesting the parallel (offset) misalignment. In addition, there are Pole Pass Frequency (PPF) sidebands (SB) visible around 1X, 2X suggesting *Broken Rotor Bars* problem too.

MBVI Power Spectral Density (PSD) Spectrum (Fig.6.) displays the misalignment as 1X sidebands ($f \pm f_r$) around Line Frequency and sidebands are exceeding the Alarm threshold (red curve), highlighting the misalignment severity. The MBVI confirms the Vibration Analysis conclusions of misalignment. With MBVI, Broken Rotor Bars should be demonstrated with PPF sidebands around Line Frequency on PSD Spectrum. The Power Spectral Density Spectrum (Fig.6) does not show the sign of Broken Rotor Bars, because the motor is unloaded.

In this case, Vibration Analysis has given more precise conclusions than Motor Current Signature Analysis. The explanation is that the vibration measurements are sensitive even the motor is unloaded, where MBVI requires 80% to 100% load, to be effective.

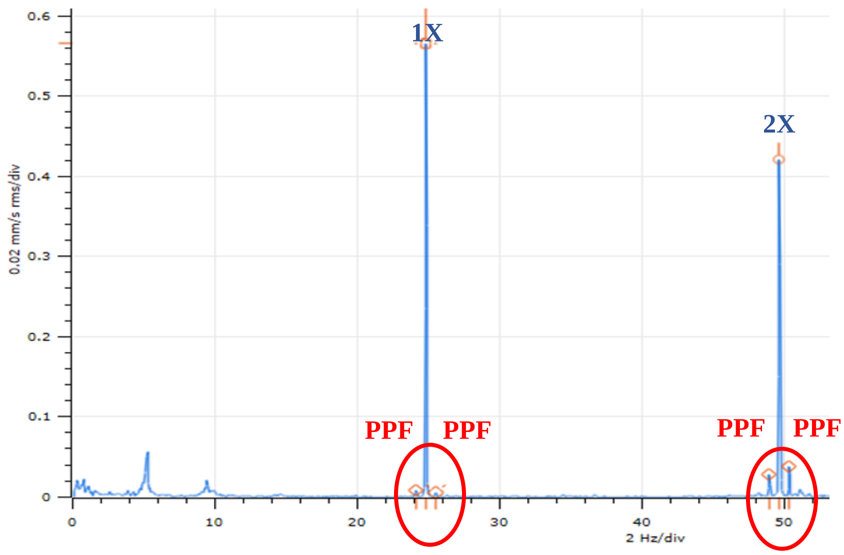


Figure 5: High resolution Spectrum Plot in Hz
1X =24.813Hz, PPF=4xSLIP=4x(25-24.813Hz)=0.748Hz, SB=25.5Hz

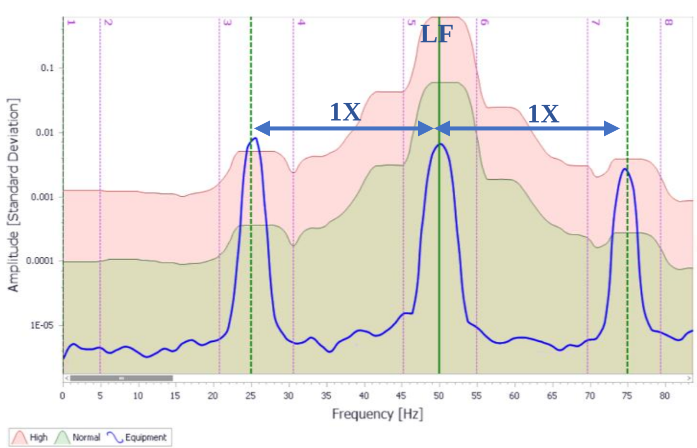


Figure 6: Power Spectral Density
1X sidebands around LF

TEST 2: The Induction Motor with two broken rotor bars, coupled, similarly misaligned as in the TEST 1, but 100% loaded.

The Vibration Analysis, Spectrum plot measured on Motor DE Bearing in horizontal direction (Fig.7) shows as amplitude peaks at 1X, 2X but this time 2X amplitudes comparing 1X amplitude are quite low suggesting decrease in *misalignment*. Presence of harmonics depends on coupling type and Elastomeric Flexible Coupling is most probably absorbing more in this test. More measurements, comparing horizontal and vertical amplitude and phase taken on opposite sides of the coupling are needed to give the better answer. In addition, Pole Pass Frequency (PPF) sidebands are less visible around 1X, 2X giving no suggestion of a Broken Rotor Bars problem.

MBVI PSD Spectrum (Fig.8), shows comparison of the curve from the TEST 1 (blue) with the curve from TEST 2 (red). The red curve displays the misalignment as 1X sidebands around Line Frequency, but sidebands are below Alarm threshold, confirming the decrease in misalignment severity, same as Vibration Analysis. The Broken Rotor Bars symptoms are now clearly visible as PPF sidebands around LF on PSD Spectrum as would be expected in the electrical signature with a fully loaded motor.

In this test MBVI has given more distinct conclusions than Vibration Analysis. Vibration Analysis would need more measurements to be more precise.

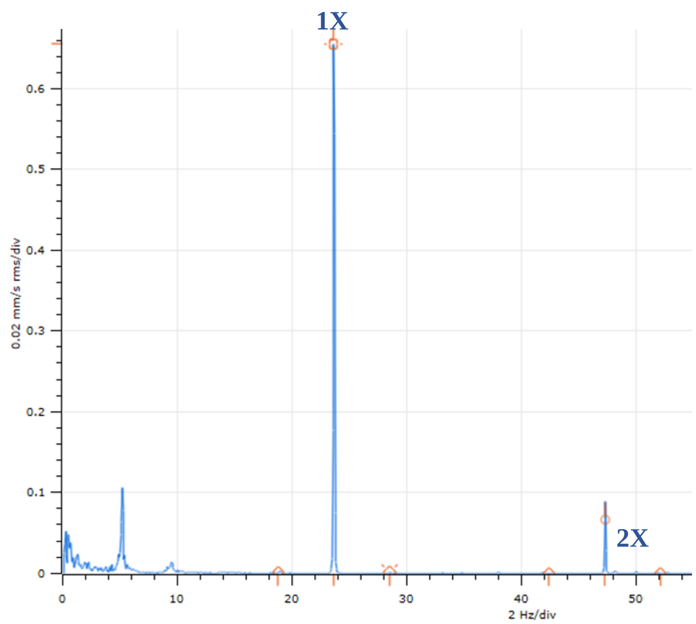


Figure 7: High resolution Spectrum Plot in Hz
1X=23.625Hz, PPF=4xSLIP=4x(25-23.625Hz)=5.5Hz, SB=29.125Hz

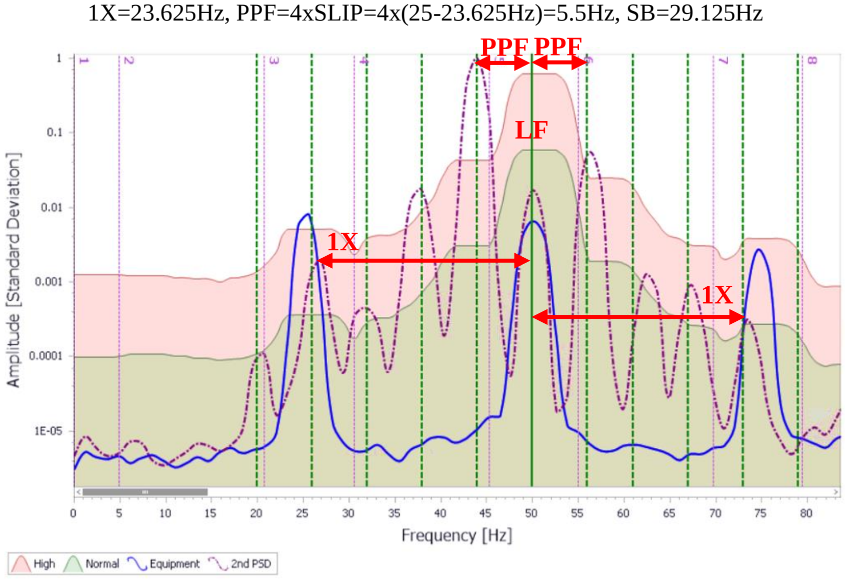


Figure 8: Power Spectral Density
LF =50Hz; PPF=4xSLIP=4x1.375Hz=5.5Hz, SB=55.5Hz

TEST 3: The Induction Motor with NDE bearing damaged inner race, coupled, misaligned as in TEST 2 and 100% loaded.

Damaged Bearing - inner race malfunction on motor Non Drive End (NDE) is presented in the Vibration Demodulated Spectrum plot (Fig.9) as high amplitude peak at Ball Pass Frequency of Inner Race (BPFI, f_I in Table I), and it is approximately calculated as BPFI=(No. of Balls/2)+1.2 (see Table I). If the Inner Race is rotating, there will be an impact each time the ball passes the damaged point and 1X sidebands around BPFI should be visible. Vibration Analyses has nicely detected damaged bearing inner race on NDE bearing.

With MBVI, the bearing faults appear as sidebands around LF at a distance of particular bearing fault frequency. The Power Spectral Density (PSD) Spectrum (Fig.10) displays in Frequency Band 10 – typical for bearing problems, BPFI sideband amplitude exceeding the Alarm threshold, suggesting the damaged bearing inner race (red ellipse).
In this test, VA as well as MBVI, confirmed the Bearing damaged inner race malfunction. The disadvantage of MBVI, in case of the same type of DE and NDE bearing and same bearing fault frequencies, it is limited in ability to distinguish which bearing is faulty. VA requires measurement on each bearing but based on the vibration amplitude at particular bearings one can distinguish which bearing is faulty.

