EVALUATION OF MOTOR BEARING CONDITION IN COMBINED CYCLE POWER PLANT USING VIBRATION ANALYSIS

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COLLEGE OF GRADUATE STUDIES
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EVALUATION OF MOTOR BEARING CONDITION IN COMBINED CYCLE POWER PLANT USING VIBRATION ANALYSIS

SATHESWARAAN A/L EDWARD RAVI

A Thesis Submitted to the College of Graduate Studies, University Tenaga Nasional in Fulfilment of the Requirements for the Degree of

Master of Electrical Engineering

SEPTEMBER 2020

DECLARATION

I hereby declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently submitted for any other degree at Universiti Tenaga Nasional or at any other institutions. This thesis may be made available within the university library and may be photocopies and loaned to other libraries for the purpose of consultation.

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Date: **07 SEPTEMBER 2020**

ABSTRACT

Electrical motor is a device that converts electrical to mechanical energy to perform a specified job and it is very significant in any plant. Any sudden failure in an electrical motor shall cause effect on the plant performance and monetary loss to the plant. Similarly, in a combined cycle power plant, many critical motors where those motors and loads must run non-stop without failures. Any failure will eventually cause downtime and production loss. Therefore, a proper maintenance philosophy and analysis can lead to proper motor maintenance in line with optimized time and cost. This study evaluated the condition of critical motor in combined cycle power plant using vibration analysis with SKF Microlog GX Series CMXA 75. This study also proposed the precision maintenance schedule subject to maintenance time and cost for critical motor. A comparison between precision maintenance and predictive maintenance cost of critical motor were established. Two critical motors were selected which are Low Pressure Feedwater Pump Motor (LPFW) and Cooling Tower (CT) Fan Motor. LPFW motor function to feed water to Heat Recovery Steam Generator (HRSG) LP section whereas CT fan motor is used to cool down the condensate water coming out from steam turbine condenser. The results of the vibration will reflect the performance of the motor and the maintenance action plan needed to be taken if required. Vibration data were collected in gravity energy (gE) peak to peak and mm/s (millimeter per second). The data then analyzed through the SKF software and Microsoft Excel. Standard results for motor less than 132kW size, vibration shall be lower than 2.0gE and 2.0mm/s respectively depending on the motor specification and its application. The maintenance cost is calculated and compared with the cost of maintenance without this vibration analyses. The cost comparison shows that, performing vibration analyses and detecting the defect or root cause in earlier stage will be cost effective compared to the defect worsen. By taking vibration data, the fault can be predicted and detected in early stage and can be eliminated with lower cost compared to without taking vibration data.

ACKNOWLEDGMENT

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Firstly, my deepest appreciation and thanks to my supervisor for this project dissertation Assoc. Prof. Dr. Jagadeesh Pasupuleti for all his support, guidance, motivation and expertise feedback and comment throughout this my study and project.

Secondly, I am very thankful to my working collogue and my condition-based monitoring team buddy Mr. Wan Haziq bin Wan Muhamad. He is my senior under the CBM team department. Both of us oversee our plant KLPP Vibration survey and report. As a senior person, he helps me a lot on the vibration analyses and other job which related to vibration. Therefore, my sincere thanks to him as well.

Besides that, I would like to extend my gratitude to my beloved mother Sarilah for the unconditional love and support during all these days. Finally, I would like to thank the COGS faculty members and staffs that assisted me throughout writing of this thesis.

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LIST OF SYMBOLS

gE	Gravity Energy (unit)
mm/s	Milli Meter per Second (unit)
SKF	This is a Manufacturing Company Name
ΔT	Temperature difference

LIST OF ABBREVIATIONS

ANN	Artificial Neural Network
Bara	Absolute Pressure
CT	Cooling Tower
CBM	Condition Based Monitoring
COGS	College of Graduate Studies
DE	Drive End
HRSG	Heat Recovery Steam Generator
HP	High Pressure
IPP	Independent Power Producers
KLPP	Kuala Langat Power Plant
kW	Kilowatt
KKS	This is German Short Form for Identification (Equipment Numbering)
LPFW	Low Pressure Feedwater
LP	Low Pressure
MW	Megawatt
mm	Millimeter
PPA	Power Purchase Agreement
PLC	Programmable Logic Controller
PBP	Pay Back Period
RPM	Revolution per Minute
TNB	Tenaga Nasional Berhad

CHAPTER 1

INTRODUCTION

1.1 Background

Electrical motor is a device that converts electrical energy to mechanical energy to perform a specified job and it is very significant to many plants or factory. Any sudden failure in an electrical motor shall cause impact on the plant performance and large monetary loss to that plant. Similarly, in a combined cycle power plant there are many critical motors where those motor (loads) must run non-stop without failures. Any failure will eventually cause downtime and production loss. However, it is impossible for an electrical motor to run 24 hours for 365 days non-stop. Therefore, a good maintenance philosophy and operation mentality are needed to smoothen the motor performance and reduce downtime in a combined cycle power plant.

Sudden catastrophic failure of an electrical motor at a combined cycle power plant (CCPP) may lead to major downtime. Therefore, a proper maintenance philosophy and analysis can lead to proper motor maintenance in line with optimized time and cost. Catastrophic failure of an electrical motor is the main concern of this proposed project evaluate the maintenance with and without the precision maintenance approach. In this precision maintenance, the main tools used shall be SKF Microlog GX Series vibration analysis. This vibration analysis approach is mainly to eliminate or prevent machinery failure repair. Precision maintenance is the combination of preventive and predictive maintenance.

1.2 Problem Statement

- Sudden catastrophic failure of an electrical motor at a combined cycle power plant (CCPP) may lead to major downtime.
- Therefore, a proper maintenance philosophy and analysis can lead to proper motor maintenance in line with optimized time and cost.
- Catastrophic failure of electrical motors is the main concern of this proposed project and the best maintenance philosophy to approach those faults.
- Preventive maintenance alone cannot reduce or eliminate these types of catastrophic failures of electrical motor. Because, the preventive maintenance is only limited to few parts of motor. It does not cover all the parts of motor. Moreover, preventive maintenance is done during the motor shutdown.
- Thus, predictive maintenance must be implemented together with preventive maintenance.
- Combination of preventive and predictive maintenance is called precision maintenance, and this will reduce the catastrophic failure to almost zero.
- This project mainly focuses on the vibration analyses of an electrical motor and its load. Eventually, with a proper vibration survey an effective maintenance can be done.

1.3 Project Objective

Electrical motor in a combined cycle power plant were selected for this analysis. The SKF toolkits were utilized for this analysis as well. Below are the main objectives to be achieved at the end of this project.

- To evaluate the condition of critical motor in combined cycle power plant using vibration analysis with SKF Microlog GX Series CMXA 75.
- To propose precision maintenance schedule subject to maintenance time and cost for critical motor.
- To compare precision maintenance and predictive maintenance cost of critical motor.

1.4 Scope of Work

Firstly, study the overall combined cycle power plant process which includes gas turbine system, steam turbine system, generator system, lube oil system, main cooling system, secondary cooling system, essential power system, balanced of plant system, and others. Then, identify the system with electrical motors that must be continuously running without failure. Any failure can affect the plant operation. Thus, two critical motor have been identified and selected. First is the Low-Pressure Feedwater (LPFW) pump motor and second is the Cooling Tower (CT) fan motor. The LPFW pump motor function to pump feedwater to low pressured Heat Recovery Steam Generator (HRSG) section. This, process must be continuously running. This is because any, failure of this pump will trip the boiler due to low water level in the boiler and eventually trip the steam turbine because of low steam production.

Secondly the selected motor is the Cooling Tower fan motor. This Cooling Tower fan has two function. The main function is act as a heat exchanger for steam turbine condenser. The low energy steam that flow out from the low-pressure steam turbine section will fall to the condenser. This steam must be recirculated as it is a closed loop system. Thus, this steam is cooled down and condensed to water then pumped back to the feedwater tank. Therefore, this CT fan will reduce the heat exchanger water temperature. This CT fan also indirectly functions to create vacuum for the condenser. The more efficient the CT fan performance, the better the vacuum amount inside the condenser. This vacuum is at approximate 0.01 bara or lower. This vacuum is very significant for a steam turbine to run in closed loop successfully.

Based on the reasoning above, these two mentioned motors are very important. Thus, the best maintenance must be applied to these motors so that it is continuously running without any catastrophic failure. Therefore, vibration analyses survey will be conducted to perform best predictive and precision maintenance along with optimized cost of maintenance.

Thus, vibration analyses will be taken for a certain period in months and maintenance will be performed accordingly. The motor performance and reliability will be measured and monitored. The maintenance cost will be calculated. Both with and without vibration analyses maintenance cost will be calculated and tabulated. With this, we can verify that, performing vibration analyses through the overall maintenance cost will be much lower compared to without the vibration analyses. Moreover, with precision maintenance the motor performance will be much better, and the reliability rate will be higher.

1.5 Thesis Outline

Chapter 1 explained introduction of the thesis, the electrical motor and its importance to CCPP. The approach and meaning of condition-based monitoring were explained. Besides that, the vibration tools and software were briefly described, and its functions were explained. Typical problem of handling or performing maintenance to critical electrical motor in CCPP was explained. Project objective was identified, and scope of work was described.

In chapter 2 of this thesis, a literature review on electrical motor predictive maintenance, types of maintenances for electrical motor, preventive maintenance, condition monitoring, vibration monitoring for electrical motor and standards were presented. The added advantage of this thesis vibration analysis compared to previous papers was also described.

Chapter 3 of this thesis starts with the clear explanation of KLPP and its operating and maintenance structure. The power plant equipment is explained. Then the critical electrical motor in power plant and how it was chosen, and its function were clearly explained. Furthermore, the vibration site survey procedure and flow work were described. Vibration data collection for electrical motors were explained. The study for two chosen electrical motor which is LPFW Pump Motor no.4 and CT Fan Motor no.4 and its technical specification has been done. Finally, the vibration survey was conducted as per planned.

In chapter 4, the results were tabulated in graphical format and the vibration data was analysed. The vibration survey, then the data were interpreted and analysed. The results were compared with vibration diagnostics chart. Best recommendation to solve the incurred problem is advised. The preventive maintenance was carried out to rectify the identified problem. Finally, the vibration data was taken again to prove that the problem is solved, and the motor is currently in good condition. All the vibration data collected after maintenance were all good. The effect and cost comparison and study were done. The return of investment study was also done. Overall, this survey proves that maintenance with vibration analysis is very much cost efficient compared to maintenance without vibration analysis.

Chapter 5 includes the overall conclusion of this thesis and some recommendation to be added as suggestions for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

There have been many researchers in literature that had discussed condition monitoring in general [1] and electrical motor condition monitoring. In [2], an intelligent diagnostic system based on stator current analysis and programmable logic controllers (PLC) was used as condition monitoring tools for electrical motors other than the conventional method. Several factors that contributes to the motor failure were detected through this stator current analysis and PLC such as thermal overloading, overloading due to undesirable stress, unbalanced voltage, broken rotor bars, bearing failure, stator winding failure, and others [2] [3].

In order to detect motor failures, vibration signatures were monitored via implementation of an Artificial Neural Network (ANN) in [4] [5] [6]. Here, the vibration information was taken as input layer and was integrated with the ANN. This is implemented as a predictive maintenance to provide information on the motor condition which is unbalanced motor, misalignment motor, bearing fault, and others [4]. The collected information was merged with the ANN schematic and interpreted accordingly as shown in Figure 2.1.

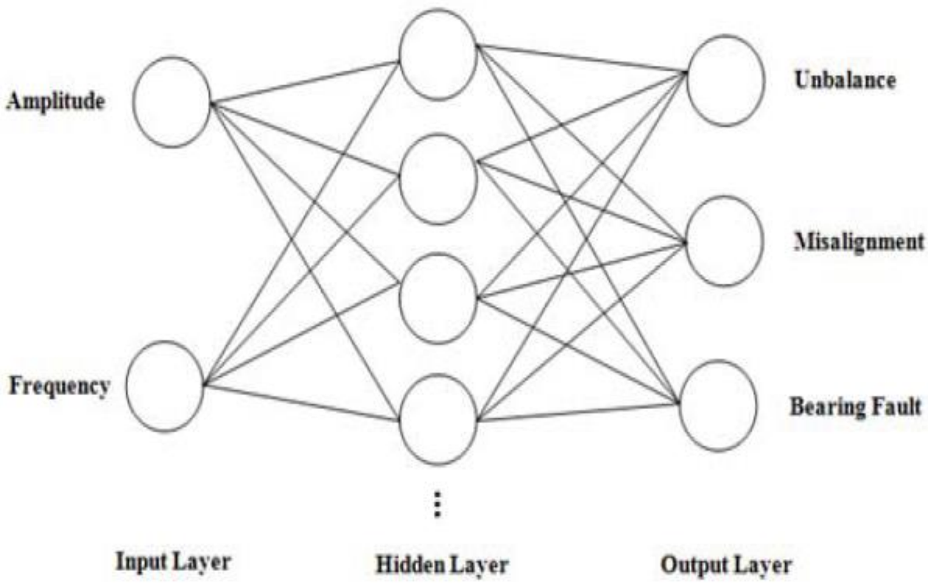

Figure 2.1 Schematic diagram of ANN [4]

In [7], magnetometer meter measurement was used to monitor the motor health by monitoring the frequency and detecting the broken rotor bars. Here, the miniature triaxial geomagnetic sensor for condition monitoring was utilized. It was used as a core for motor predictive maintenance [8]. BMC050 eCompass sensor from Bosch Sensortec was used as shown in Figure 2.2.

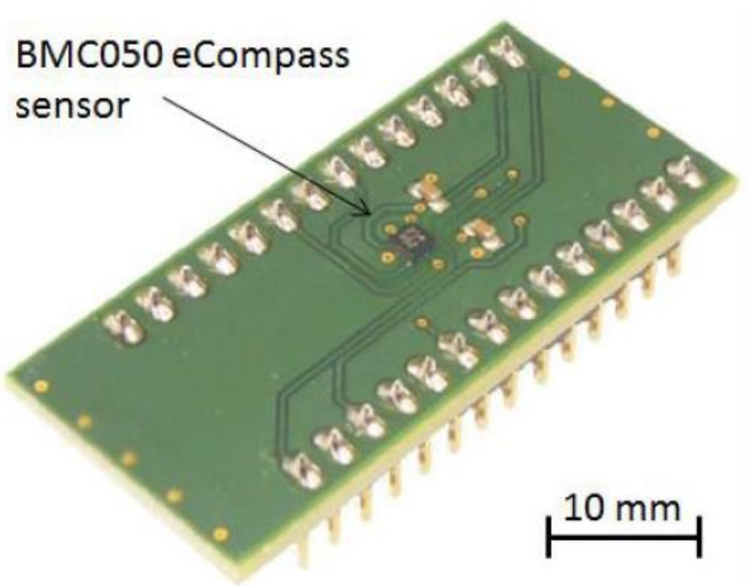

Figure 2.2 Sample BMC050 eCompass Sensor [7]

The researchers [9] [10] proved that specific vibration frequency can be monitored to determine the electrical motor stator winding deterioration. This enable electrical motor failure to be identified in advance and help to pre-plan the maintenance [11] [12]. The plus point of this technique is the potential of providing information related to the air gap flux created by the winding deterioration as shown in Figure 2.3 that would have been not available through voltage or current monitoring.