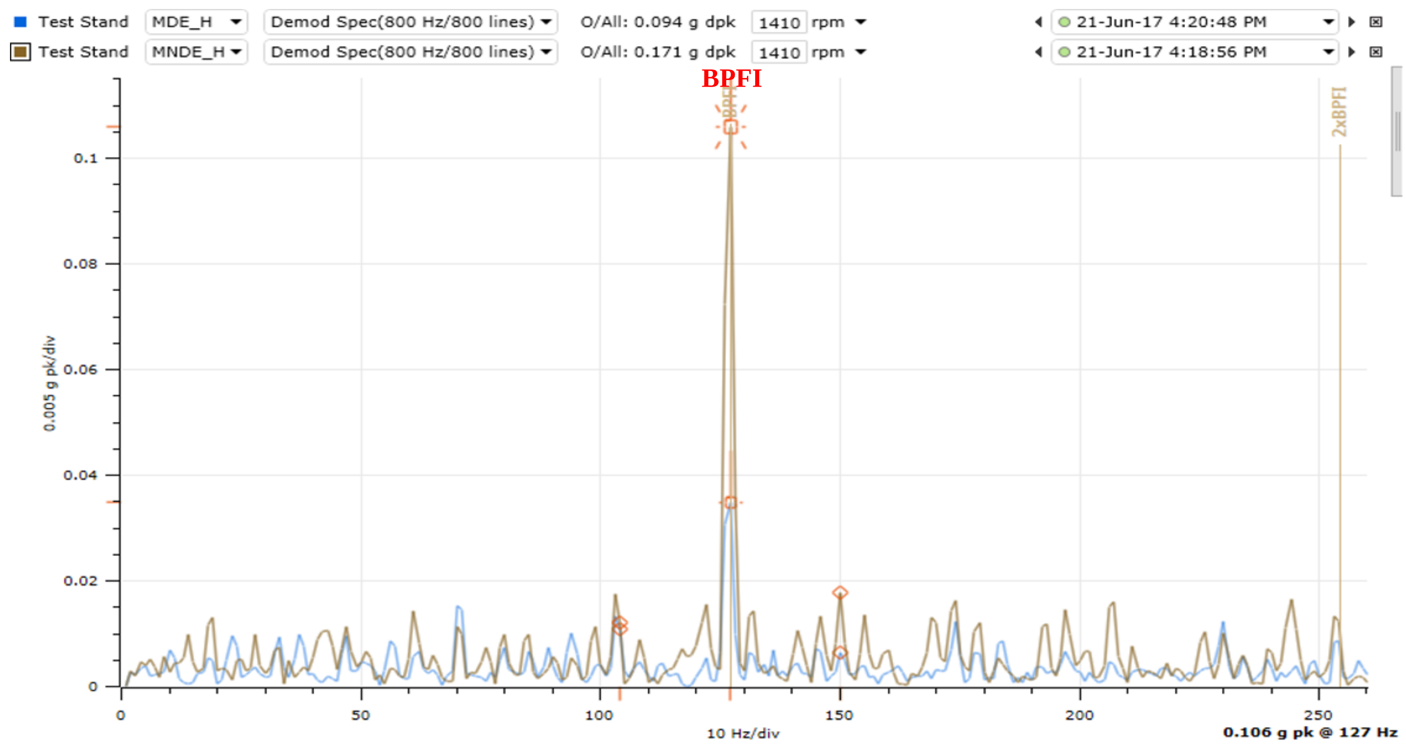


Figure 9: Demodulated Spectrum Plot in Hz
1X =23.5Hz; SLIP=(25-23.5Hz)=1.5Hz

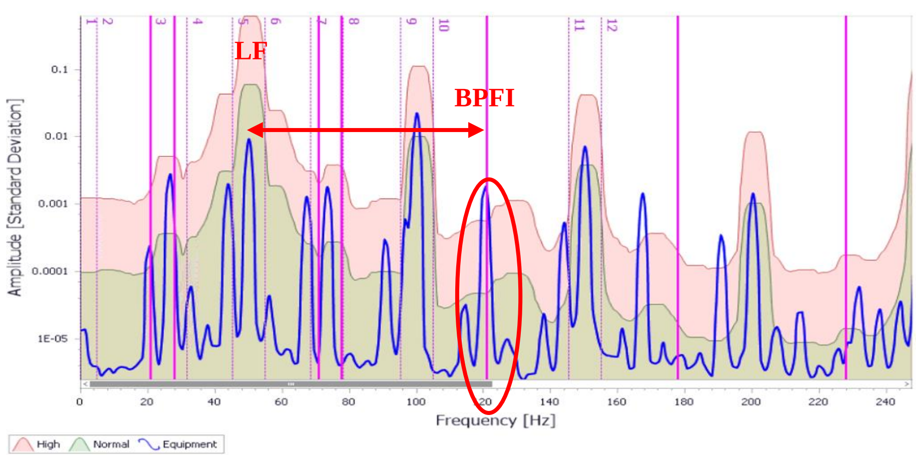


Figure 10: Power Spectral Density
LF=50Hz; BPFI=(Nb/2+1.2)=5.4xRPM (pink)

TEST 4: The Induction Motor with NDE bearing damaged (same as in TEST 3) but uncoupled and unloaded.

Damaged Bearing - inner race malfunction is not visible in the Vibration Demodulated Spectrum plot (Fig.11), due to unloaded motor and bearing condition and no radial preload due to the lack of misalignment.

With MBVI, Power Spectral Density (PSD) Spectrum (Fig.12) displays comparison of PSD Spectrum from previous TEST 3 (red dotted line curve) with motor loaded and TEST 4 (blue line curve) with motor uncoupled and unloaded. There is significant decrease in amplitude on all the sidebands due to uncoupled and unloaded motor state. Due to uncoupled motor state, there is no misalignment present and the 1X sidebands around Line Frequency as symptoms of misalignment have disappeared. This confirms a correct MBVI Analysis of misalignment in test one. Due to the unloaded motor condition, the damaged bearing inner race symptoms are not visible in Frequency Band 10 – typical for bearing problems, neither on BPFI sidebands around LF.
The limitation for both methods (VA and MBVI) in bearing damage detection is that, for VA bearing must be radially loaded with a preload and for MBVI tested Motor should be at close to 80% of the full load. Given that the electrical and mechanical loads are minimal, the resulting data shows no indication of PPF, misalignment nor bearing faults. The amplitude of sidebands will be generally higher if the damaged area is in the bearing load zone, thus accentuating the fault condition of the bearings.

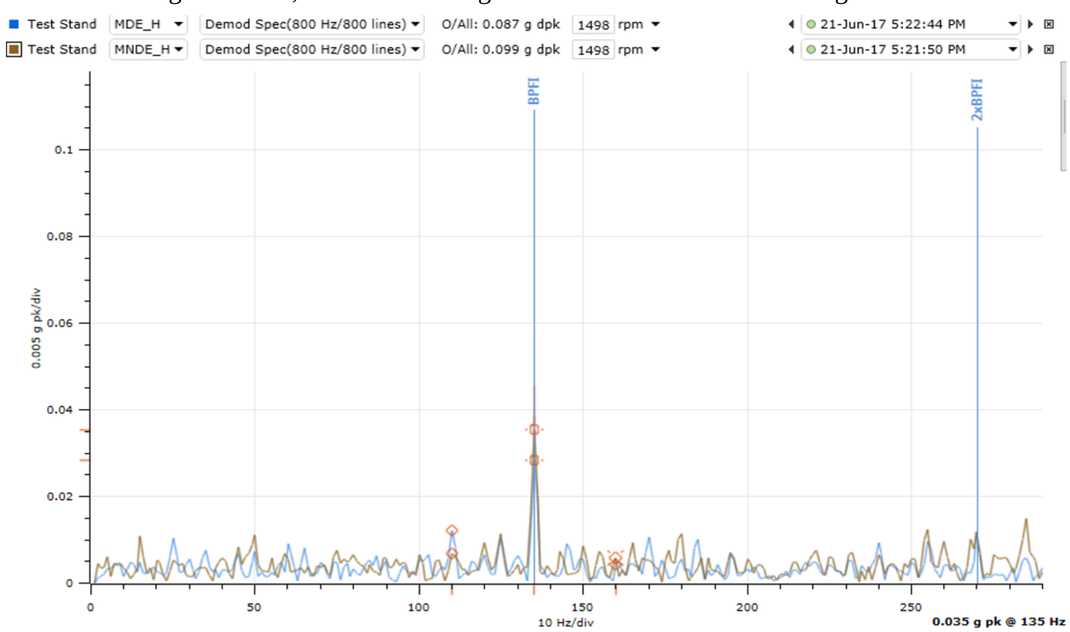


Figure 11: Demodulated Spectrum Plot in Hz
1X =24.94Hz; SLIP=(25-24.94Hz)=0.06Hz

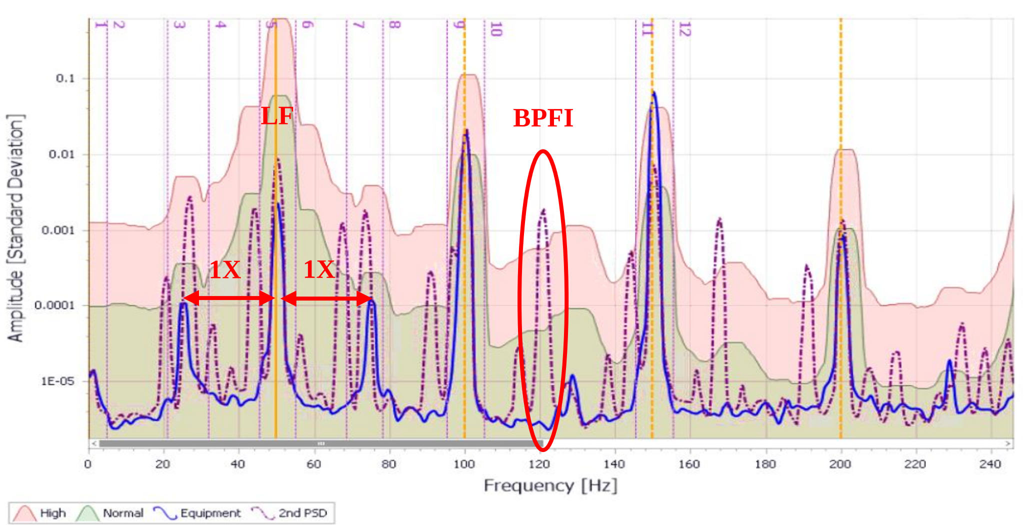


Figure 12: Power Spectral Density
Blue curve – Test 4 PSD, Red dotted curve -Test 3 PSD

TEST 5: The Induction Motor with NDE bearing damaged and motor uncoupled (same as in TEST 4), but with 36g of unbalance added on motor coupling hub.

Unbalance malfunction is presented in the Vibration Spectrum plot (Fig.13) as high amplitude peak at 1X rotating frequency, measured in horizontal and vertical direction. The amplitude in horizontal and vertical direction should be about the same depending on system support stiffness in a given direction. With MCSA/MBVI, the unbalance fault appears as 1X sidebands around LF and sidebands are exceeding the Alarm threshold red curve, same as misalignment would (Fig.14).

Structural Looseness in VA will normally generate high amplitude peak at 1X rotating frequency significantly higher in one direction with greatest weakness. In our case, the vertical 1X amplitude is three times higher than the horizontal amplitude, which is unusual and suggests structural looseness in addition to existing unbalance (Fig.13). Note, that motor base plate is not bolted to the base and base is likely weak in the vertical direction. With MBVI, the structural looseness is typically displayed in Band 1. In our case there is only small amplitude peak in Band 1, not clearly confirming the structural looseness.

This test has shown the disadvantage of MBVI, as it cannot simply distinguish between unbalance and structural looseness. The structural looseness was clearly visible on Vibration Analysis spectrum, but not on MBVI in this test.