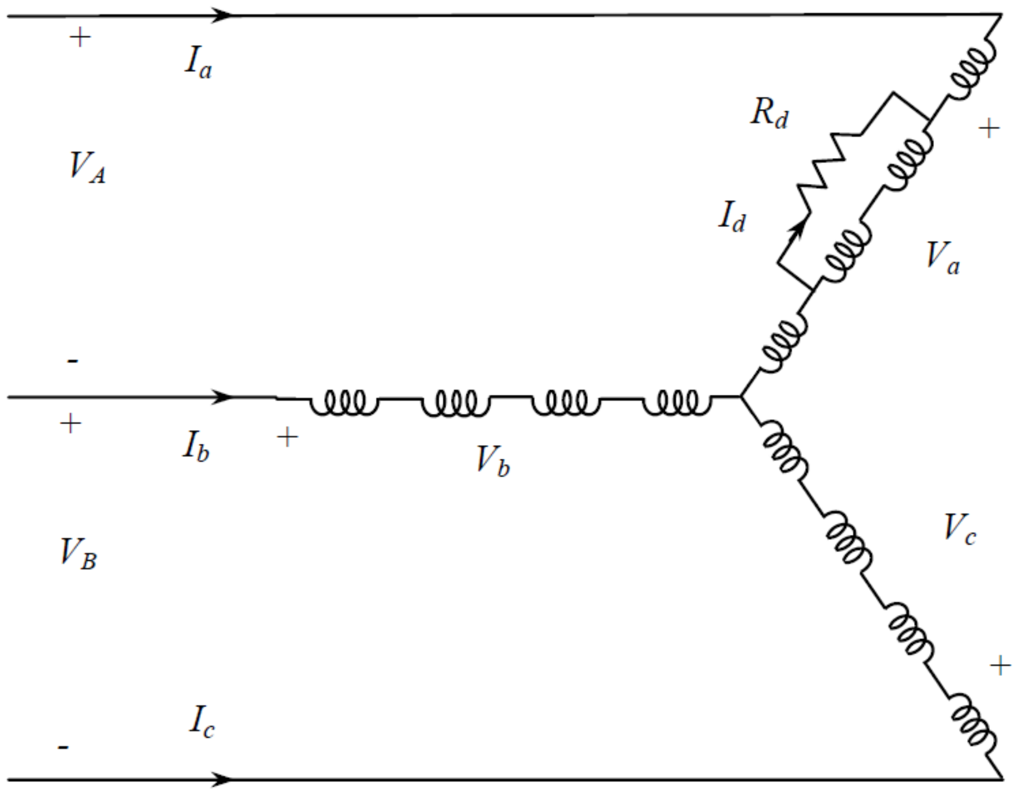

Figure 2.3 Sample Stator Winding of an Induction Motor with Simulated Deterioration [9]

On the other hand, infrared thermography survey technique was used as a preventive maintenance for electrical motor in [13] [14] [15]. Most of the electrical motor failure problems were due to bad contact point, winding short circuit, overload, defects in motor body or starter. The infrared camera was used to capture the motor terminal and motor starter terminal for abnormal temperatures or hotspot. The temperature difference (ΔT) was used as the basis for the action plan as shown in Table 2.1.

Table 2.1 Classification of Thermal Profile of Electrical Systems [13].

ΔT over ambient temperature, (°C)	ΔT similar equipment, (°C)	Action required	Level of priority
> 40	> 15	Repair immediately - major discrepancy	**1**
21 – 40	–	Monitor until corrective measures can be accomplished	**2**
11 - 20	4 – 15	Repair as time permits - indicates probable deficiency	**3**
1 - 10	1 - 3	Warrants investigation - possible deficiency	**4**

In this paper [16], a better comparison between preventive and corrective maintenance repair cost was established. They tried to optimize the repair cost by providing the maximized preventive and corrective maintenance schedule. The researchers concluded that preventive maintenance cost is much lower compared to corrective maintenance. In [17] [18] the researchers studied the temperature and vibration analysis for electrical submersible motor fault diagnostics. The fault analysis in this paper divided into two parts and integrated with temperature estimation technique as shown in Figure 2.4.

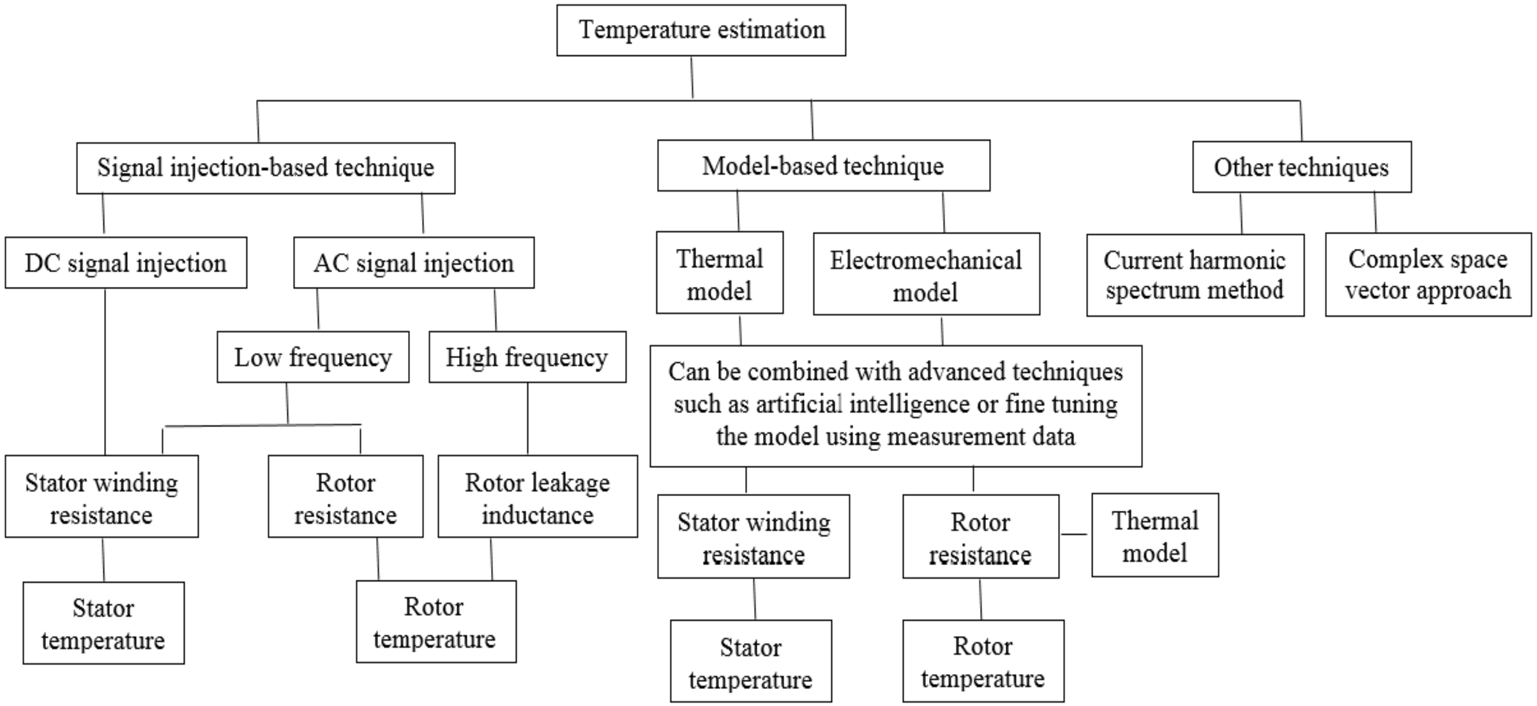

Figure 2.4 Sample motor temperature estimation techniques [17]

The author of [19] [20] discussed the most significant part of an electrical motor failure which is the bearings. In this work, envelope analysis of vibration signal was used to verify the existence of bearing defects. The global kurtosis and crest factor signals were used to detect the bearing defects. Instantaneous frequency of motor voltage was introduced to get trend of bearing condition [21].

On top of that, in [22] [23] an acoustics measurement was used to analyse the electrical motor fault. Localizing the sound source through acoustics method allow identification of the points of vibration to be measured. Piezoelectric accelerometers and data collector were used to measure the vibration signals in this paper which eventually were used for condition monitoring [24]. A special acoustic camera with special illustration as shown in Figure 2.5 was utilized to collect the specific sound components as tabulated in Table 2.2.

Table 2.2 Acoustic camera microphone characteristics [22].

Parameter	Value
Equivalent noise level:	27 dB(A)
Maximum equivalent sound level:	130 dB
Microphone Frequency response:	20 Hz-20 kHz

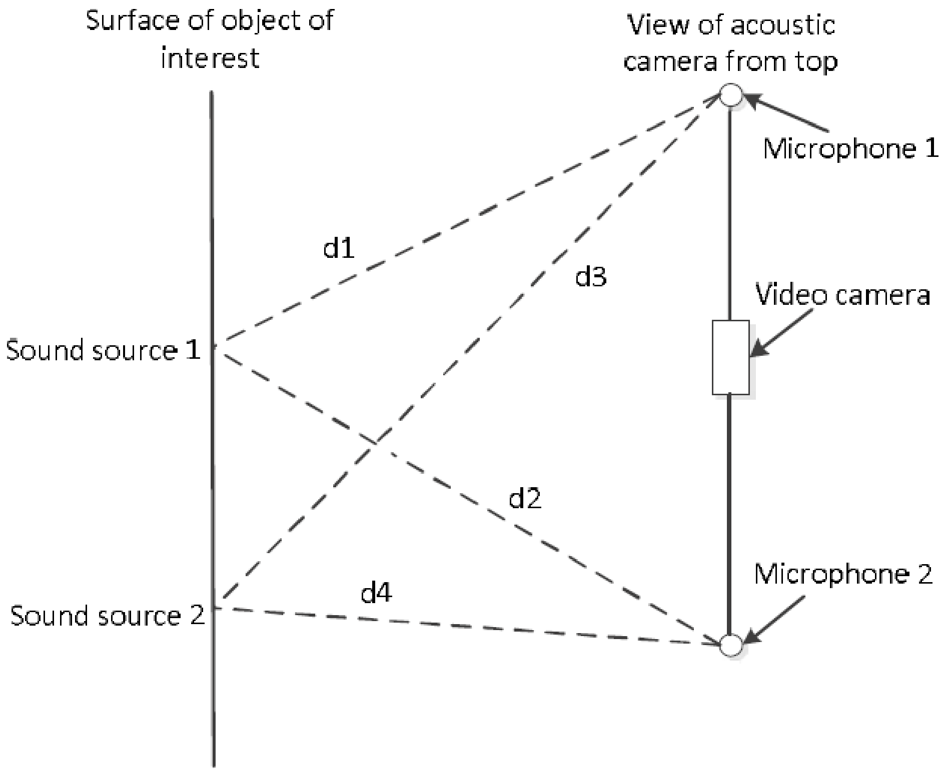

Figure 2.5 Sample view of acoustic camera from top, schematic illustration of principle of acoustic camera [22]

2.2 Types of Maintenance for Electrical Motor

In this paper [25] [26], the significant difference and the effect of preventive & predictive maintenance compared with corrective maintenance were established. To study this, researchers selected certain instrument and first group performed the predictive and preventive maintenance. The second group didn't perform those maintenance. The instrument failure rate for both indicates the difference of both maintenance type. The instrument that was under preventive and predictive maintenance tend to fail very seldom. Whereas the instrument that didn't perform any maintenance, the failure rate is very high. The bathtub curve as in Figure 2.6 [25] was used as reference for this paper experiment.

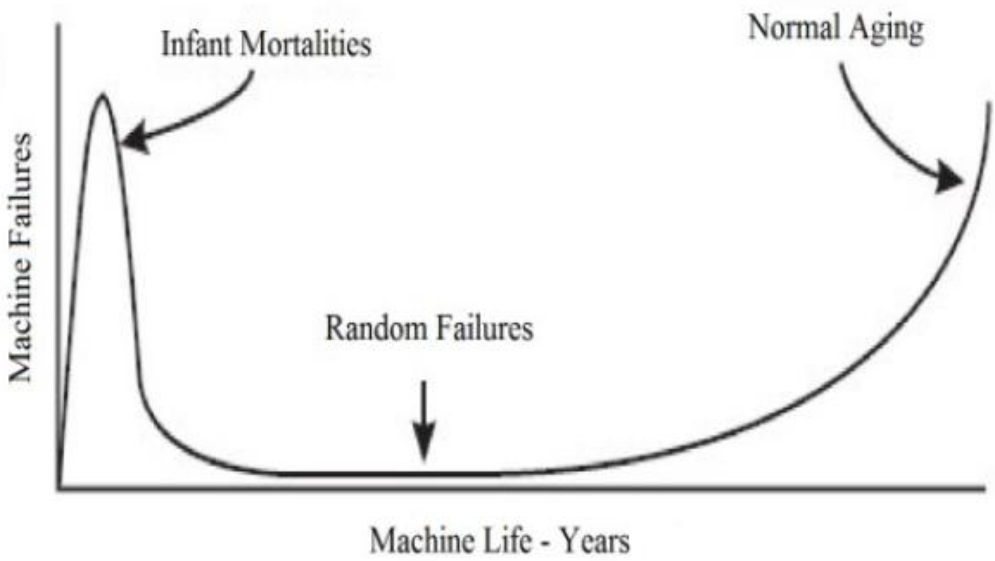

Figure 2.6 Sample Bathtub Curve [25]

2.2.1 Preventive Maintenance

This means the care and servicing by personnel for the purpose of maintaining the specific equipment in good condition all the while to maintain high reliability and availability. This is done by providing proper and scheduled systematic inspection, detection and correction of incipient failures either before they occur or before they develop into major disasters. The lack of preventive maintenance will lead to catastrophic failure [27] [28] [29]. By comparing to predictive maintenance graph as shown in Figure 2.8, the normal random failures are highly elevated, and the normal aging begins earlier for this preventive maintenance graph as shown in Figure 2.7.

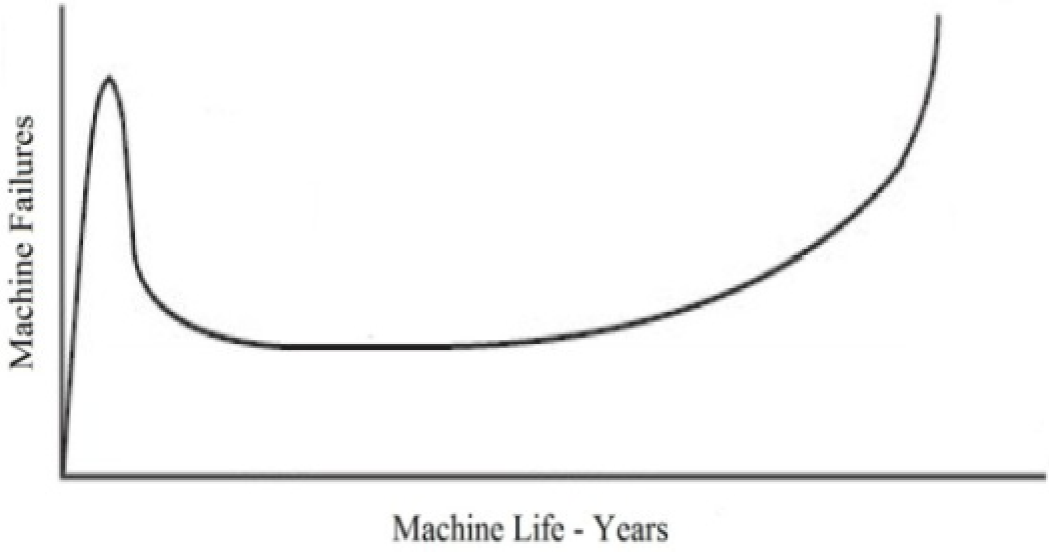

Figure 2.7 Effect of Preventive Maintenance [25]

2.2.2 Predictive Maintenance

Condition monitoring [30] [31]or also known as predictive maintenance which collect and compares the data and trend against known engineering limits for the purpose of detecting, analysing, and correcting problem before failures occur. This will eventually prevent equipment from getting damaged seriously, the root cause can be eliminated in early stages and reduce sudden failure rate as well [25] [32] [33]. Figure 2.8 predictive maintenance shows that the failures rates are much lower compared to Figure 2.7 preventive maintenance.

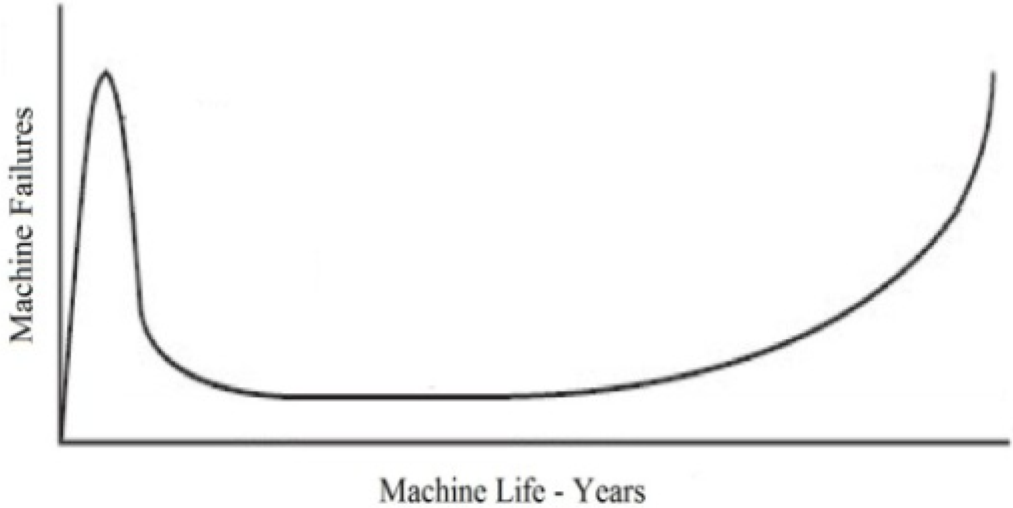

Figure 2.8 Effect of Predictive Maintenance [25]

2.3 Electrical Motor Vibration and Bearing

In this paper [34], a review on various vibration analysis techniques used to monitor the rolling element on bearings. Few techniques were reviewed in this paper such as Fast Fourier Transform (FFT) [35], Short Time Fourier Transform (STFT), Wigner-Ville Distribution (WVD), Envelope Analysis (EA) Figure 2.10, Wavelet Transform (WT) and Empirical Mode Decomposition (EMD). The bearing fault signal were obtained from few points which are normal state, inner race fault, ball fault, outer race fault at different motor speed. The basic Fourier Transform for vibration analysis were explained in this paper [36]. In general case, a Fourier Transform of an arbitrary function *f(x)* or sequence of amplitude *Xn*, is computed as follows in both the continuous (1) and discrete (2) cases: -

$$\hat{f}(\xi) = \int_{-\infty}^{\infty} f(x)\ e^{-2\pi i x \xi}\, dx \qquad (1)$$

$$X_k = \sum_{n=0}^{N-1} x_n e^{-i 2\pi k \frac{n}{N}} \qquad k = 0, \dots, N-1 \qquad (2)$$

In these equations, *f(x)* is the continuous function being transformed, *f(ξ)* is the transformed function (with *ξ* representing size of oscillations rather than distance from the origin), *Xn* is one of a discrete sequence of *N* data points, and *Xk* is the amount of oscillation found in the kth frequency band of that sequence.

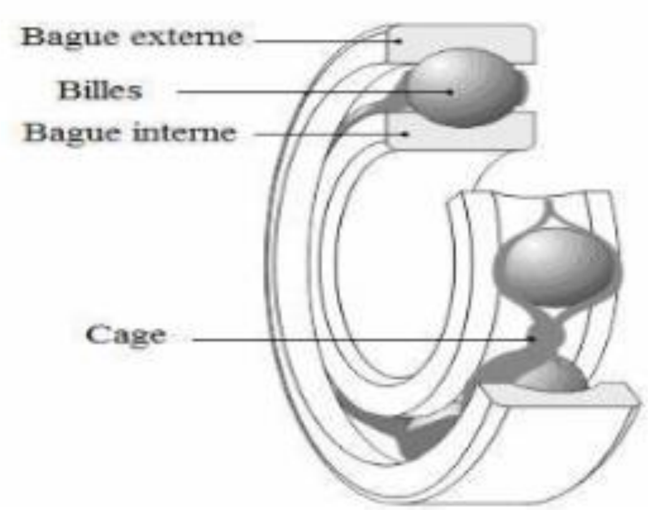

Figure 2.9 The component of bearing [34]

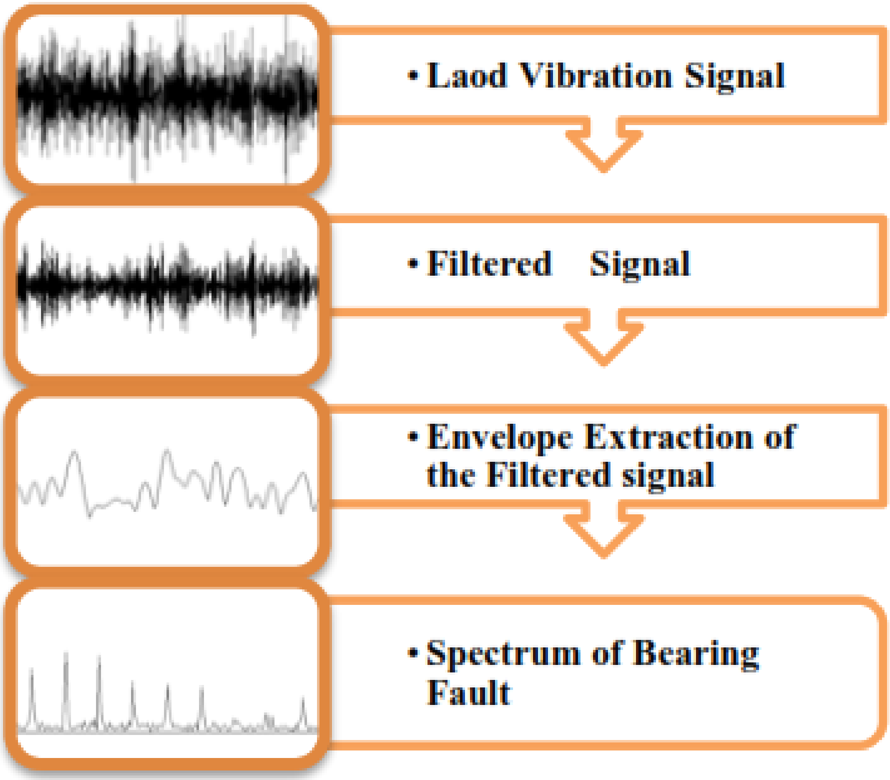

Figure 2.10 Procedure for Envelope Analysis (EA) [35]

Whereas in this paper [37], zero sequence current spectrum were used to diagnose motor bearing fault. The author used the Finite Element Method (ANSOFT MAXWELL-2D) to diagnose bearing fault in three phase induction motor. In this paper [38], the author used the complete ensemble empirical mode decomposition with adaptive noise (CEEMDAN) analysis of motor current signature to detect bearing fault in electrical motor. The CEEMDAN is used to decompose the stator current signal into several independent intrinsic mode functions (IMF), then the most sensitive IMF can be extracted, and this is very effective to study bearing outer race fault detection as shown in Figure 2.11.

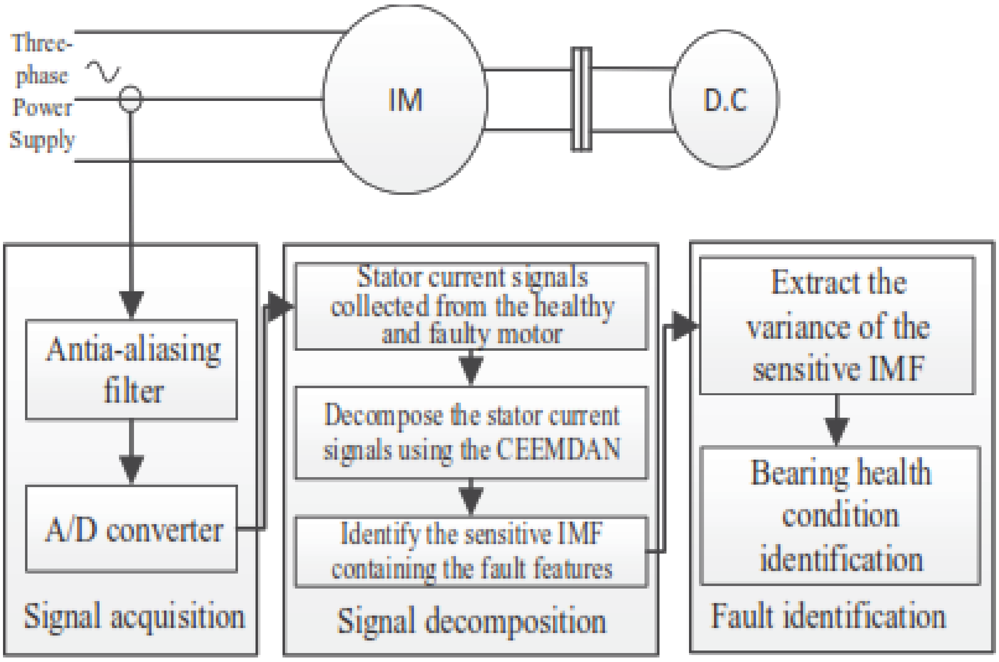

Figure 2.11 The proposed bearing fault detection block diagram [37]

In this paper [39], an improved technique which is Short Time Approximate Discrete Zolotarez Transform (STADZT) has been used to identify the transient associated with faulty bearing vibration signals. The author classified the bearing faults and their defect frequencies to three group which are outer raceway faults, inner raceway faults and ball or rolling element faults as shown in Figure 2.12 and Table 2.3.

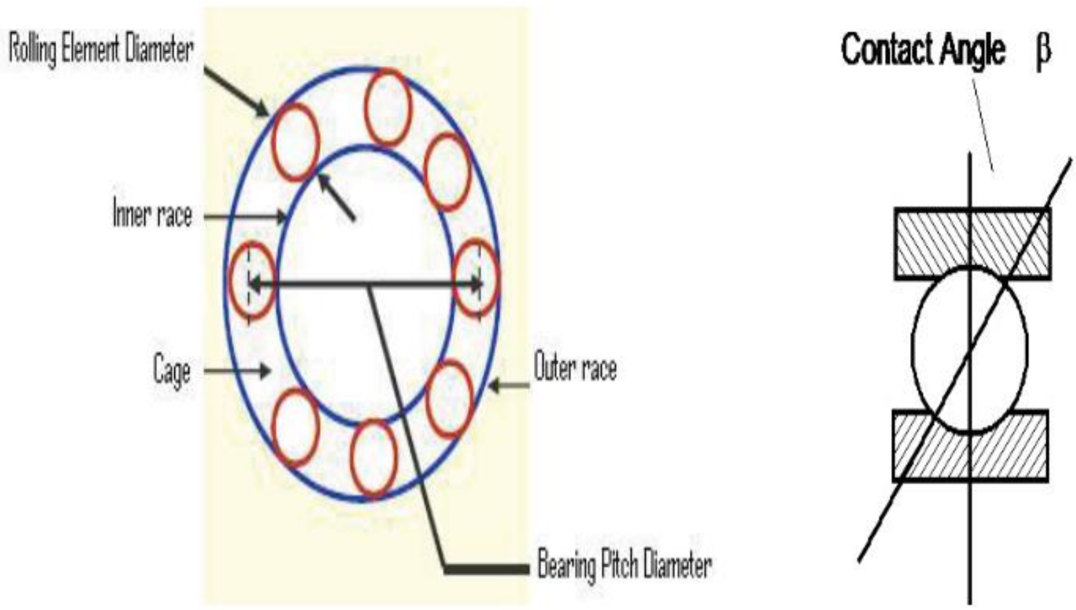

Figure 2.12 Bearing details [39]

Table 2.3 Characteristics Frequencies of Bearing [39].

Name of Frequency	Abbreviation	Equation	Frequency
Fundamental Train Frequency (Cage frequency)	FTF	$\frac{S}{2} \times [1 - \left(\frac{Bd}{Pd} \times \cos(\beta)\right)]$	13.18Hz
Ball Spin Frequency	BSF	$\frac{S*Pd}{Bd*2} \times \left[1 - \left(\frac{Bd}{Pd} \times \cos(\beta)\right)^2\right]$	95.62 Hz
Ball Pass Frequency (Outer race)	BPFO	$\frac{Nr}{2} \times S\left[1 - \left(\frac{Bd}{Pd} \times \cos(\beta)\right)\right]$	105.08 Hz
Ball Pass Frequency (Inner race)	BPFI	$\frac{Nr}{2} \times S[1 + \left(\frac{Bd}{Pd} \times \cos(\beta)\right)]$	121.45Hz

The author used 6203-2Z-H320B-JEM-SKF bearing for the research work. This bearing is a deep grove type ball bearing with following specifications: -

- Inside diameter = 17mm
- Outside diameter = 40mm
- Race thickness or width = 12mm
- Ball diameter (Bd) = 5mm
- Pitch diameter (Pd) = 35mm
- No of rolling elements (Nr) = 8
- Contact angle (beta) = 60 radians

2.4 Vibration Monitoring for Electrical Motor and Standards

Like this thesis, here [40] [41] [42] the researchers also used the vibration analysis technique to identify and eliminate the root cause of motor failure [43]. In this paper [44], the vibration spectrum was used to determine the mass unbalance problem within the motor and the load. Standard vibration according to ISO 10816-1 (as shown in Table 2.4 and Table 2.5) was used as reference similar to this thesis [45] [46] [47].

Table 2.4 General Guideline ISO 10816-1 [45] [46].

Driver Capacity	Fans	Pumps with multivane impeller				Other Machines
	Industrial	Separated driver			Integrated driver	
		Centrifugal	Mixed flow	Axial flow		
>300kW	ISO10816-3 Gr.1	ISO10816-3 Gr.3			ISO10816-3 Gr.4	ISO10816-3 Gr.1
<=300kW	ISO14694 BV-3					ISO10816-3 Gr.2
>15kW						
<=15kW		ISO10816-1 Class I (*1)				

Table 2.4 indicates the standard that each machine belongs to base on the power rated. For example, for a fan with power more than 300kW, thus the standard that must be referred to is ISO10816-3 Gr.1.