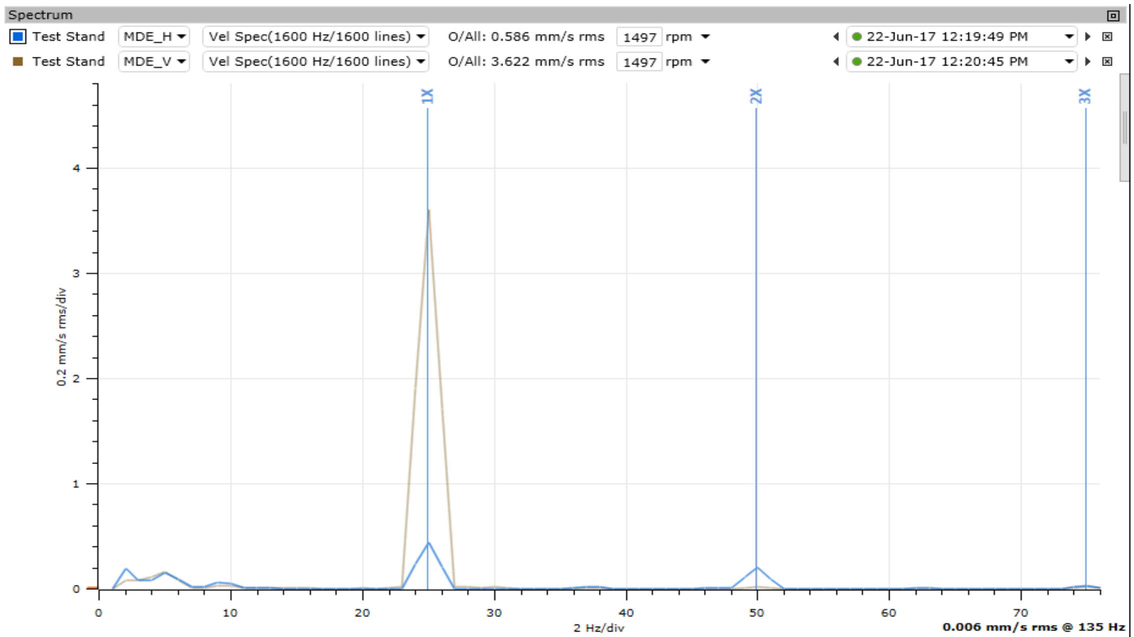


Figure 13: Vibration Spectrum Plot in Hz

1X =24.94Hz; SLIP=(25-24.94Hz)=0.06Hz

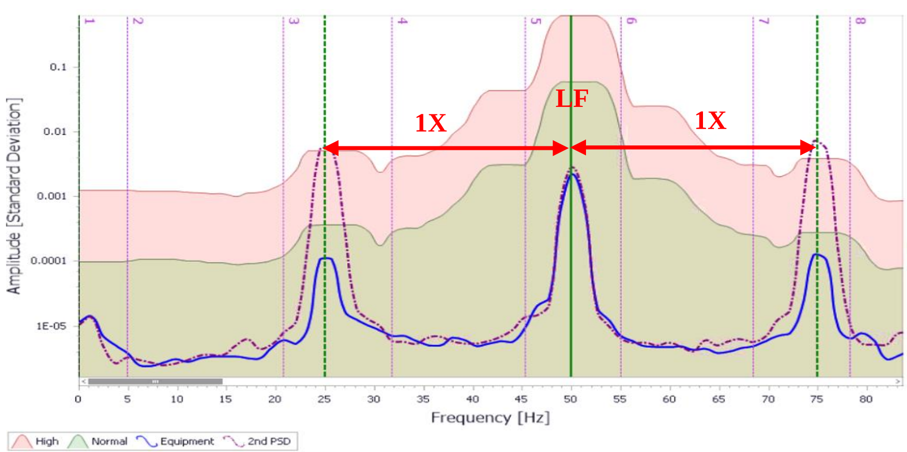


Figure 14: Power Spectral Density

Blue curve – Test 4 PSD, Red dotted curve -Test 5 PSD

TEST 6: The Induction Motor with NDE bearing damaged, uncoupled with 36g of unbalance (same as in TEST 5), but with two casing bolts loosened on the right side of the motor on DE and NDE

Unbalance malfunction is presented in the Vibration Spectrum plot (Fig.15) at 1X rotating frequency, and the amplitude is higher than in previous test despite the same 36g unbalance, possibly due to lowered stiffness due to loosened bolts. The same behavior is visible on MBVI PSD Spectrum, where 1X sidebands around LF are higher, due to lowered stiffness due to loosened bolts (Fig.16).
Rotating Looseness in Vibration Spectrum will normally generate large number of harmonics and may cause the lifted noise floor, as visible in our case (Fig.15). With MBVI, the rotating looseness seems to be demonstrated same as unbalance fault as 1X sidebands around LF, but the sidebands are higher in amplitude due to looseness and lowered stiffness and are exceeding the Alarm threshold red curve (Fig.16).
This test again confirms the limitation of MBVI, as without additional tests one cannot simply distinguish between unbalance, misalignment and increased 1X sidebands due to looseness. In this case involving the Vibration Analysis providing additional information would help to pinpoint the motor malfunction.

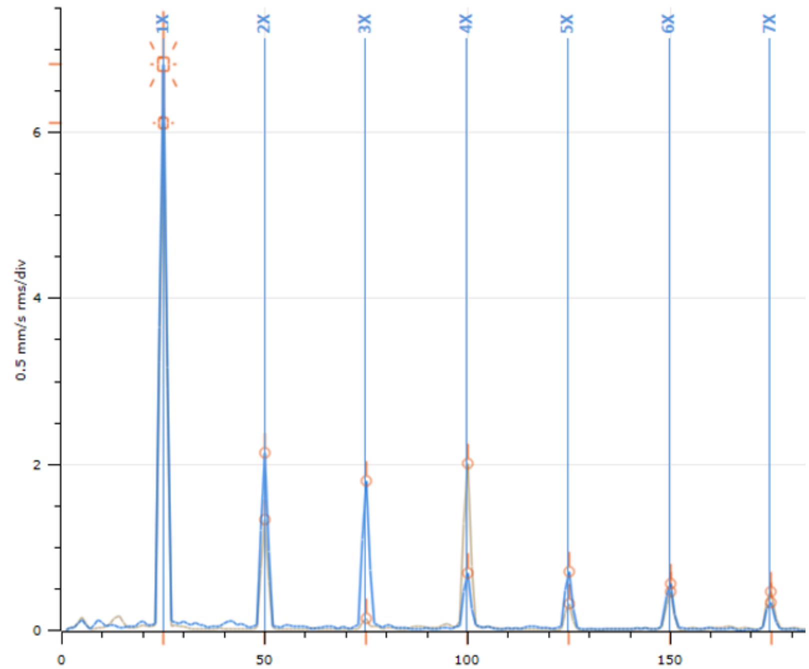


Figure 15: Vibration Spectrum Plot in Hz
1X =24.94Hz; SLIP=(25-24.94Hz)=0.06Hz

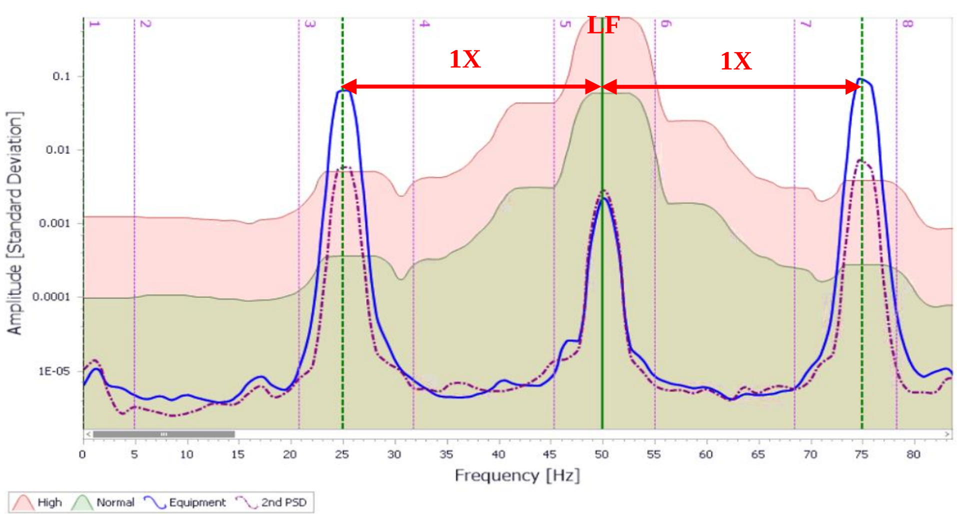


Figure 16: Power Spectral Density
Blue curve – Test 6 PSD, Red dotted curve -Test 5 PSD

SUBMERGED SEA WATER LIFT PUMPS CASES

The following case studies are selection of authors successful diagnostics conclusions using Motor Current Signature Analysis or Vibration Analysis, whichever method was more suitable or simply available on site.

CASE 1: SWLP, Ski-slope

The Sea Water Lift Pump (SWLP) experienced spiking signal on one of the accelerometer vibration transducers. Diagnostics Analysis revealed that spiking occurred even when machine was in stopped condition. There are four vibration transducers on this SWLP and only one (green) was showing the spikes on stopped or running pump (Fig.17)
The Waterfall Spectrum plot (Fig.18) shows the low frequency ski-slope appeared in vibration signature. The ski-slope is called a typical erroneous pattern in the spectrum with very high amplitude, at very low frequency. The error in the measured signal is usually caused by transducer overloading, due to transient shock – mechanical, thermal or electrical.
The waveform plot (Fig.19) shows abnormal waveform pattern, sign of step change, explaining the ski-slope pattern in the spectrum.
The symptoms in this case suggests faulty vibration transducer, as the problem is only on one transducer out of four and spikes appears also on the stopped machine. The case demonstrates the challenges with the vibration transducers installations as a main disadvantage of the Vibration Analysis in the case of submersible pumps but case shows good diagnostics on sensor system health.