Table 2.5 ISO 10816-1 Standards for Mechanical Vibration [45] [46].

The main standard for this vibration analysis survey which was taken as reference is ISO 10816-1 and ISO 10816-3. The ISO 10816-1 replaces the ISO2372 as a general guide outlining measurement and evaluation of mechanical vibration in typical industrial machinery. For vibration survey, there are mainly two main sets of parameters which is enveloping frequency measure in gE units and velocity vibration measured in mm/s units. The enveloping frequency indicates the severity of bearing defect or severity of the vibration defect. Whereas, velocity vibration indicates the source of vibration. As per the ISO 10816-1 the vibration measurements (velocity Acceleration) can be categorized into four classes. The classes mentioned are related to the Table 2.6 zone boundaries [48].

I. Class 1 indicates that machines may be separated driver and driven, or coupled units comprising operating machinery up to approximately 15kW (approximate 20HP).

II. Class 2 indicates that machinery (electrical motors 15kW(20HP)) to 75kW(100HP), without special foundation, or rigidly mounted engines or machines up to 300kW(400HP) mounted on special foundations.

III. Class 3 indicates that machinery are large prime movers and other large machinery with large rotating assemblies mounted on rigid and heavy foundations which are reasonably stiff in the direction of vibration.

IV. Class 4 indicates that machinery includes large prime movers and other large machinery with large rotating assemblies mounted on foundations which are relatively soft in the direction of measured vibration (ex: turbine generators and gas turbine greater than 10MW output).

Table 2.6 Vibration Zone Boundaries according to Classes [48].

<table>
<tr><th colspan="2">Velocity Severity</th><th colspan="4">Velocity Range Limits and Machine Classes</th></tr>
<tr><th rowspan="2">mm/s RMS</th><th rowspan="2">in/s Peak</th><th rowspan="2">Small Machines Class I</th><th rowspan="2">Medium Machines Class II</th><th colspan="2">Large Machines</th></tr>
<tr><th>Rigid Supports Class III</th><th>Less Rigid Supports Class IV</th></tr>
<tr><td>0.28</td><td>0.02</td><td rowspan="3">Good</td><td rowspan="4">Good</td><td rowspan="5">Good</td><td rowspan="6">Good</td></tr>
<tr><td>0.45</td><td>0.03</td></tr>
<tr><td>0.71</td><td>0.04</td></tr>
<tr><td>1.12</td><td>0.06</td><td rowspan="2">Satisfactory</td></tr>
<tr><td>1.80</td><td>0.10</td><td rowspan="2">Satisfactory</td></tr>
<tr><td>2.80</td><td>0.16</td><td rowspan="2">Unsatisfactory (alert)</td><td rowspan="2">Satisfactory</td></tr>
<tr><td>4.50</td><td>0.25</td><td rowspan="2">Unsatisfactory (alert)</td><td rowspan="2">Satisfactory</td></tr>
<tr><td>7.10</td><td>0.40</td><td rowspan="6">Unacceptable (danger)</td><td rowspan="2">Unsatisfactory (alert)</td></tr>
<tr><td>11.20</td><td>0.62</td><td rowspan="4">Unacceptable (danger)</td><td rowspan="2">Unsatisfactory (alert)</td></tr>
<tr><td>18.00</td><td>1.00</td><td rowspan="3">Unacceptable (danger)</td></tr>
<tr><td>28.00</td><td>1.56</td><td rowspan="2">Unacceptable (danger)</td></tr>
<tr><td>45.00</td><td>2.51</td></tr>
</table>

Besides the velocity vibration, enveloping frequency also has their own limits and standards. The enveloping frequency limits are shown in Table 2.7.

Table 2.7 Enveloped Acceleration in gE [48].

Enveloping Severity	Shaft Diameter & Speed		
gE peak to peak	Dia. between 200 & 500mm and Speed <500rpm	Dia. Between 50 & 300 mm & speed between 500 & 1800rpm	Dia. Between 20 & 150mm & Speed is either 1800 or 3600rpm
0.1	Good	Good	Good
0.5	Satisfactory	Good	Good
0.75	Satisfactory	Satisfactory	Good
1	Unsatisfactory (alert)	Satisfactory	Satisfactory
2	Unacceptable (danger)	Unsatisfactory (alert)	Satisfactory / Unsatisfactory (alert)
4	Unacceptable (danger)	Unacceptable (danger)	Unsatisfactory (alert) / Unacceptable (danger)
10	Unacceptable (danger)	Unacceptable (danger)	Unacceptable (danger)

Besides that, ISO 10816-3 also play a significant role in this vibration survey. Below is the machine group classification for velocity measurements.

1. Group 2 & 4: Group 2 and 4, is for medium size machines and electrical machines with shaft height in between 160mm and 315mm. These machines are normally equipped with rolling element bearings, but may use sleeve bearing, and operate at speed above 600 revolution per minute (rpm). These machines also include pumps with multi vane impeller and with integrated driver.
2. Group 1 and 3, is for large machinery and electrical machines with shaft height greater than 315mm. These machines usually use sleeve bearings or rolling element bearings. These machines also include pumps with multi vane impeller and with integrated driver.

On top of that, foundation criteria also play an important role in this vibration analysis severity as mentioned in Table 2.8 [48].

Table 2.8 Relation between Vibration Class and Foundation [48].

	Rigid Foundation	Flexible Foundation
Group 2 & 4	Alert: 2.8mm/s Danger: 4.5mm/s	Alert: 4.5mm/s Danger: 7.1mm/s
Group 1 & 3	Alert: 4.5mm/s Danger: 7.1mm/s	Alert: 7.1mm/s Danger: 11mm/s

Table 2.8 explains whether the rotating machines is categorized in which velocity trend group to select its threshold in SKF software. For example, an electrical motor rotor shaft length of 180mm on a concrete base platform, will be in group 2 & 4 where their alert level is 2.8mm/s and danger level of 4.5mm/s. Secondly the enveloping frequency severity also classified based on the machine speed and its shaft diameter as mentioned in Table 2.9 [48].

Table 2.9 Enveloping Frequency and its Range [48].

	Alert	Danger
Class 1 (shaft speed < 500rpm, shaft diameter between 200mm and 500mm)	1gE	2gE
Class 2 (shaft speed between 500rpm and 1800rpm, shaft diameter between 50 and 300mm)	2gE	4gE
Class 3 (shaft speed either 1800rpm or 3600rpm, shaft diameter between 20 and 150mm)	4gE	10gE

Table 2.8 and 2.9 is used to check the measure motor vibration threshold is within which range. For example, a 2-pole motor with speed of 2985rpm will have an alert level of 4gE and danger level of 10gE threshold by referring to Table 2.9.

2.5 Advantages of Vibration Analysis in this thesis

Many past researchers explored vibration analysis technique as predictive maintenance, however table 2.10 distinguish the different between those papers compared to this thesis. Few added values are implemented into this thesis.

Table 2.10 Research Gap Analysis.

Past Research Papers	Improvement
Most papers only explored one type of maintenance, either preventive or predictive maintenance [20] [39] [35] [9] [2] [22] [44] [41].	This thesis will combine both predictive and preventive and come out with precision maintenance.
All Papers didn't cover much on cost analysis [13] [34] [35] [9] [22] [21] [44] [38].	Maintenance cost comparison between with vibration analysis and without vibration analysis.

2.6 Pay Back Period (PBP)

The payback period is the amount of time required for cash inflows generated by a project or spend for an equipment to offset its initial cash outflow or its initial investment. Payback period [49] can be calculated in two different methods which are: -

- Averaging method. Divide the annualized expected cash inflows into the expected initial expenditure for the asset. This approach works best when cash flows are expected to be steady in subsequent years.
- Subtraction method. Subtract each individual annual cash inflow from the initial cash outflow, until the payback period has been achieved. This approach works best when cash flows are expected to vary in subsequent years. For

example, a large increase in cash flows several years in the future could result in an inaccurate payback period if using the averaging method.

2.7 Chapter Summary

Many researches can be found for preventive and predictive maintenance, but this paper will combine the predictive and preventive maintenance and perform precision maintenance. With this precision maintenance, zero failure rate could be achieved. A comparison between the cost of maintenance with vibration analysis and cost of maintenance without vibration analysis, which was not been explored by previous research papers.

CHAPTER 3

METHODOLOGY

3.1 Kuala Langat Power Plant

Kuala Langat Power Plant Sdn Bhd, KLPP is formerly known as Genting Sanyen Power Sdn Bhd. It started in 1995 with 720MW gas fired combined cycle power plant in Kuala Langat, Selangor. This power plant is among the five initial independent power producers (IPP) in Malaysia, selling electricity to Tenaga Nasional Berhad, the national utility company. In October 2012, 1 Malaysia Development Berhad (1MDB) acquired Genting Sanyen Power and in March 2013 the company name officially changed to Kuala Langat Power Plant Sdn Bhd. In February 2016, China General Nuclear Power Corporation and its subsidiaries (China General Nuclear Power Group) acquired 1MDB, and its entire power assets under Edra Global Energy Sdn Bhd and its subsidiaries. Kuala Langat Power Plant is one of the power assets under Edra Power Holdings Sdn Bhd.

KLPP combined cycle power plant comprise mainly of 3 units of Alstom 13E2 Gas Turbines, 2 GE Frame 5 and Frame 6 Gas Turbines, 5 HRSG and 1 unit of Alstom Steam Turbine. The 720MW natural gas fire CCPP with distillate as standby fuel supplies power to TNB on a base load dispatchable basis under a 21 years Power Purchase Agreement, signed on January 1994. This initial PPA which expired in 2016 was successfully extended to another 10 years until February 2026. Besides providing electricity power to grid, the plant also supplies process steam and power to the adjacent paper mill factory, making it a Combined Cycle Co-Generation Plant in Malaysia.

3.2 Site and Motor Selection

KLPP was chosen to be the CCPP site survey for this project mainly because of a few criteria. Firstly, is because the author is one of the condition monitoring engineers at this plant, thus the vibration measurement system is familiar to the author. The vibration survey shall be very systematic. As the author is a Maintenance Engineer at KLPP, collecting data for the mentioned electric motor were very convenient. CCPP has many significant electric motors which contributes to the plant performance. Based on this, two critical electrical motor were selected which are the Low-Pressure Feedwater Pump Motor (LPFW) and the Cooling Tower (CT) Fan Motor. LPFW motor functions to feed water to the HRSG LP section whereas the CT fan motor is used to cool down the condensate water coming out from the steam turbine condenser. An energy or performance calculation can be done for this both motors. If either one motor fails to perform its function, then the plant might trip or its power capacity reduced.

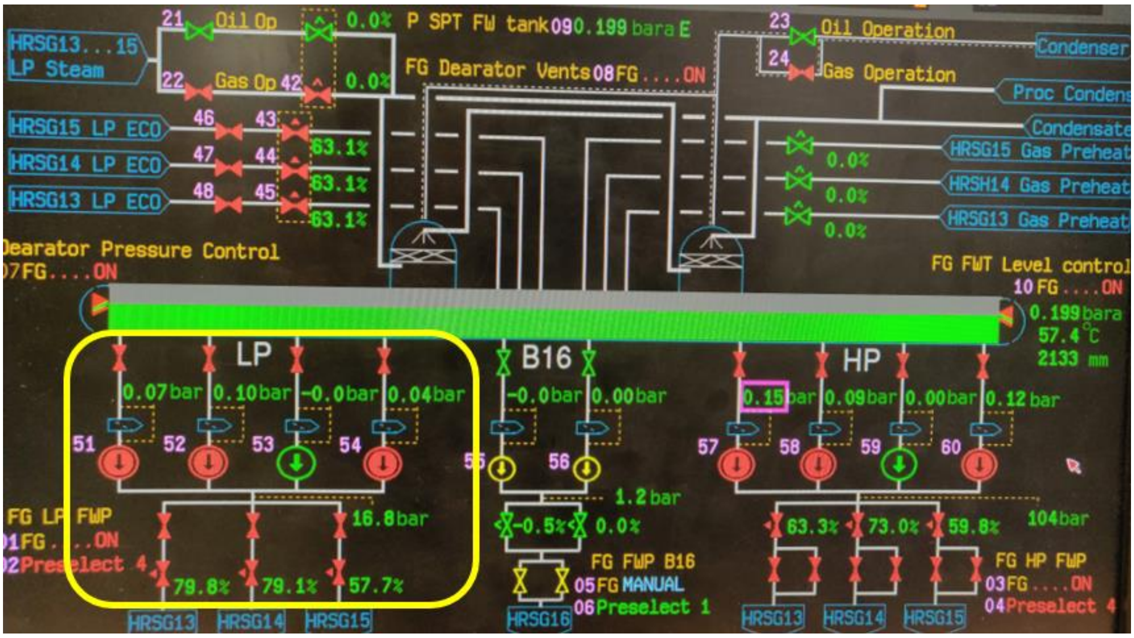

Figure 3.1 The LPFW motor in the HMI of the CCPP

Figure 3.2 The actual LPFW motor on site at the CCPP

As shown in Figure 3.1 and Figure 3.2 (yellow circle), KLPP has four units of the LPFW motor. Three units of the motor will be operating, and one unit will be on standby. The red indication in Figure 3.1 shows motor is running while the green indication shows the motor is off and standby. The pipeline pressure after the LPFW motor must be around 15-20bar, so that all three units of HRSG can be fully operating while the plant on base load (around 660MW). Sudden catastrophic trip of any one or two of the LPFW motor shall affect the overall MW output of the plant.

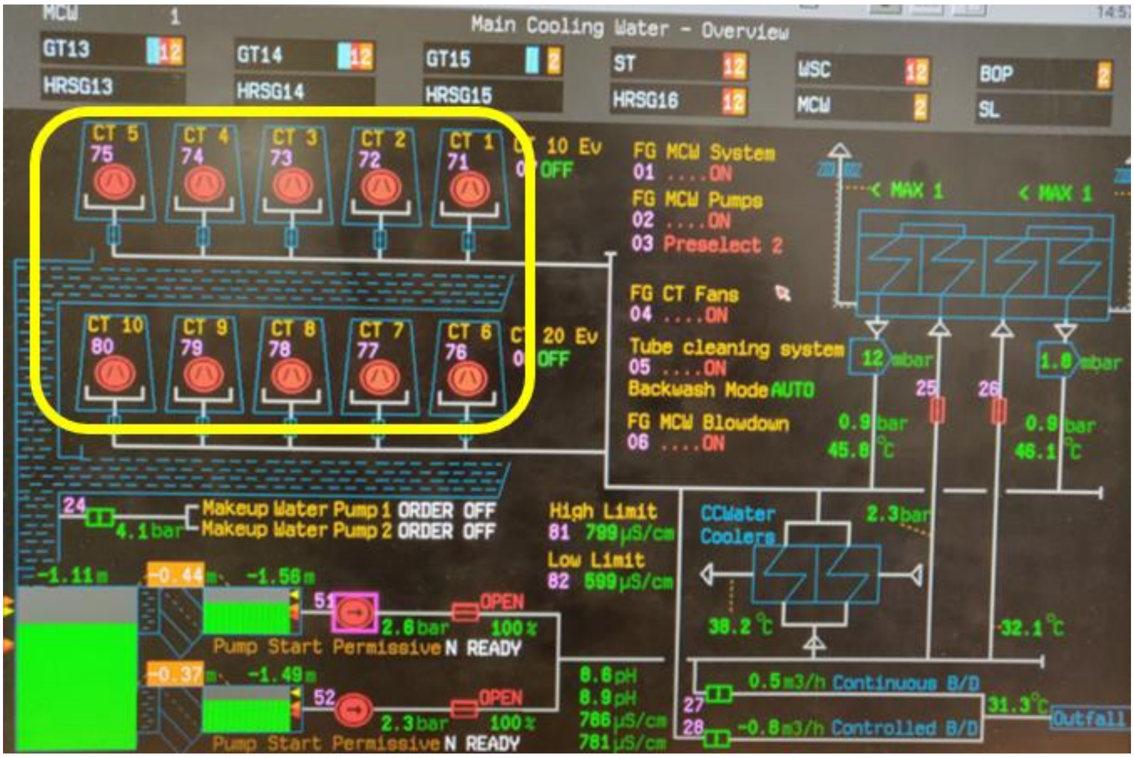

Figure 3.3 CT fan motor in the HMI of the CCPP

As shown in Figure 3.3 (yellow marked), KLPP has 10 units of CT fan motor. All the 10 units will be running continuously. If any two consecutive units of the motor tripped, thus will affect the plant overall output. This is because, the CT fan motor is used for several functions. First is to cool down the low energy steam in the steam turbine condenser. Second is to create a vacuum pressure (0.09-0.01 bara) inside the steam turbine through the condenser. Thirdly, it is used as a secondary (additional) cooling system for the gas turbine lube oil system and generator winding cooling system. Thus, all 10 units of the motor must be well maintained to avoid catastrophic failure.

The LPFW no.4 and CT fan no.4 was randomly chosen. The vibration survey was done for all the motors, however only no.4 some abnormalities detected. Thus, choosing those motors will be more reasonable compared to choosing different motor which has no abnormalities.

3.3 Tools and Software Background

This project will mainly collect and analyse electrical motor vibration data and relate it to maintenance. For this vibration data, the main equipment to be used is the SKF Microlog GX series data collector/analyser (firmware version 4.x) [48]. The part number of this equipment is 32298500-EN with revision C manual. This GX Series Microlog device as shown in Figure 3.5 is used to collect and analyse vibration data. This device is used to collect all rotating machinery vibration, temperature and other condition monitoring measurements.

This GX Series Microlog system consists of three components which are: -

- GX Series Microlog Data Collector.
- Application modules installed on the Microlog Data Collector.
- A host computer with Aptitude Analyst Software and Reporting Software.

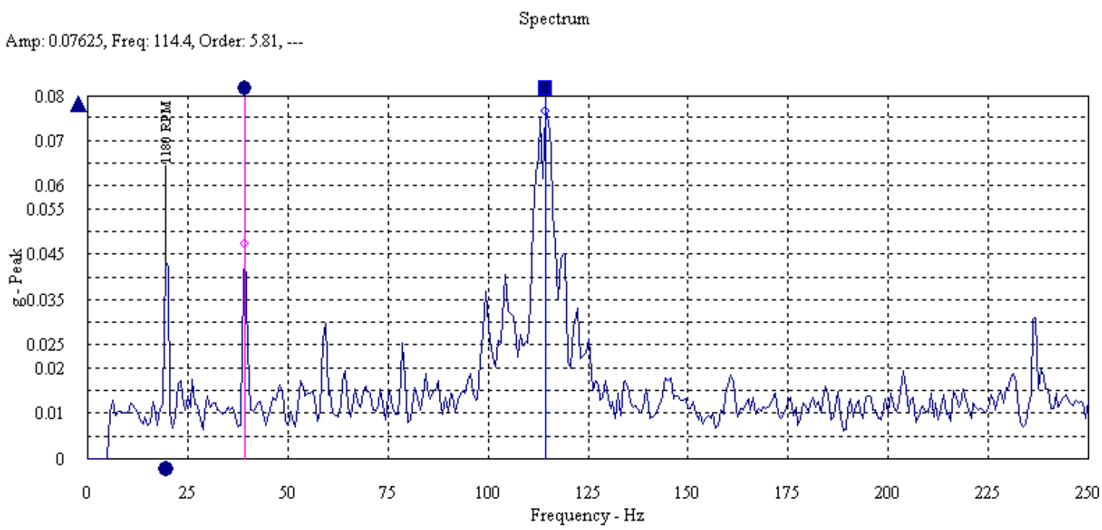

Figure 3.4 Sample Aptitude Analyst Spectrum Display

Sample measurement as shown in Figure 3.4 will be used to analyse the vibration data. The frequency will reflect the source of vibration or also indicate what is vibrating. The amplitude reflects the strength the vibration or how severe is the vibration. These two parameters are standard for analysing vibration trend.

Figure 3.5 The SKF CMXA75 GX Series Device

3.4 Site Survey

For this thesis, the vibration survey was collected, and the data were interpreted for the year 2018. The vibration survey is carried out by the condition monitoring engineer along with the electrical engineer. All the necessary parameters shall be set (setting up the measurement hierarchy) into the SKF Microlog GX Series device and software. This process is called fill up Asset Information Page (AIP). The survey is carried out twice a month during full capacity (motor run at rated Full Speed). Full capacity is when power plant generating its maximum power (base load) which is during the daytime from 10am-8pm. During midnight 10pm-6am, power plant generates only 50% power. A simple flowchart for the predictive maintenance is shown in Figure 3.6.

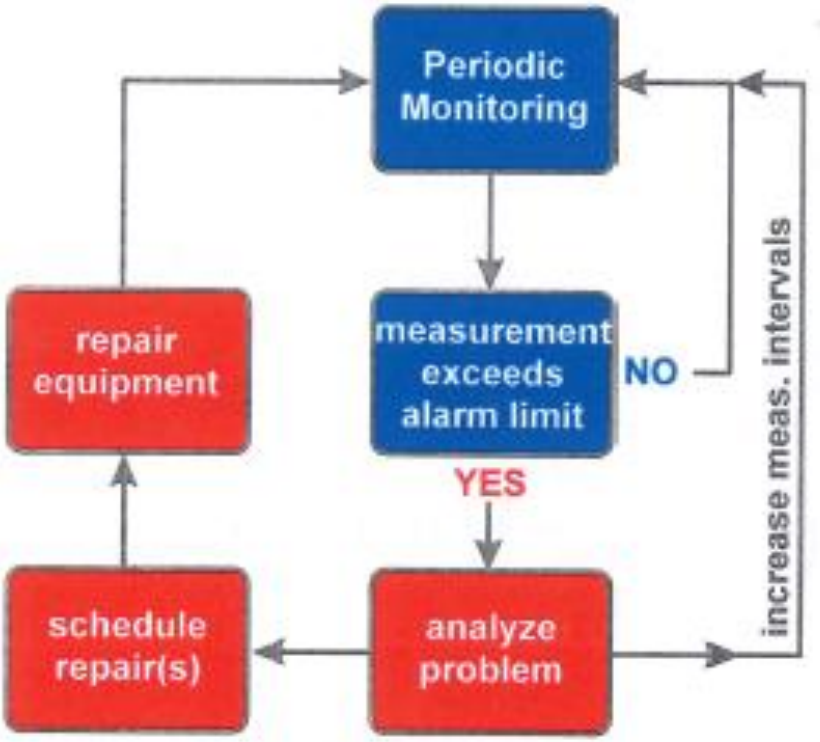

Figure 3.6 Simple flow work for predictive maintenance

The predictive maintenance is very simple in fact. Firstly, the predictive techniques were utilized to collect parameters such as vibration, temperature, pressure, lubrication viscosity and others. Secondly, engineering limits for those parameters were established. These limits are improved as time goes on. Then, perform periodic monitoring and data collection. Once the data exceed the limit set, then analyse those data. Plan for scheduled maintenance. Troubleshoot the root cause and eliminate it during scheduled maintenance.

For a horizontal motor and pump as shown in Figure 3.6, on each bearing, the plane of data acquisition is identified by H for horizontal measurements and, V for vertical measurements, A for axial measurements or R for radial measurements. For example, using a simple 4-bearing, horizontally mounted pump, measurement locations are as below: -

- Motor NDE = 1H, 1V, and 1A
- Motor DE = 2H and 2V
- Pump DE = 3H and 3V
- Pump NDE = 4H and 4V

In the field, the pump drive end (DE), bearing may not be accessible for testing due to the coupling guard, or some other physical constraints. In this case, the measurements are taken as below: -

- Motor NDE = 1H, 1V, and 1A
- Motor DE = 2H and 2V
- Pump NDE = 4H and 4V

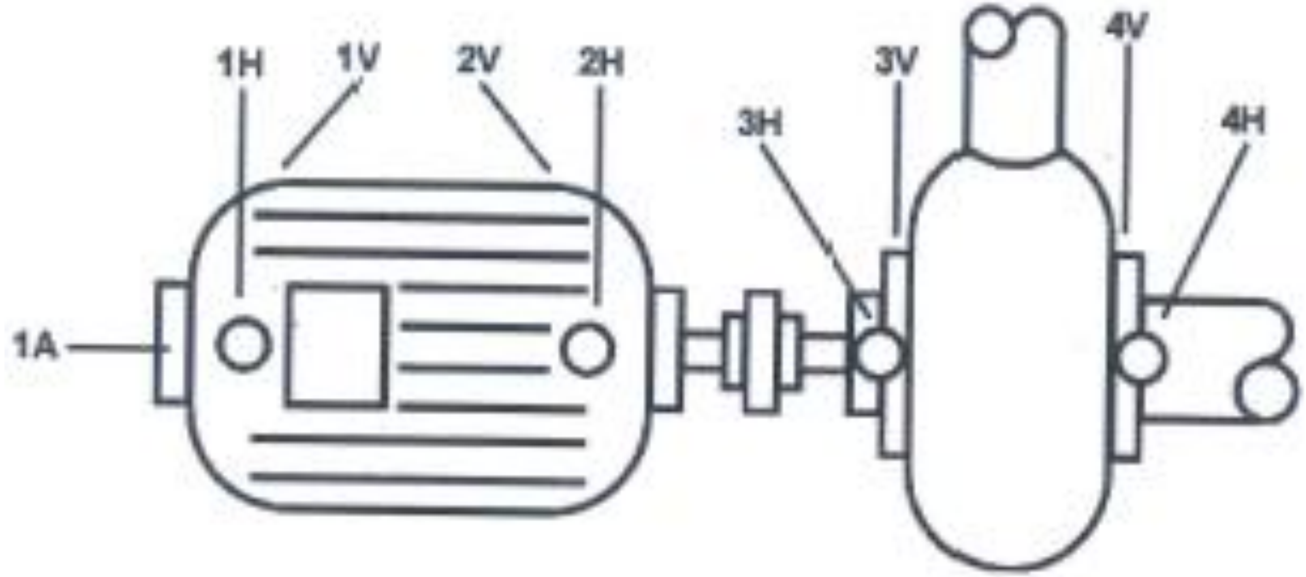

Figure 3.7 Measurement identifications for horizontal motor and pump [47]

3.4.1 LPFW Motor Details and Survey

Firstly, a study on the induction motor and its load study were carried out. The LPFW the motor is a horizontal motor with a normal SKF roller bearing used on it. It is also known as an asynchronous motor or an induction motor. The load that it runs is a standard centrifugal pump. The pump brand is Sulzer whereas the motor brand is ABB. Table 3.1 shows the electrical motor details. The KKS for this motor is 17LAC40AP001.

Table 3.1 LPFW motor specification and details.

Motor Type	ABB 3 phase	**IP rating**	55
Weight	800kg	**PF**	0.91
Voltage	415V	**Current**	152A
Frequency	50Hz	**Bearing DE**	6318 ZZ
Speed	2980rpm	**Bearing NDE**	6318 ZZ
Power	90kW	**Insulation**	Class F

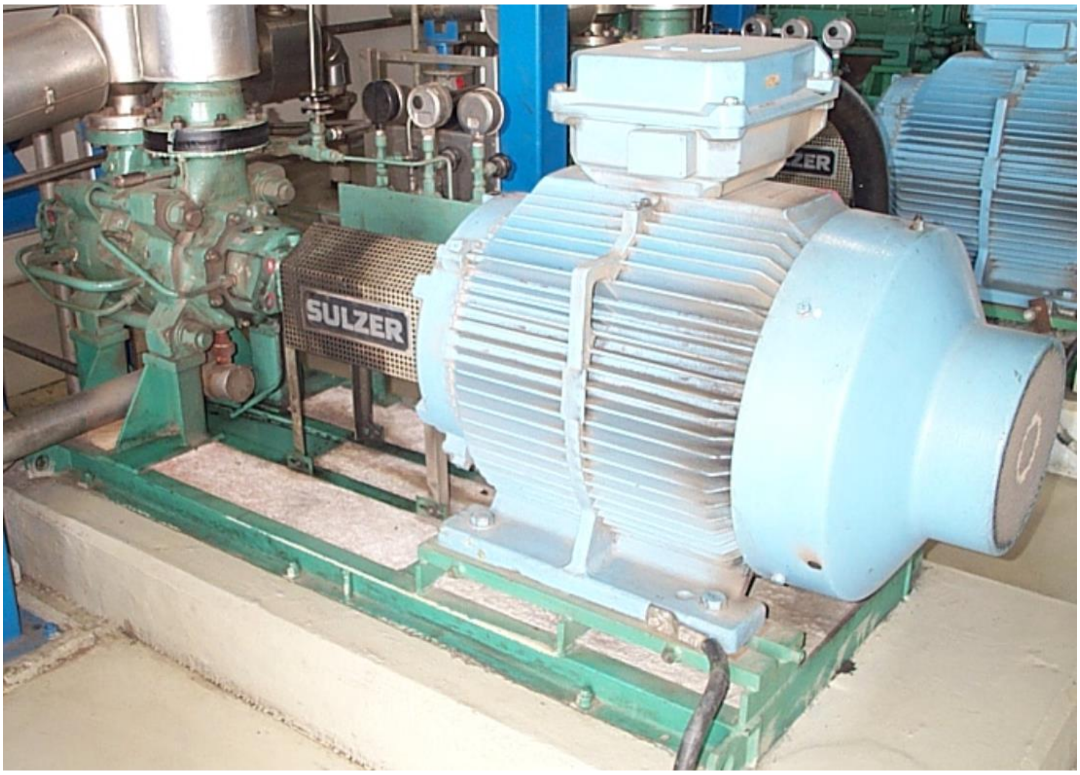

Figure 3.8 The LPFW pump motor no.4

The vibration survey was conducted on the LPFW motor no.4 and its data were analysed. The motor was on full load and rated speed during readings taken. The starter used for starting the motor is direct online starters. As per Table 3.1, the bearing used for this motor is 6318 ZZ which means it is a double shielded bearing where it is difficult for foreign objects to enter the bearing and damage it. The full specification and details were studied prior to getting the vibration readings. The vibration for horizontal motor is taken at 2 major points and 3 minor points. A total of 5 points were taken. The point at motor NDE side is 1A, 1V and 1H whereas at motor DE side is 2V and 2H as shown in Figure 3.7.

3.4.2 CT Fan Motor Details and Survey

The CT fan motor is also a horizontal motor with a normal SKF roller bearing used on it. It is also known as an asynchronous motor or an induction motor. The load that it runs is a vertical fan with the aid of a gear box in between the motor and the fan. Table 3.2 shows the electrical motor details. The KKS for this motor is 19PAD14AN001.