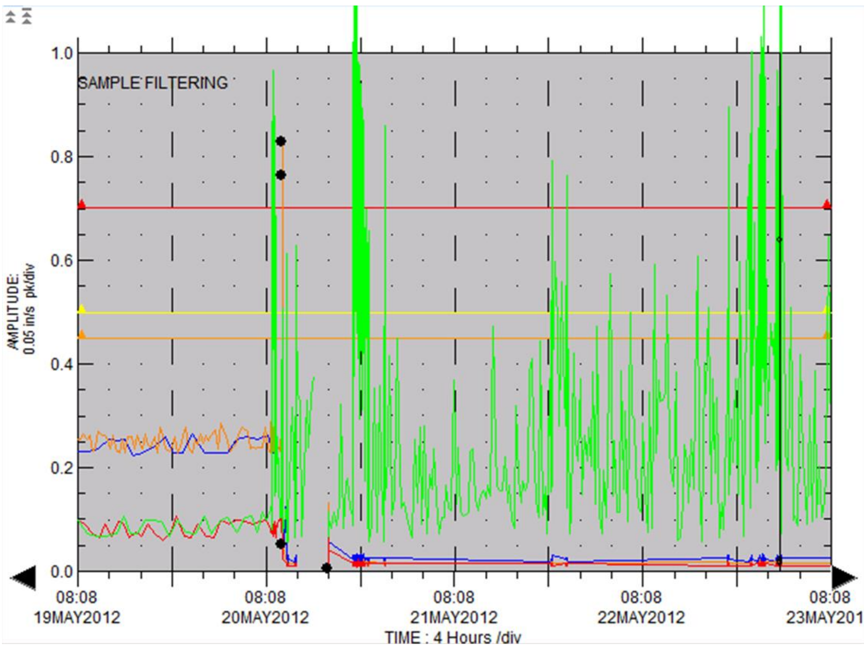
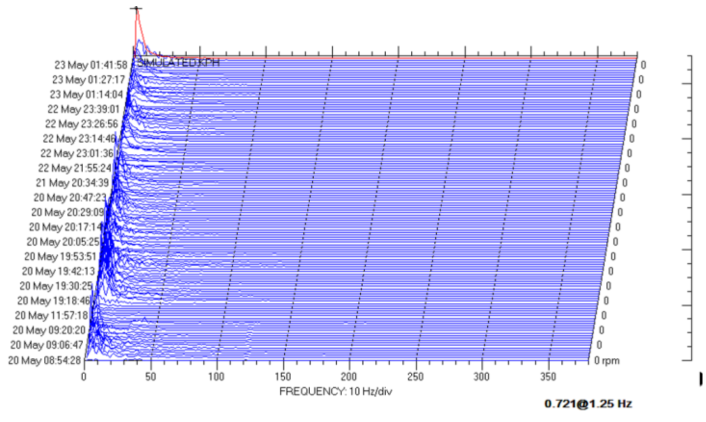


Figure 17: Vibration Trend Plot for all the probes



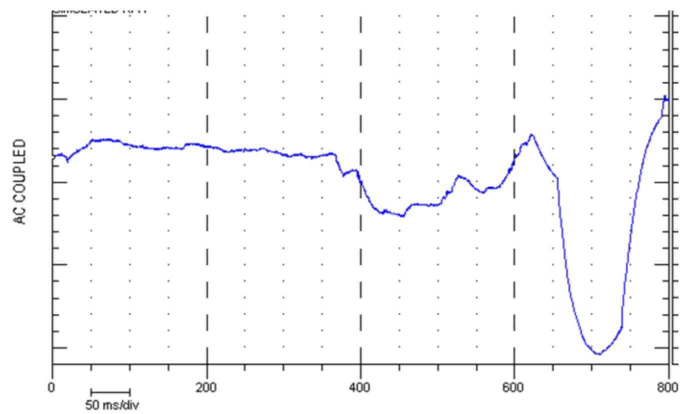


Figure 18: Waterfall Spectrum Plot **Figure 19: Time base plot**

CASE 2: SWLP, Cavitation

Cavitation, as described by *Mokhatab, et al. (2014)*, is a phenomenon that occurs when vapor bubbles form and move along the vane of an impeller. As these vapor bubbles move along the impeller vane, the pressure around the bubbles begins to increase. When a point is reached where the pressure on the outside of the bubble is greater than the pressure inside the bubble, the bubble collapses. It does not explode, it implodes. This collapsing bubble is not alone but is surrounded by hundreds of other bubbles collapsing at approximately the same area on each impeller vane.

The Engineering methods, as summarized by *Al-Hashmi, (2005)*, are the most commonly applied methods for monitoring cavitation in centrifugal pumps. There two the most popular:

Vibration Method: This method is based on the analysis a vibration signal. The vibration signal is acquired on the structure of the pump by mounting a transducer near the pump outlet where the bubbles are collapsing. The measured signal indicates cavitation as excited a broadband frequency, lifted noise floor.

Motor Current Signature Analysis (MCSA): It is based on the principle that cavitation causes a drop in head and capacity, therefore reduces the overall hydraulic load on the motor, causing a decrease in the load current and a slight increase in the motor speed.

Spectrum-based current analysis for detection of cavitation use approximately 1/2X sideband frequencies around the fundamental supply frequency. The sidebands frequency span changes in the same way as the rotor speed changes with the cavitation. The sideband frequency increases as the flow rate increases during pump normal operation. During the cavitation, span between the fundamental frequency and the approximately 1/2X sidebands decreases relatively.

It was also found that the lifted noise floor around the fundamental supply frequency can be used as an indication of cavitation intensity in a centrifugal pump.

The changes in the phase current RMS values with respect to the flow rate can be also used for cavitation detection. Normally, the RMS value of the phase current increases as the flow rate increases. This range represents the normal operating range of the pump. Increasing the flow rate above the cavitation threshold, RMS value of phase current decreases as the flow rate increases, during the cavitation. In this way, the phase current RMS value can be used for detecting and diagnosing cavitation in a centrifugal pump.

The Sea Water Lift Pump (SWLP) experienced sudden increase in overall vibration levels on all four casing velocity transducers. The vibration increased rapidly within 1 minute over the danger limit and tripped automatically (Fig.20). It appears this condition also exists briefly on the re-start of the pump.

The Waterfall spectrum plots (Fig.21) display frequency components development in time, on two casing velocity transducers. It is nicely visible as the spectrum at the bottom is clear with 1X rotating frequency component only. Later, the sudden broad band frequency excitation (in red square), with the lifted noise floor rises up in the frequency range of 200-400Hz, as well as in the frequency range of 600-800Hz. This random burst of energy is a typical sign of increased cavitation in the pump.

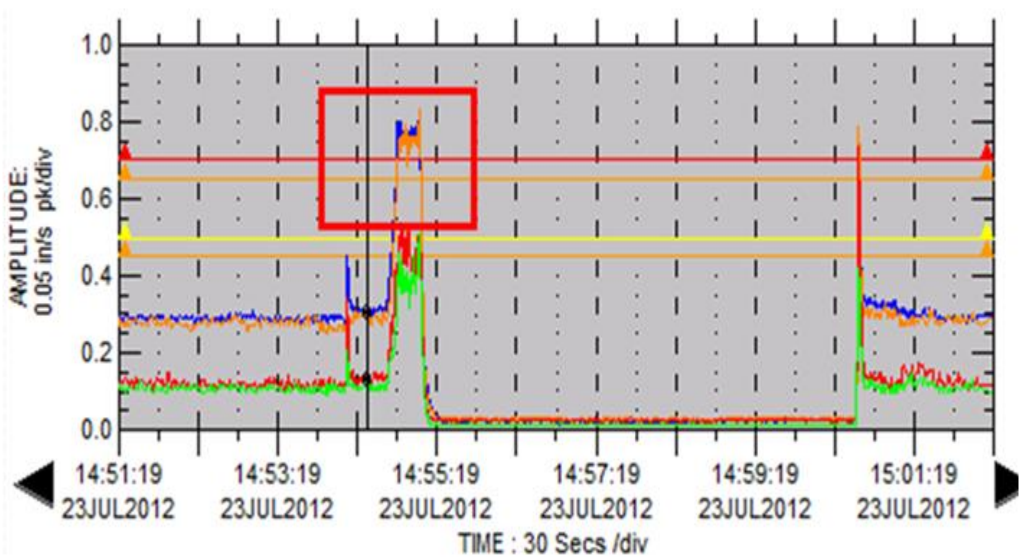


Figure 20: Overall Vibration Trend Plot for SWLP

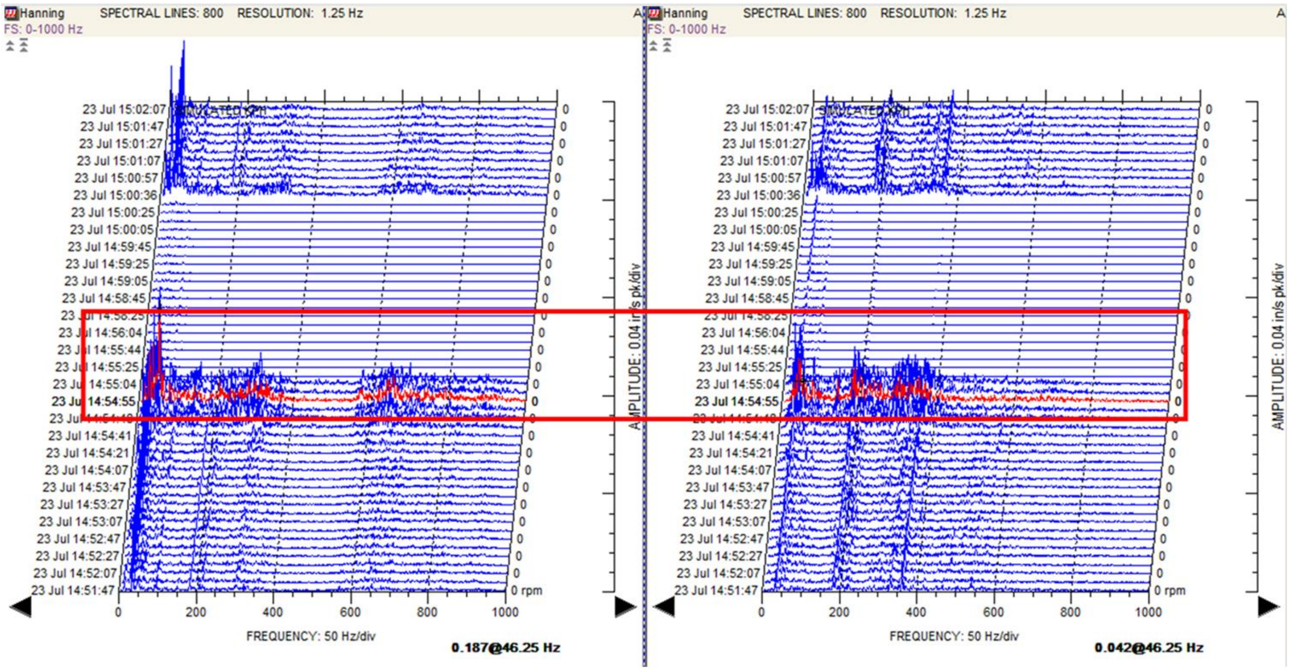


Figure 21: Waterfall Spectrum Plot for SWLP

CASE 3: SWLP, Cavitation

The same Sea Water Lift Pump (SWLP) as in previous case was monitored using Model-Based Voltage and Current System (MBVI).

The comparative Power Spectral Density (PSD) curves (Fig.22) show comparison of SWLP A (blue curve) and SWLP B (red curve). There is a broad band noise excitation in the frequency range of 160-220Hz on SWLP A. This broad band lifted noise floor indicates **cavitation** in the Sea Water Lift Pump A and is not visible in SWLP B, as verified there was no cavitation.
Further, the current unbalance of 6.8 percent was measured on SWLP A, which is more than the recommended 5 percent. Current unbalance causes motors to overheat and lose torque. Developing short circuit faults due to the degradation of isolation materials may also cause change in current unbalance over the time.