Table 3.2 CT fan motor specification and details.

Motor Type	ABB 3 phase	**IP rating**	55
Weight	1080kg	**PF**	0.87
Voltage	415V	**Current**	312A
Frequency	50Hz	**Bearing DE**	6319/C3 ZZ
Speed	1485rpm	**Bearing NDE**	6319/C3 ZZ
Power	180kW	**Insulation**	Class F

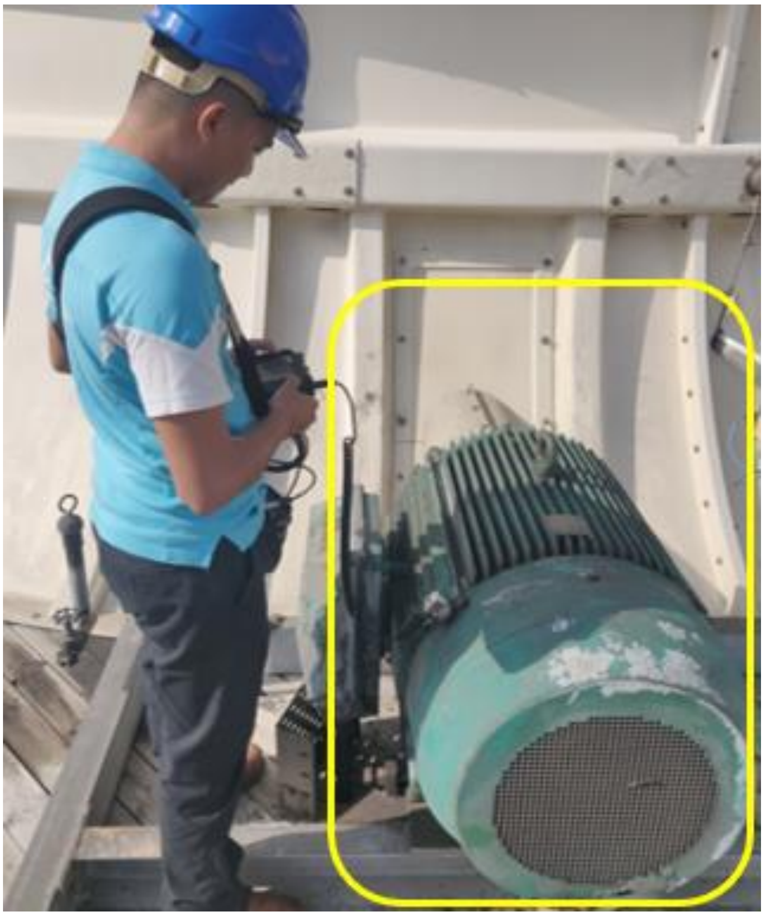

Figure 3.9 The CT fan motor no.4

The vibration survey was conducted on the CT fan motor no.4 and all the data were analysed. During data collection the motor was in same running condition as previous LPFW motor where it was on full load and rated speed. The starter used for starting the motor is direct online starters. As per Table 3.2, the bearing used for this motor is 6319/C3 which means it is a non-shielded bearing. The C3 indicates the bearing roller element gap is slightly bigger to reduce heat.

3.5 Vibration Data Survey

Data for both the LPFW pump no.4 and CT fan motor no.4 were collected twice a month during full load. The data were analysed using the SFKF software [48]. A total of six significant criteria for vibration analyses were analysed.

- Motor NDE Enveloping Trend (gE - peak to peak)
- Motor NDE Enveloping Spectrum (gE - peak to peak)
- Motor NDE Velocity Trend (mm/s - RMS)
- Motor DE Enveloping Trend (gE - peak to peak)
- Motor DE Enveloping Spectrum (gE - peak to peak)
- Motor DE Velocity Trend (mm/s - RMS)

3.6 Chapter Summary

As summary, this chapter starts with the detail introduction on KLPP and the CCPP. The major machines in KLPP and the critical equipment are explained. The operating and maintenance structure of KLPP is explained. Then the two units of critical motor which is the LPFW Pump Motor no.4 and CT Fan Motor no.4 were described and why both were chosen was explained. The CBM workflow and structure was briefed. Then the technique used to collect the vibration data was explained. The main aim is to collect the data and analyse it in the next chapter 4.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

The survey was conducted, and the data collected was tabulated in the form of graph and table. The root cause for all the abnormal data readings were analysed. Recommended preventive and corrective maintenance were carried out with minimal downtime. The vibration data was taken again after the maintenance was done to make sure the reading return to normal.

4.2 Vibration/Spectrum Analysis

4.2.1 LPFW Pump Motor No.4 (before maintenance)

During the survey along the year 2018 [50], an intermittent abnormal noise was detected the at motor side on 4 April 2018. Then the vibration readings were taken again (during full load 2980rpm) on the same day and abnormalities were found in the data.

I. LPFW Pump Motor no.4 NDE Enveloping Trend in shown in Figure 4.1, and it is observed that on 4 April 2018 the motor NDE enveloping reading shot above 6gE which is 6.2gE as circled. By referring to [48], this reflects that the motor NDE bearing is lack of lubrication and rubbing had occurred due to that. Comparing with the vibration diagnostics table, this NDE side is highly recommended to be greased.

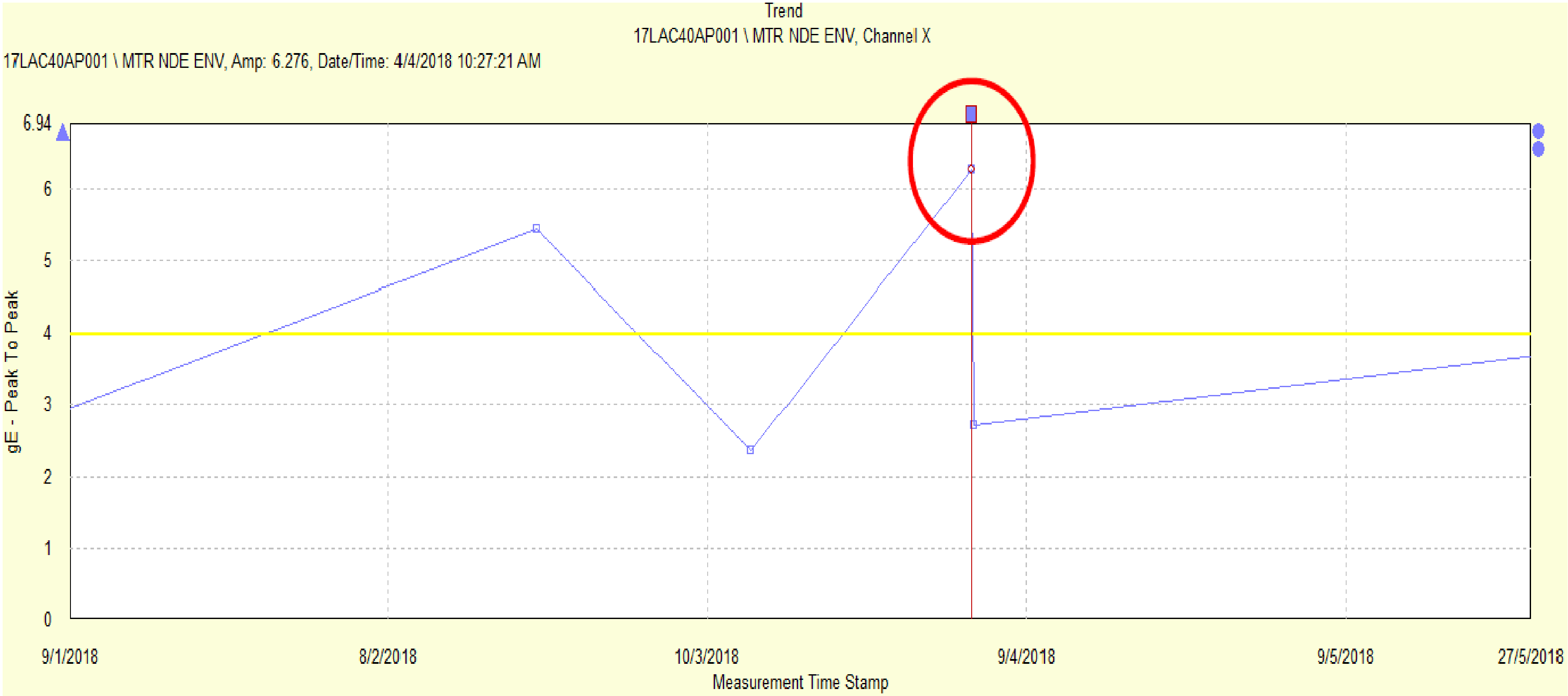

Figure 4.1 LPFW no.4 Motor NDE Enveloping Trend

II. LPFW Pump Motor no.4 NDE Enveloping Spectrum is shown in Figure 4.2, and it is observed that on 4 April 2018 the motor NDE enveloping spectrum readings were all good. The spectrum at 2950rpm, is below 1gE which means no bearing frequency defect was detected [48]. The spectrum readings at four fundamental frequencies do not show any abnormalities. The fundamental and its significant harmonics frequencies are 2950, 2x2950=5900, 3x2950= 8850 and 4x2950=11800.

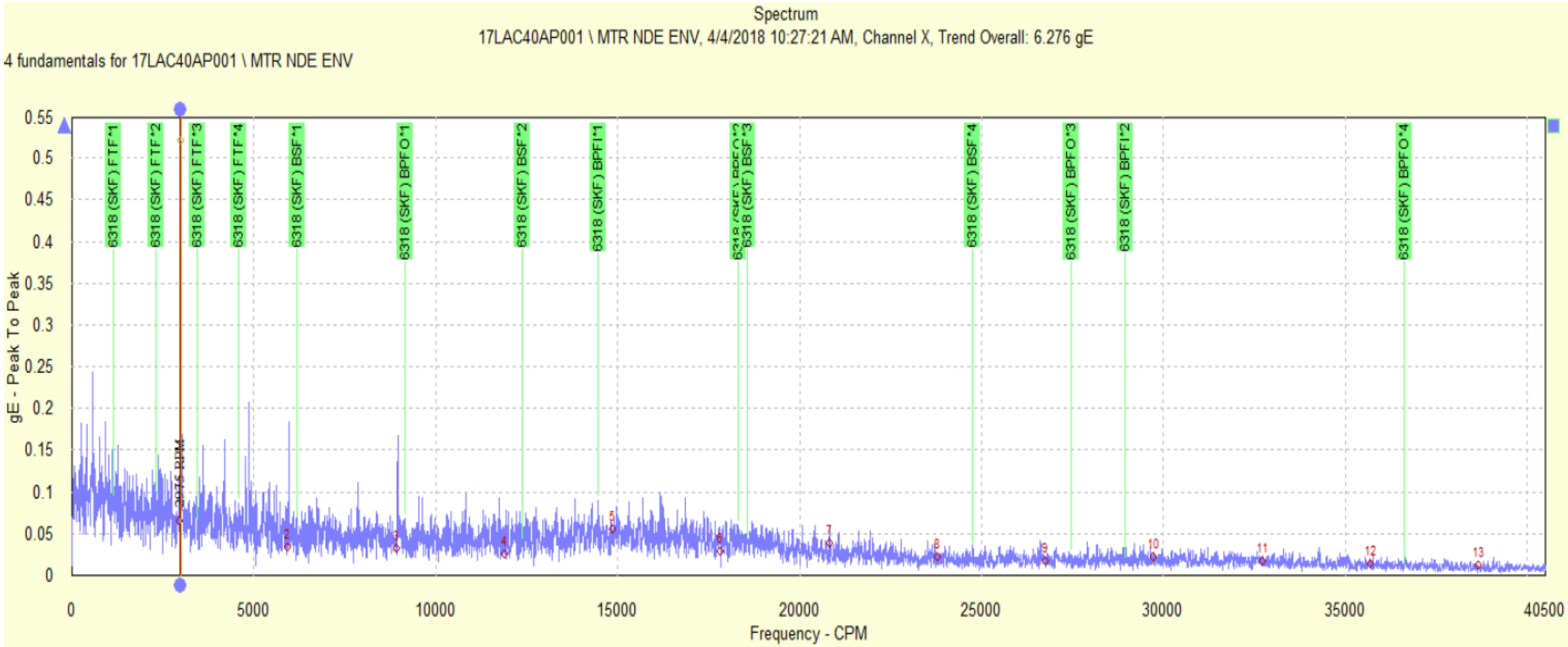

Figure 4.2 LPFW no.4 Motor NDE Enveloping Spectrum

III. LPFW Pump Motor no.4 NDE Velocity Trend is shown in Figure 4.3, which showed that on 4 April 2018 the motor NDE Velocity Trend were recorded at 2.2mm/s as circled [48].

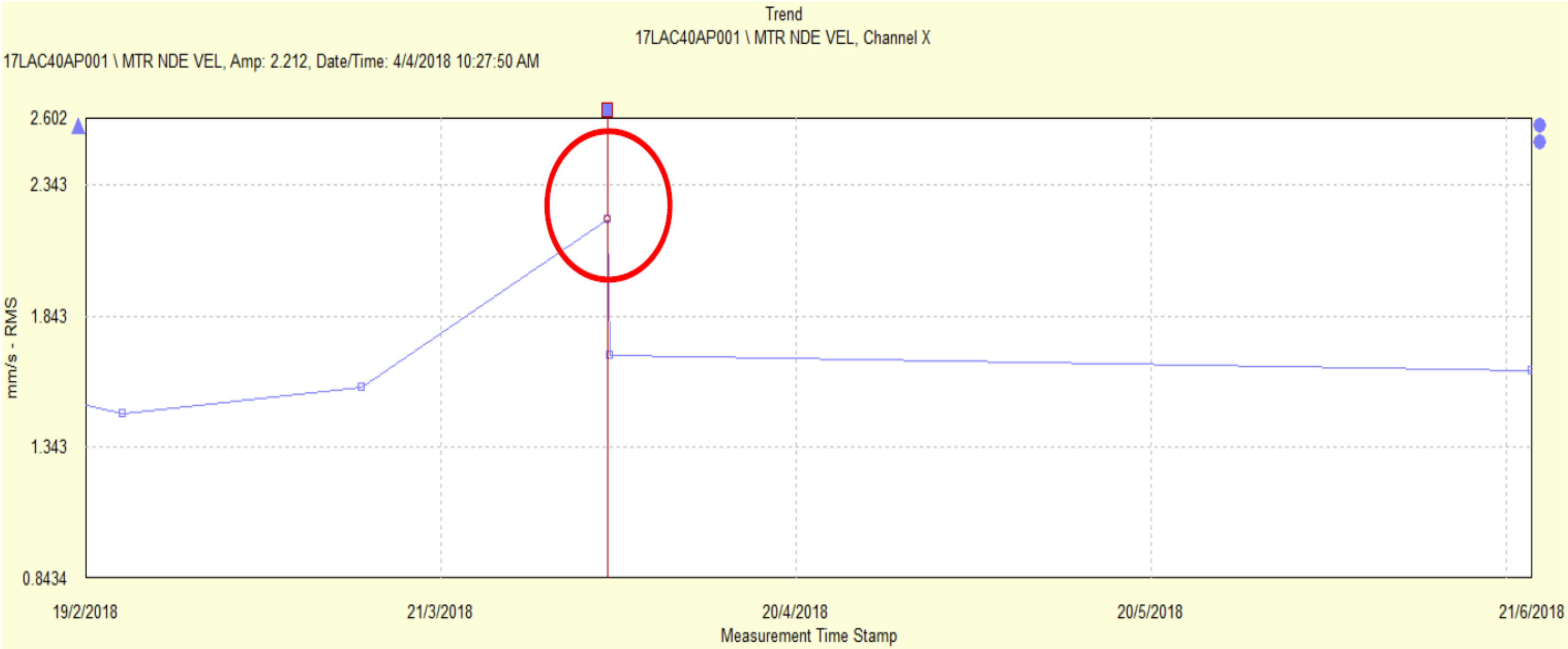

Figure 4.3 LPFW no.4 Motor NDE Velocity Trend

IV. LPFW Pump Motor no.4 DE Enveloping Trend is shown in Figure 4.4, and on 4 April 2018 the motor DE Enveloping Trend was at 5.2gE as circled. This also indicates that the bearing lacks lubrication as referring to [48].