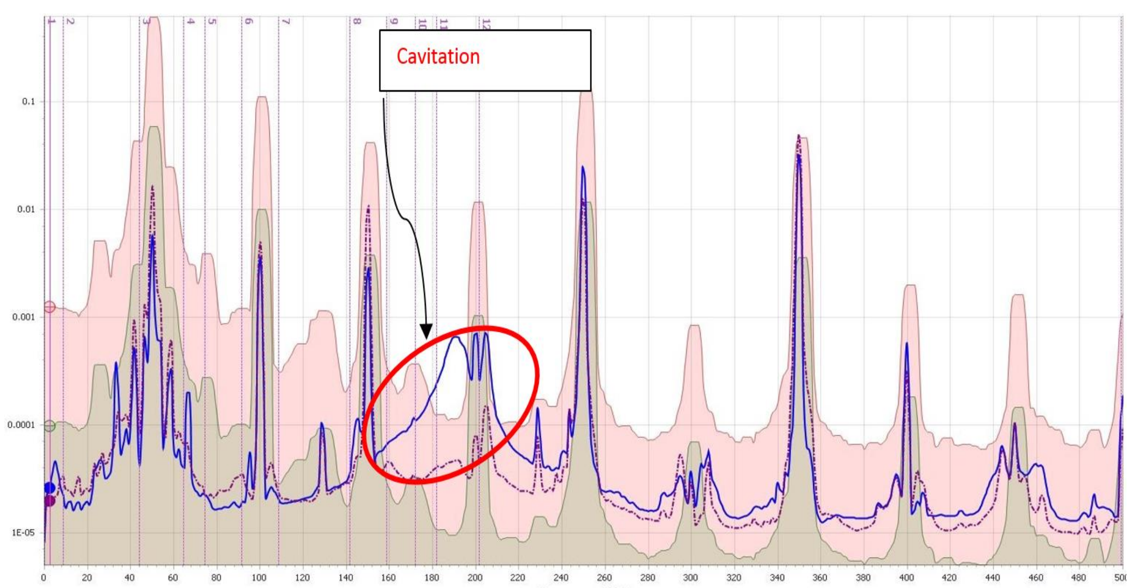


Figure 22: Power Spectral Density
Blue-SWLP A, Red-SWLP B

CASE 4: SWLP, Mechanical Unbalance

The Sea Water Lift Pump (SWLP) experienced a gradual increase of 1X rotating frequency component sidebands around the Line Frequency (LF) on Power Spectral Density (PSD) curve over the period of five months (Fig.23). Next plot (Fig.24) shows, the Equipment PSD curve (blue) obtained during the learning process of MBVI system modeling the conditions of good SWLP condition and it is within the green envelope, indicating normal pump condition. Figure 24 further shows, the increased Instant PSD curve (red), exceeding the red envelope high alarm threshold. This instantaneous PSD shows increased 1X rotating frequency (±16.5Hz, 990 rpm) sidebands around LF (50Hz), confirming the mechanical unbalance.

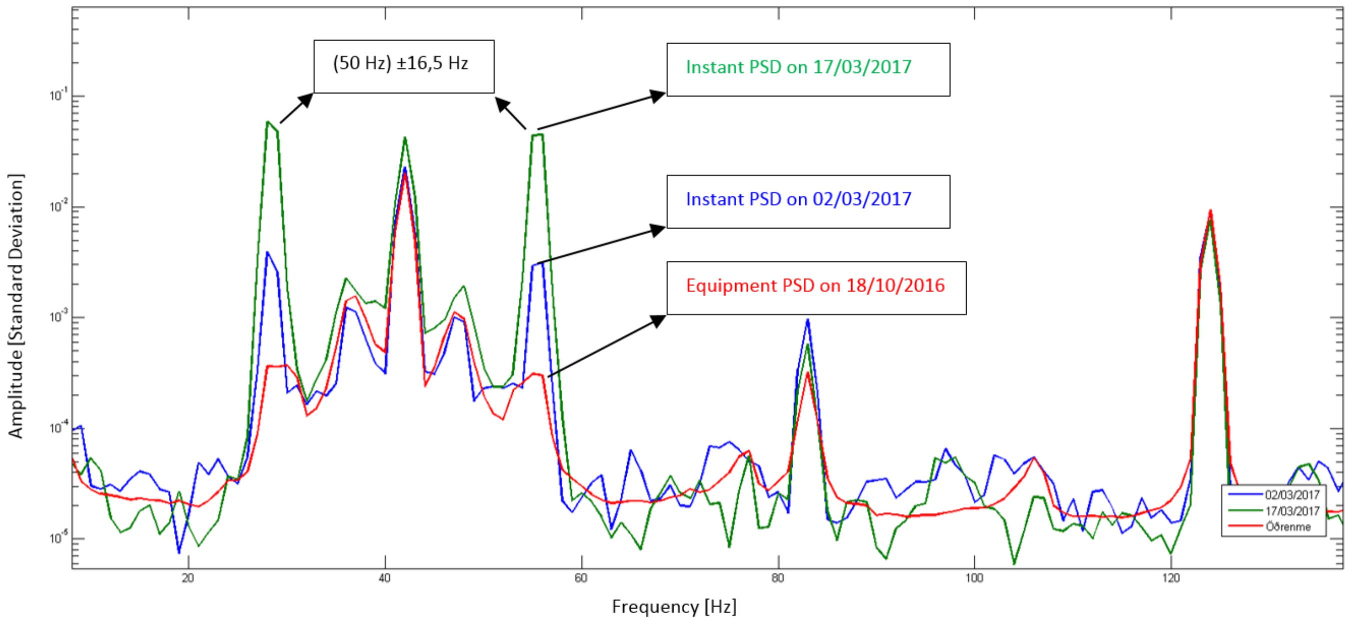


Figure 23: Power Spectral Density

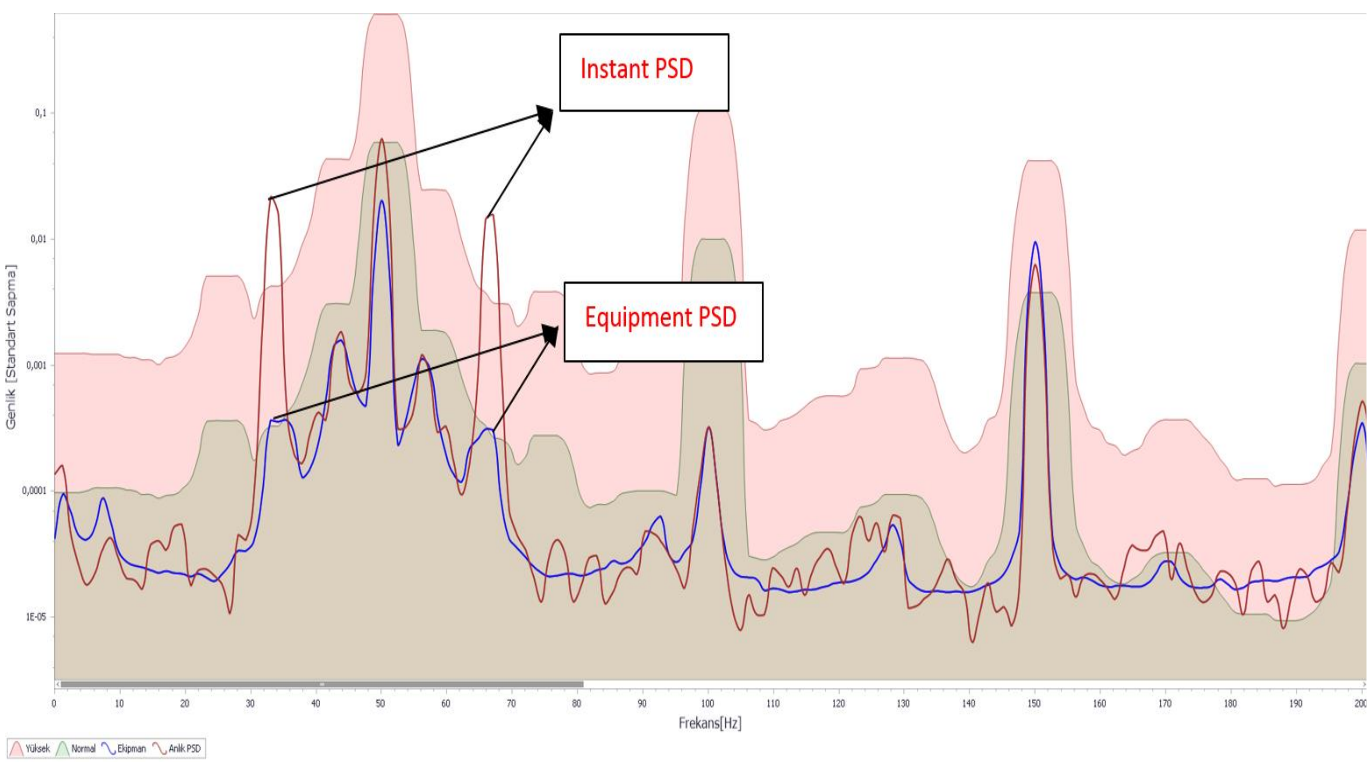


Figure 24: Power Spectral Density

CASE 5: SWLP, Rotor Fault

The Sea Water Lift Pump (SWLP), Power Spectral Density (PSD) plot (Fig.25) shows increased peak (red curve) in frequency band 3 – rotor related, exceeding the red envelope high alarm threshold. Figure 26 shows the trend of band 3 – rotor fault parameter and its value above the Alarm threshold (16 Standard Deviations), dotted red horizontal line and its increased over the one month period (red arrow). The above mentioned findings suggest SWLP rotor fault in worsening trend state, recommending closer follow up and overhaul planning.