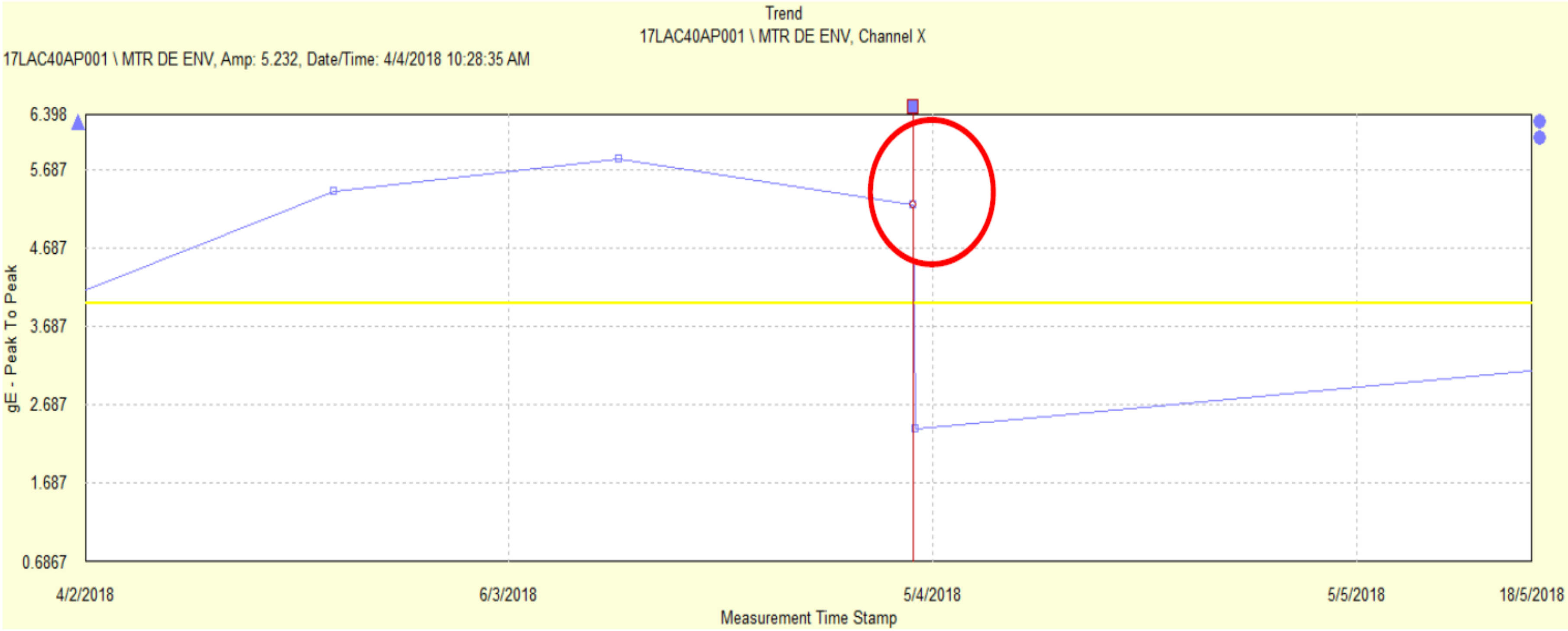

Figure 4.4 LPFW no.4 Motor DE Enveloping Trend

V. LPFW Pump Motor no.4 DE Enveloping Spectrum is shown in Figure 4.5, and it shows that all the 4 fundamentals frequency spectrum for the DE bearing indicates no bearing defect detected. As shown, all the spectrum readings at 4 fundamental frequencies are below 1gE peak to peak. By referring to [48], this indicates only lubrication problem. The fundamental and its significant harmonics frequencies are 2950, 2x2950=5900, 3x2950= 8850 and 4x2950=11800.

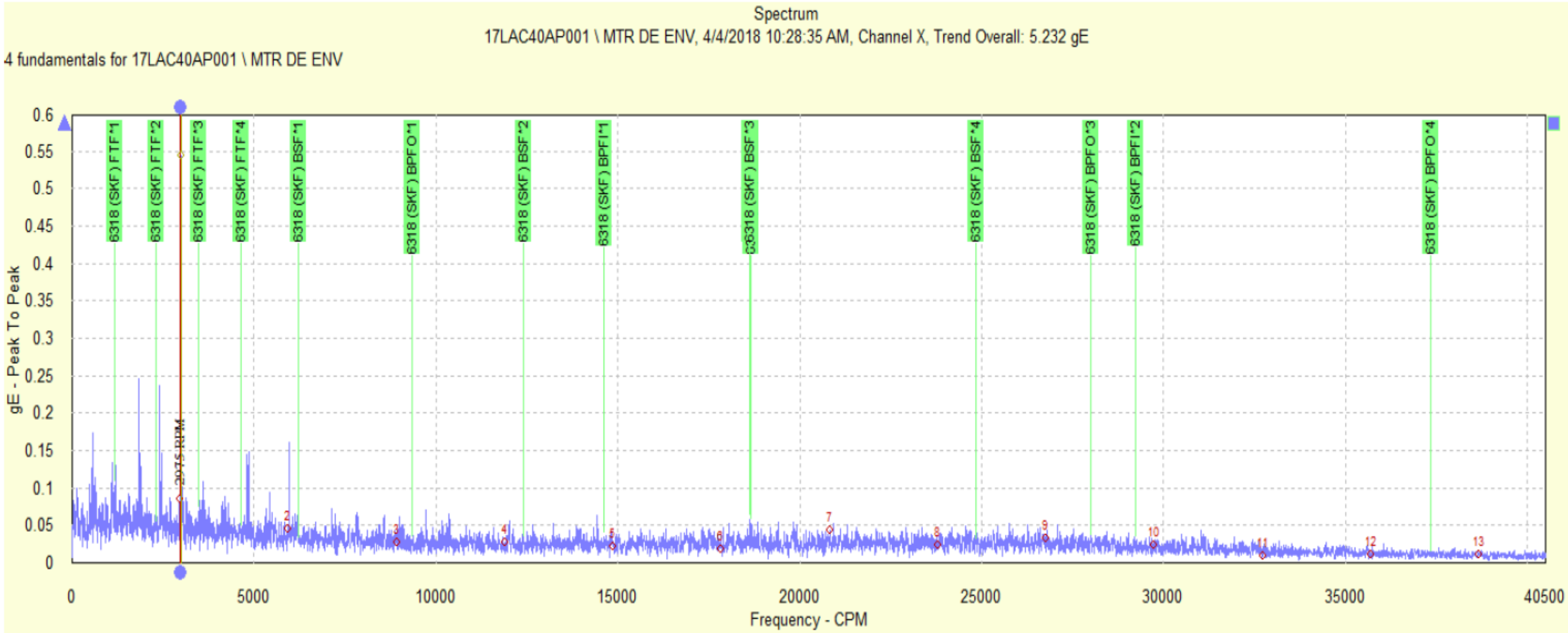

Figure 4.5 LPFW no.4 Motor DE Enveloping Spectrum

VI. LPFW Pump Motor no.4 DE Velocity Trend is shown in Figure 4.6, and it is seen that on 4 April 2018 the motor DE Velocity Trend has recorded at 1.69mm/s as circled. This value indicates that the DE side of motor bearing is normal [48].

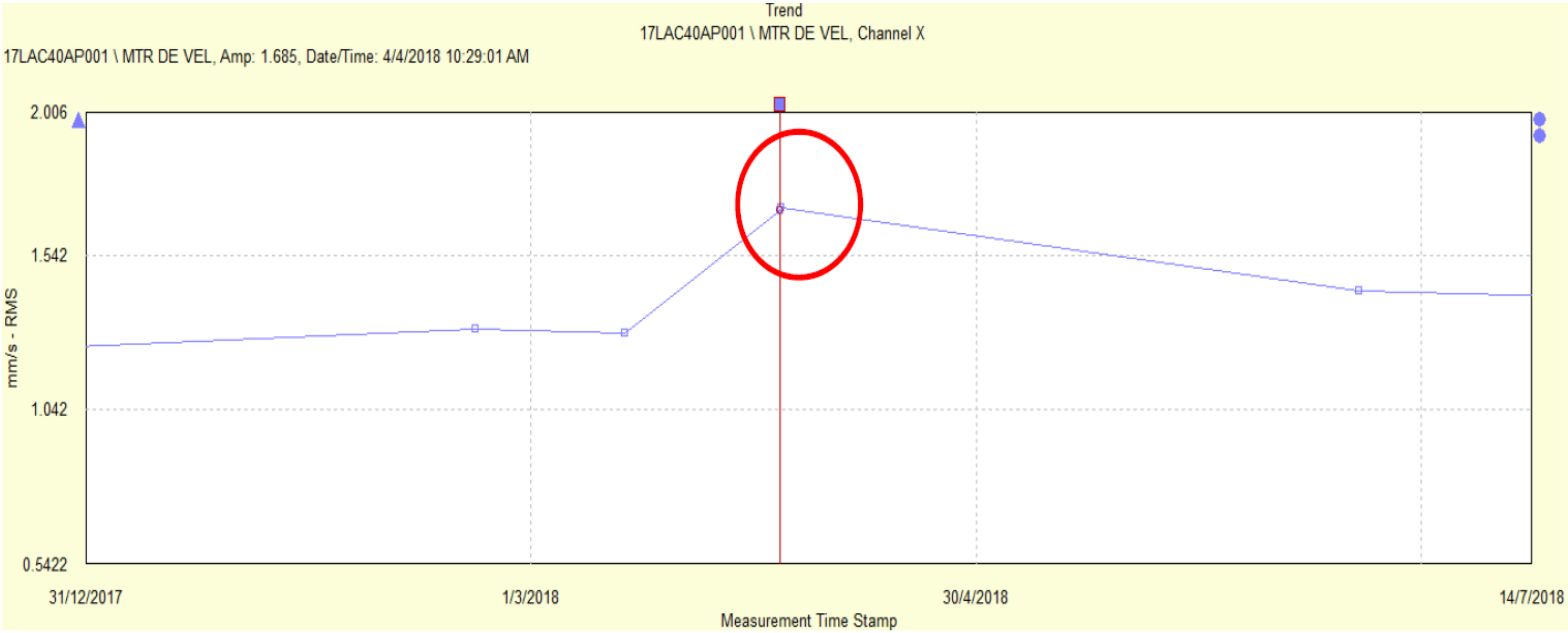

Figure 4.6 LPFW no.4 Motor DE Velocity Trend

4.2.2 LPFW Pump Motor No.4 (after maintenance)

After taking the vibration reading and analysing, it was found that the main root cause of the abnormal sound and vibration was due to lack of lubrication in both DE and NDE bearings. The bearings are still in good condition as the frequency spectrum all shows below 1gE peak to peak value [48].

Therefore, online greasing was performed by KLPP Electrical Technician recommended by KLPP Condition Monitoring Engineer. Shell high temperature electrical motor grease was applied. Online greasing means, grease is applied without motor shutdown. There will be a greasing pinpoint in the motor (Figure 4.7) for both DE and NDE bearing side. Thus, grease was pumped using the greasing pump with a certain quantity. After 1 hour of motor running at full speed and load, the vibration data were collected to counter check whether the problem was solved. The vibration data collected are as shown below in Figure 4.8 to Figure 4.13.

Figure 4.7 Shows sample electrical motor greasing point

I. LPFW Pump Motor no.4 NDE Enveloping Trend is shown in Figure 4.8, which shows after greasing done, the motor NDE enveloping reading drops from 6.2gE as circled to 2.7gE as circled. The threshold is 6gE [48] as shown in Table 2.5. The two red circle indicates the value drops from 6.2gE to 2.7gE.

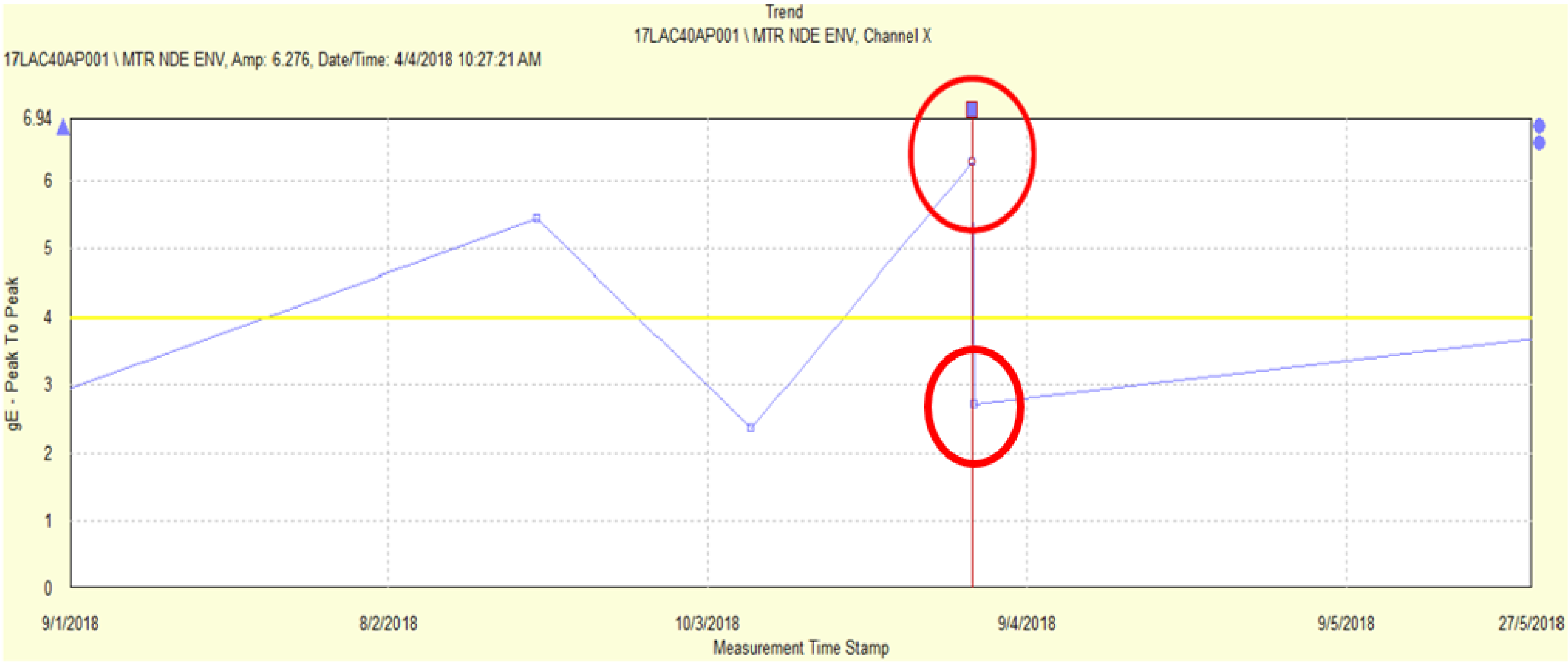

Figure 4.8 LPFW no.4 Motor NDE Enveloping Trend after maintenance

II. LPFW Pump Motor no.4 NDE Enveloping Spectrum is shown in Figure 4.9, which shows after greasing done, the motor NDE enveloping spectrum readings were all good as before. The spectrum at 2950rpm, all are below 1gE which means no bearing frequency defect detected [48]. The spectrum readings for the 4 fundamental frequencies do not show any bearing defect. The fundamental and its significant harmonics frequencies (x-axis) are 2950, 2x2950=5900, 3x2950= 8850 and 4x2950=11800.