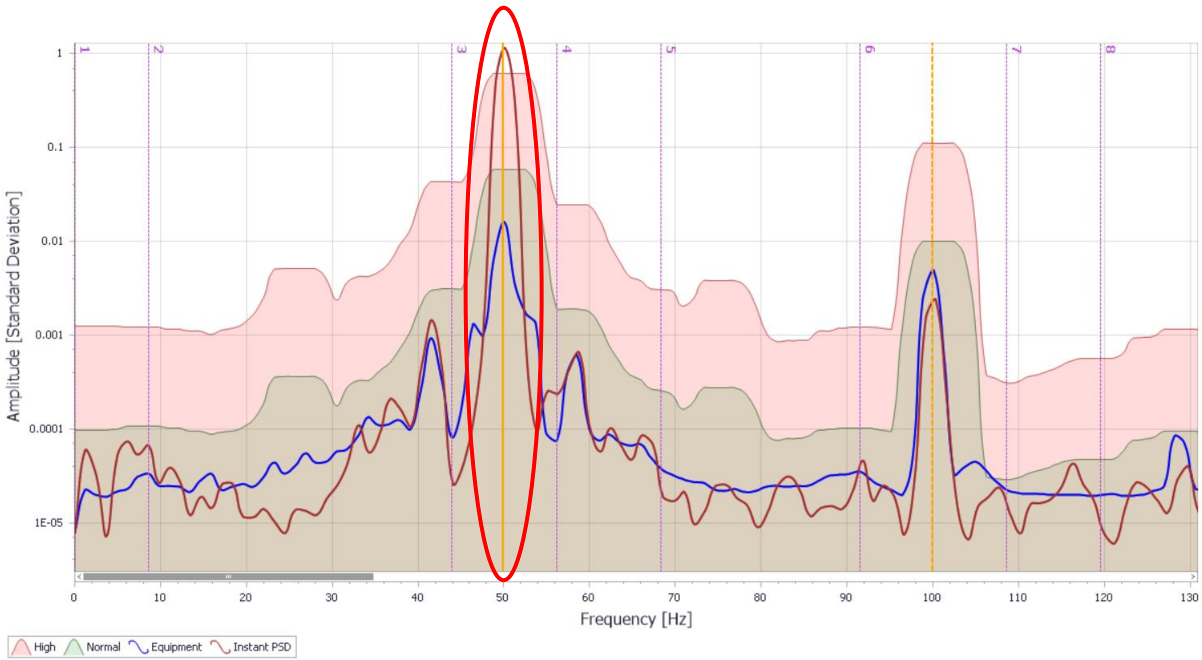


Figure 25: Power Spectral Density

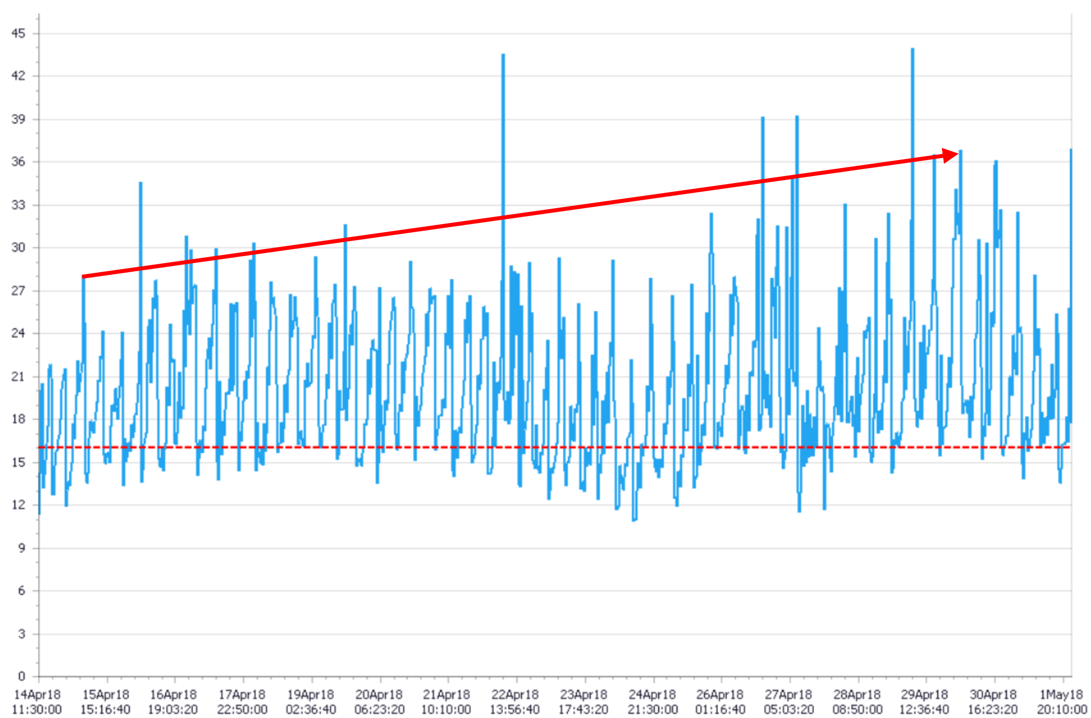


Figure 26: Trend of Rotor Fault parameter

CASE 6: SWLP, Bearing Inner Race Fault

The Sea Water Lift Pump (SWLP) Power Spectral Density (PSD) plot (Fig.27) shows increased peaks (red circles) at bearing Ball Pass Frequency of Inner Race (BPFI) and its harmonics exceeding the red envelope high alarm threshold, suggesting the bearing fault. Figure 28 shows the trend of bearing fault parameter over the two months period and its value above the Alarm threshold (8 Standard Deviations), dotted red horizontal line. Figure 29 shows, MBVI Expert System bar graph, transferring the diagnostics Analysis obtained from the PSD spectral bands, into the user friendly bar graph plot. The bar graph of bearing fault increased in the "Caution" yellow region, suggesting attention and closer monitoring of the fault parameter, at this stage.

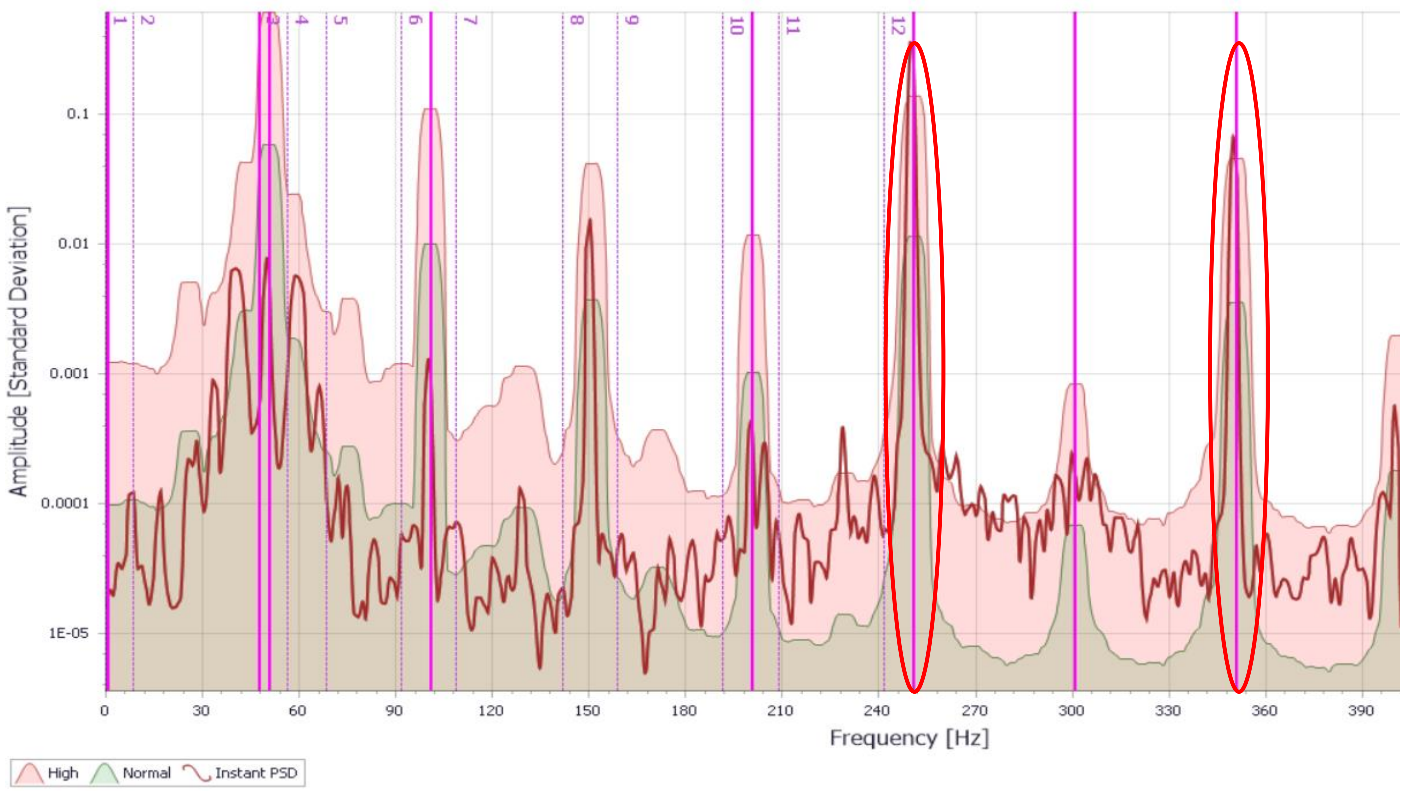


Figure 27: Power Spectral Density

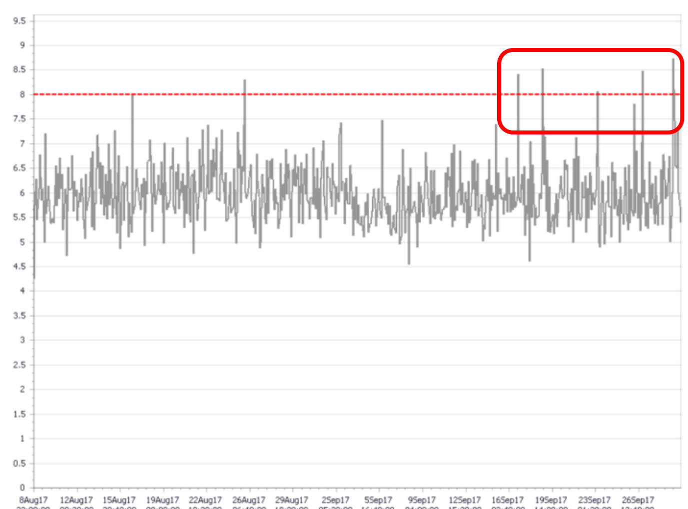


Figure 28: Trend of Bearing Fault parameter

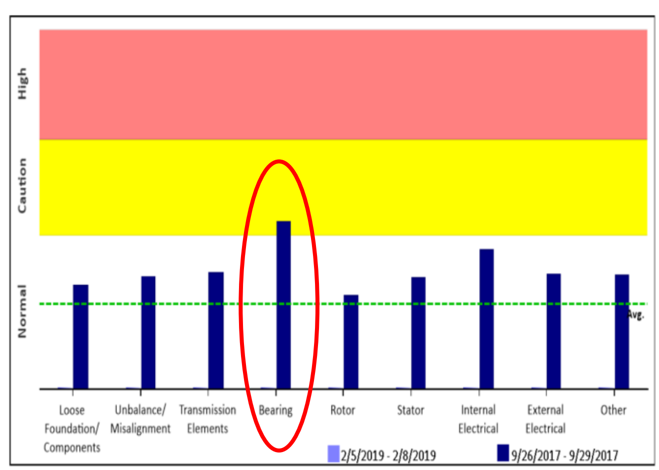


Figure 29: Trend of Bearing Fault parameter

LNG SUBMERGED CRYOGENIC PUMPS CASES

The following cases are just few examples from authors *Popálený and Péton, (2019) paper on this topic.*

CASE 7: HPSO, Rolling Element Bearing Failure

An increase of the direct vibration amplitudes was observed on both accelerometer transducers (Fig.30) of a High Pressure Send-Out pump (HPSO), aka. Vessel type, secondary Ex-Tank pump. After some days of increasing trends, the plant technicians noticed a noise coming from the pump. Due to the noise and the high vibration amplitudes, the unit was stopped.
The top bearing inner ring damage was indicated by sidebands at 245 Hz (the inner ring fault frequency) from running speed and not as one would expect by the IRBP frequency and harmonics of this fault frequency. The sidebands were evident in amplitude logarithmic scale (in linear scale not so clear) (Fig.31). The inspection confirmed the diagnosis (Fig.32).

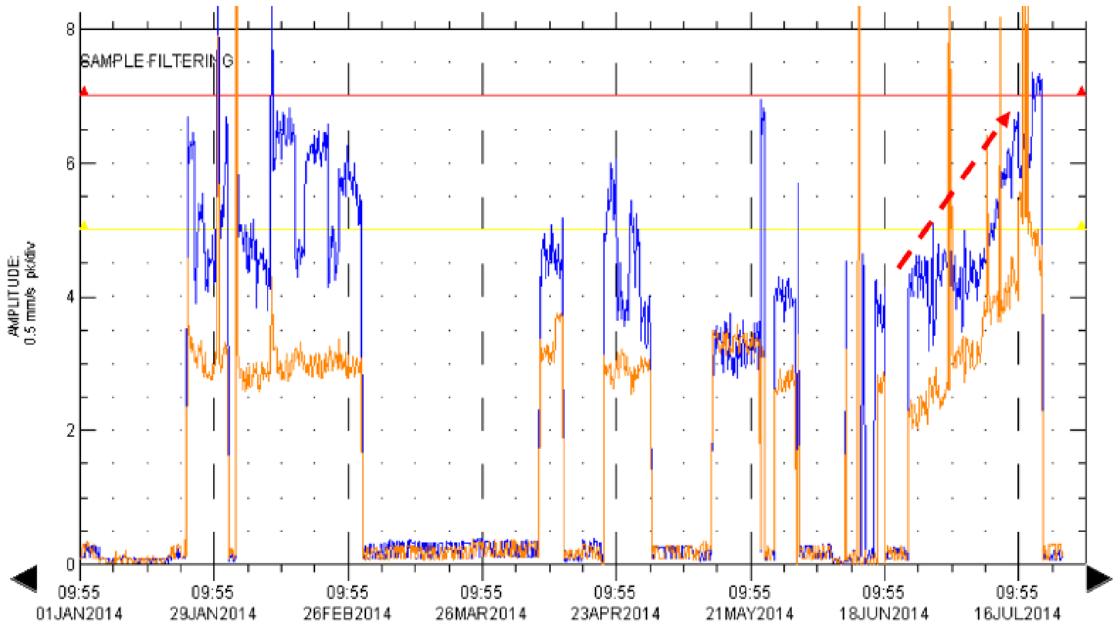


Figure 30: Both Accels Vibration On HPSO,
Top Accel-Orange, Bottom Accel-Blue

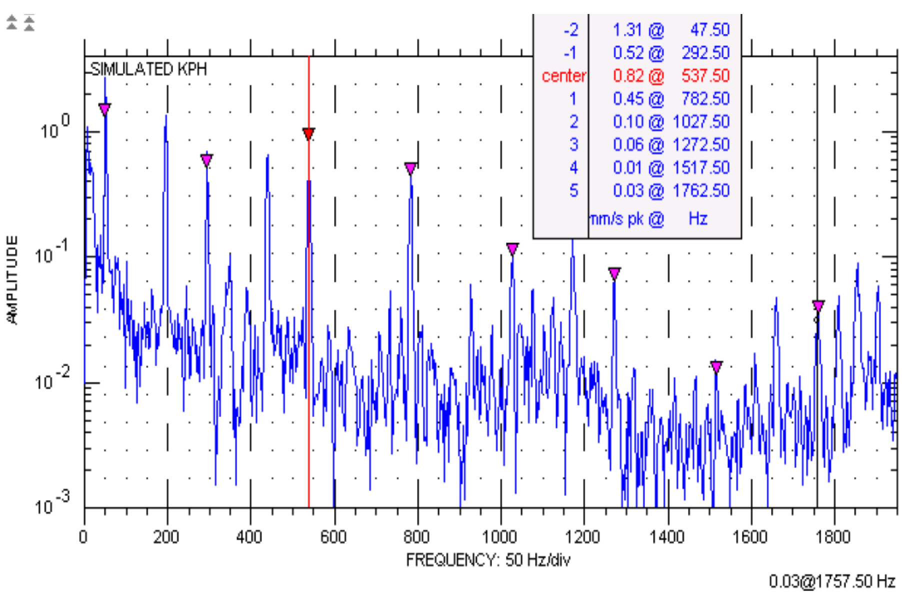


Figure 31: Spectrum Top Accel, Log Scale

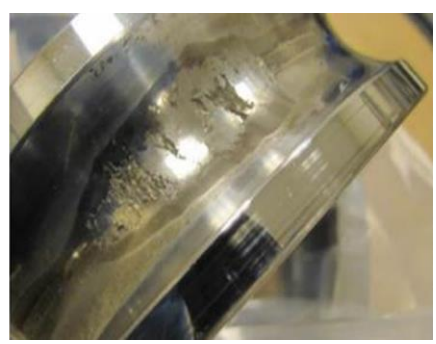


Figure 32: HPSO Top Bearing Inner Ring Spall

CASE 8: HPSO, Rolling Element Bearing Failure

The HPSO, vessel type pump was monitored with a MCSA/MBVI portable monitoring system.

The Expert System (Fig.33) suggested a high severity of the Bearing fault, based on the mechanical parameters and Power Spectral Density (PSD). The Expert System further suggested increased severity of the Current unbalance.

The detail Analysis of PSD (Fig.34), revealed that the Tail bearing cage frequency sidebands amplitude around Line Frequency (LF) exceeded the alarm threshold, suggested a problem with the bearing cage of the Tail bearing. Where, the bearing cage frequency (FTF) sidebands are calculated as:

FTF=(1/2-1.2/Nb)=0.6135xRPM=30.4Hz (black); where Nb is number of rolling elements (Balls).

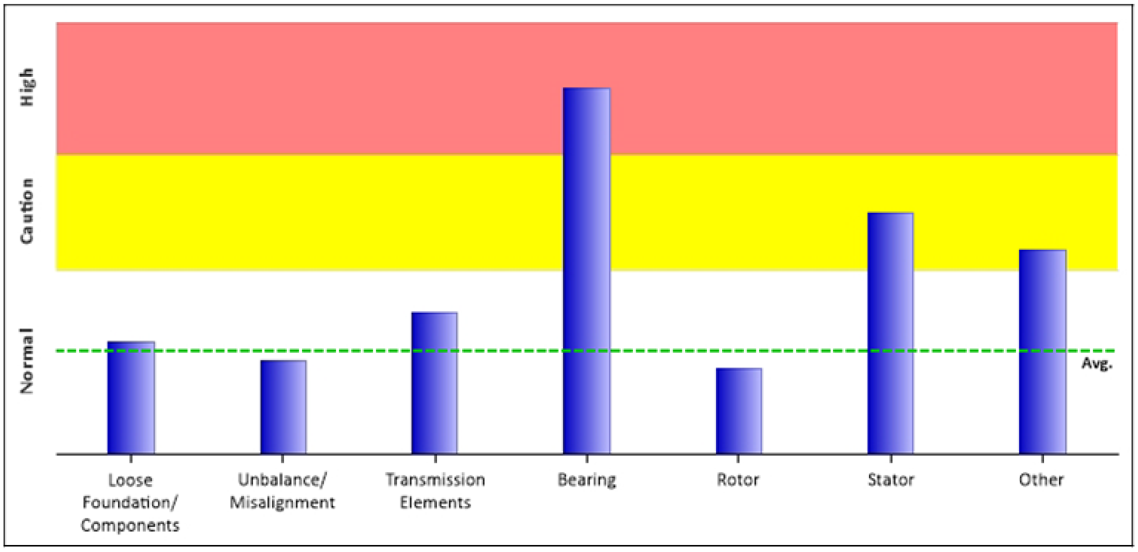


Figure 33: Expert System Bar Graphs

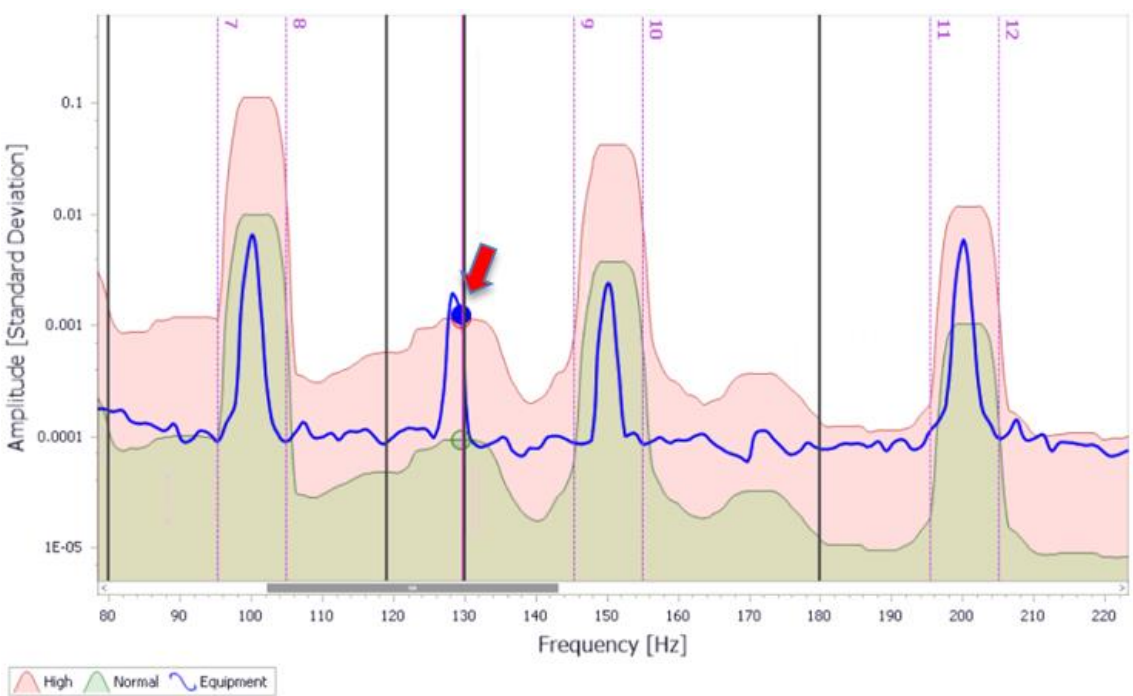


Figure 34: Power Spectral Density (PSD)

CASE 9: HPSO, Pump Vane Pass Frequency

The HPSO, vessel type pump was monitored with a MCSA/MBVI portable monitoring system. This is continuation of the detail PSD Analysis from the previous Case 8.

The Expert System suggested "Caution" severity for "Other" faults on the bar graph, not able to specify the problem exactly and Human Expert detail Analysis of the Power Spectral Density (PSD) was required.
The detail Analysis of PSD (Fig.35), revealed that the 7x running speed sideband around LF was visible (green dashed line). The pump vane pass frequency 7x sideband, due to 7 impeller vanes, was exceeding the alarm threshold. The pump impeller check was recommended in the next opportunity. PSD plot (Fig.36) further showed slightly increased amplitude in the Transmission Element band (no.3 and 5) due to 0.23x freq. sideband component, indicating the flow turbulence - possibly normal for this HPSO.
Based on measured electrical parameters, the current unbalance was 7.3% and exceeded the 5% reference alarm threshold. Current unbalance of an electric motor system is defined as the percentage of the maximum deviation of phase currents from the average current. As mentioned above, current unbalance causes motors to overheat and lose torque. Electric motors should not be operated with high current unbalance.

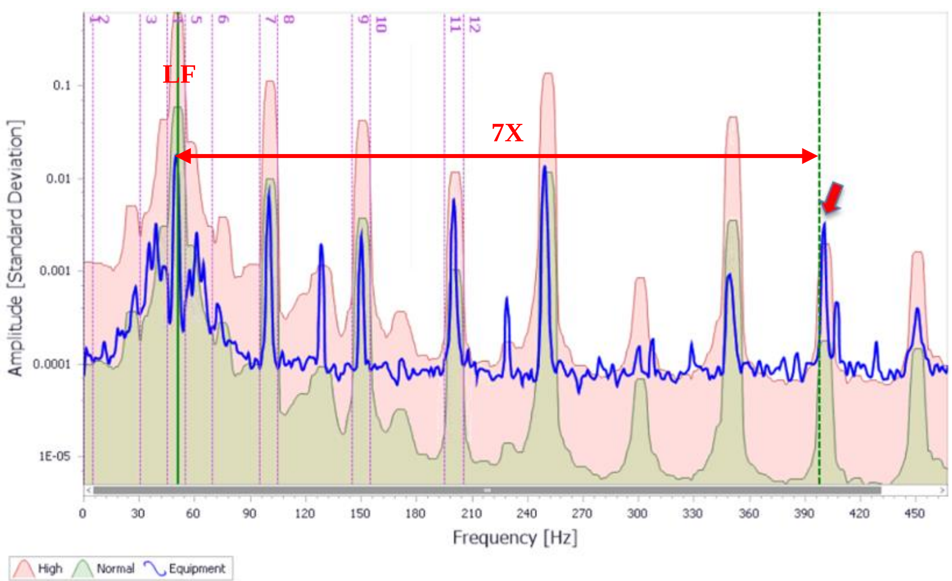


Figure 35: Power Spectral Density (PSD)

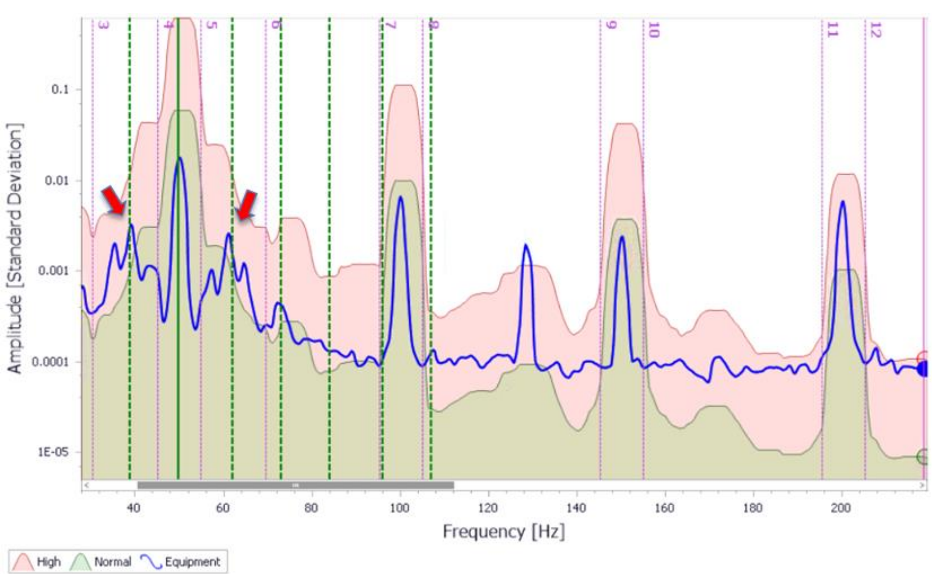


Figure 36: Power Spectral Density (PSD)

CONCLUSIONS

The article presents the comparison of condition monitoring and diagnostics techniques using Model-Based Voltage - Current Analysis (MBVI) and Vibration Analysis (VA). Further, shows utilization of various diagnostics plots as Current Spectrum with MBVI and with Vibration Analyses - Overall Trends, Spectrums and Timebase Waveforms. The paper clarifies the formulae of the frequency components amplified by the different malfunctions when using MCSA/MBVI and VA. Despite the different nomenclature and different definitions, the sidebands frequencies are equivalent between both methods. This analogy was demonstrated and was visible with various malfunctions, like unbalance, misalignment, looseness, bearing damage. The difference is that with Vibration Analysis the fault frequency is directly visible on Vibration Spectrum and with MCSA/MBVI fault frequency is visible as sidebands around Line Frequency aka. Fundamental Supply Frequency.

Vibration analysis is a well proven method, with reliable results and good overall understanding in the industry. There are many vibration based international standards with the recommended practices and alarm values to compare the machine condition across the fleet. The overall vibration can be trended and compared against the set alarm values for typical classes of machines. The submersible pumps condition monitoring mainly depends on frequency spectrum and time waveform based analysis, which are well understood. The main disadvantages of the Vibration Analysis in case of submersible pumps are challenges with the vibration transducers installations. The vibration transducer must be suitable for a submersible application and in case of cryogenic pumps able to operate in cryogenic temperatures ranges below -162°C. Despite the installation risks, the correct transducer installation, as shown on the described case stories, can give very detailed results and can pinpoint the bearing or pump problems and correlate mechanical issues with other process parameters.

The main advantage of improved MCSA, Model-Based Voltage and Current Analysis (MBVI) is easy installation of the current transducer/transformer, usually installed in the air conditioned motor control cabinet, in dry location, with no flammable or hazardous atmosphere. This is significant advantage in case of the submersible pumps, especially cryogenic pumps, which suffer the most with vibration transducer installation problems. A significant advantage of MBVI is the built in Expert System, which automatically identifies the faults, assign the severity and send the notification to the user. The ultimate advantage of MBVI is the voltage and current measurements of all three phases which can highlight faults such as voltage/current imbalance, total harmonic distortion, current harmonics, internal and external electrical faults diagnostics. Despite similarities of MBVI Power Spectral Density Analysis to Vibration Spectrum Analysis, MBVI is not that widely used and understood in the industry. There are limited international standards with the recommended alarm values to compare with other machines across the fleet. There is not one overall set of alarm values for MCSA and MBVI which can be trended and compared against the alarm values or standards.

The tests have demonstrated that MCSA/MBVI can detect different motor malfunctions as early as Vibration Analyses. In case of motor electrical problems, the MBVI can give more precise conclusions in general, but motor must be loaded close to the full load. On the other hand, the vibration measurements are sensitive even the motor is unloaded, where MBVI requires 80% to 100% load, to be effective. In the test with damaged bearing malfunction, both methods MBVI and VA detected the problem. The disadvantage of MBVI, in case of more bearings of the same type, with the same bearing fault frequencies, its inability to distinguish which bearing is faulty. Vibration Analyses requires measurement on each bearing, but then base on the vibration amplitude, can distinguish which bearing is faulty exactly. The tests show limitations of MBVI, as without additional tests one cannot simply distinguish between unbalance, misalignment or looseness as all are demonstrated as increased 1X sidebands around Line Frequency. Furthermore, the structural looseness was clearly visible on VA, but not on MBVI in these tests. The Vibration Analyses also cannot distinguish between 1X unbalance, misalignment and looseness simply from one-point measurement only. But, with Vibration Analyses measuring the vibration on all the bearings in horizontal, vertical and axial direction, measuring vibration amplitude and phase (direction of vibration), all the above-mentioned malfunctions can be clearly distinguished.

Model-Based Voltage and Current Analysis (MBVI) are proven to be used independently or together with Vibration Analysis, as a complementary tool for detecting electrical and mechanical faults. MBVI can be used independently with limitations, where dedicated vibration monitoring is not practical, economical or comprehensive enough. It is recommended to use MBVI complementary with vibration analyses to create the most robust and reliable monitoring system, leveraging from both methods pros and eliminating cons.

The presented results, using both approaches, prove the potential of both techniques and the advantages of their combined use for reaching a maximum reliable Condition Monitoring and Diagnostics of Submersible Pumps. MBVI can overcame the problems with the vibration sensors and can give additional information on electrical faults and parameters. Vibration Analyses can give more precise diagnostics in motor transient conditions, unloaded state and can help distinguish between the most common problems as unbalance, misalignment, looseness or resonance, simply and reliably.

NOMENCLATURE

Acronyms

AC = Alternating Current
ASME = American Society of Mechanical Engineers
BPFI = Ball Pass Frequency of Inner Race
BPFO = Ball Pass Frequency of Outer Race
BSF = Ball Spin Frequency
CBM = Condition Based Maintenance
CT = Current Transformer
FC = Fundamental Component
FFT = Fast Fourier Transform
FTF = Fundamental Train Frequency
FIG = Figure
H = Horizontal direction
HPSO = High Pressure Send-Out pump
IEPE = Integrated Electronic Piezoelectric
LF = Line Frequency
LNG = Liquefied Natural Gas
LSL = Lower Specification Limit
USL = Upper Specification Limit
MBVI = Model-Based Voltage and Current Analysis
MCSA = Motor Current Signature Analysis
NPSH = Net Positive Suction Head
NPSHa = Net Positive Suction Head available
NPSHr = Net Positive Suction Head required
PPF = Pole Pass Frequency
PSD = Power Spectral Density
PSH = Principal Slot Harmonics
REB = Rolling Element Bearing
RMC = Remote Monitoring Center
RMS = Root Mean Square
RPM = Revolutions Per Minute
SD = Standard Deviation
SSA = Supporting Services Agreement
SWLP = Sea Water Lift Pump
SWVP = Sea Water Vaporizer Pump
TEM = Thrust Equalizing Mechanism
V = Vertical direction
VA = Vibration Analysis
WH = Winding Harmonics

Variables

f = supply frequency
f_r = rotor rotating frequency
f_s = slip frequency
f_O = REB Outer Race Frequency
f_I = REB Inner Race Frequency
f_B = REB Ball Frequency
f_C = REB Cage Frequency
n = number of poles
N_b = number of rolling elements
N_r = rotor rotating speed
N_s = field synchronous speed
p = number of pole pairs
R = number of rotor slots
s = slip

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