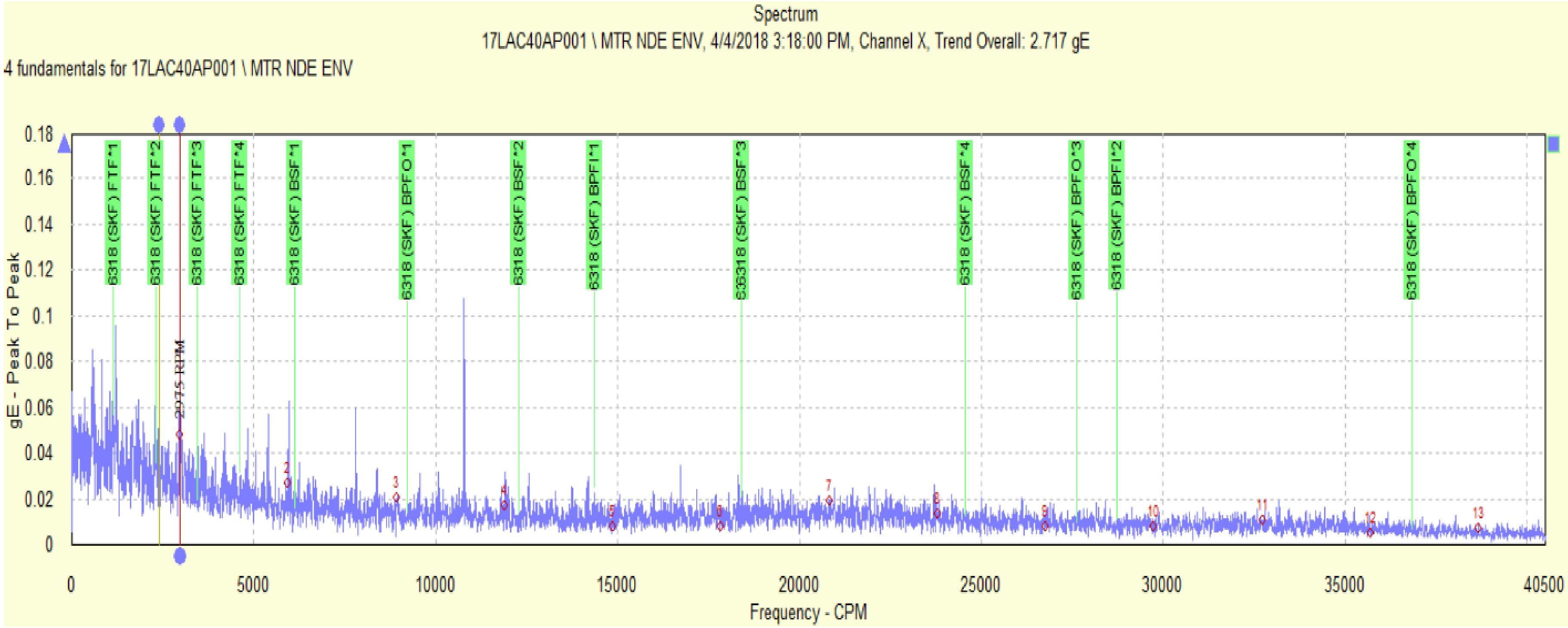

Figure 4.9 LPFW no.4 Motor NDE Enveloping Spectrum after maintenance

III. LPFW Pump Motor no.4 NDE Velocity Trend is shown in Figure 4.10, which shows after greasing done, the motor NDE Velocity Trend reduced from 2.2mm/s as circled to 1.69mm/s as circled [48].

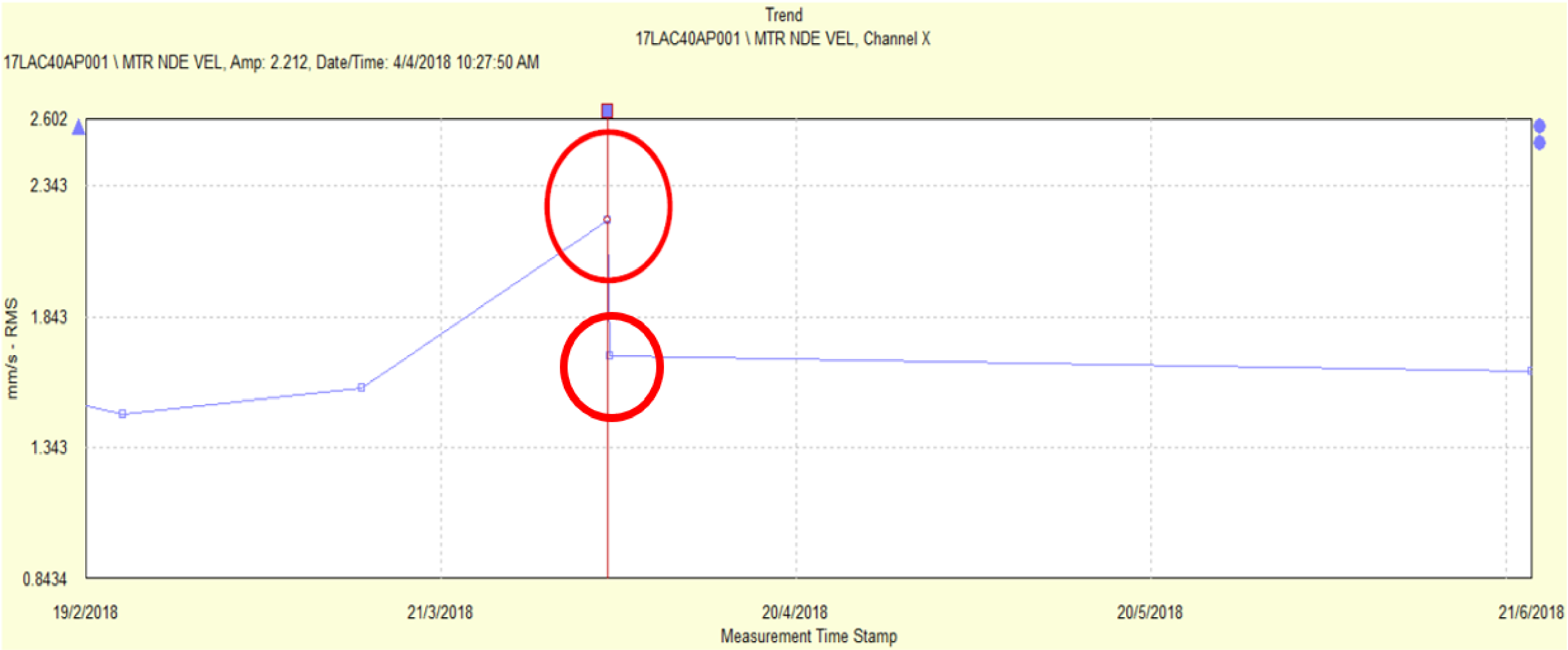

Figure 4.10 LPFW no.4 Motor NDE Velocity Trend after maintenance

IV. LPFW Pump Motor no.4 DE Enveloping Trend is shown in Figure 4.11, which shows after greasing done, the motor DE Enveloping Trend drop from 5.2gE to 2.0gE peak to peak as circled [48].

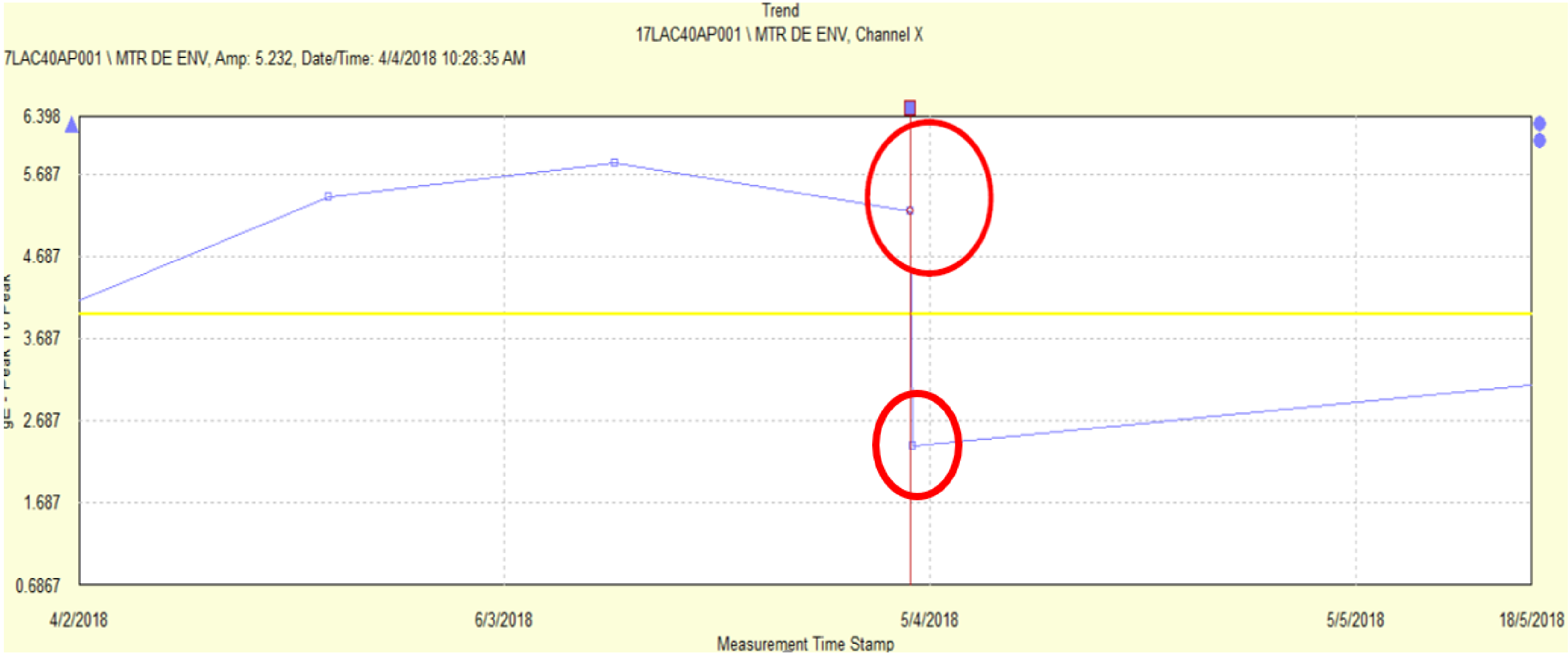

Figure 4.11 LPFW no.4 Motor DE Enveloping Trend after maintenance

V. LPFW Pump Motor no.4 DE Enveloping Spectrum is shown in Figure 4.12, which shows after greasing done, all 4 fundamental frequencies (red line) spectrum for the DE bearing indicates no bearing defect detected as before. As shown, all the fundamentals and its significant harmonics frequency spectrum are below 1gE peak to peak [48]. The fundamental and its significant harmonics frequencies are 2950, 2x2950=5900, 3x2950= 8850 and 4x2950=11800.

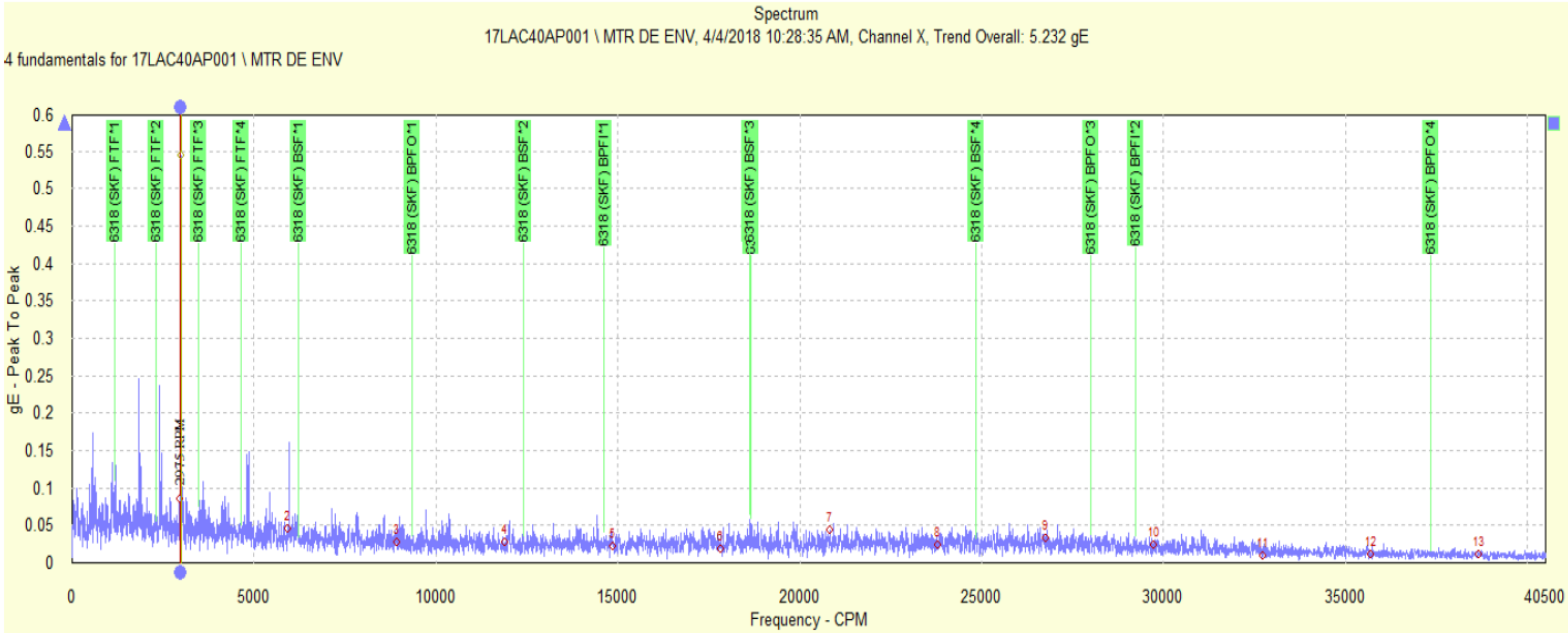

Figure 4.12 LPFW no.4 Motor DE Enveloping Spectrum after maintenance

VI. LPFW Pump Motor no.4 DE Velocity Trend is shown in Figure 4.13, which shows after greasing done the motor DE Velocity Trend data maintain at 1.69mm/s as circled [48].

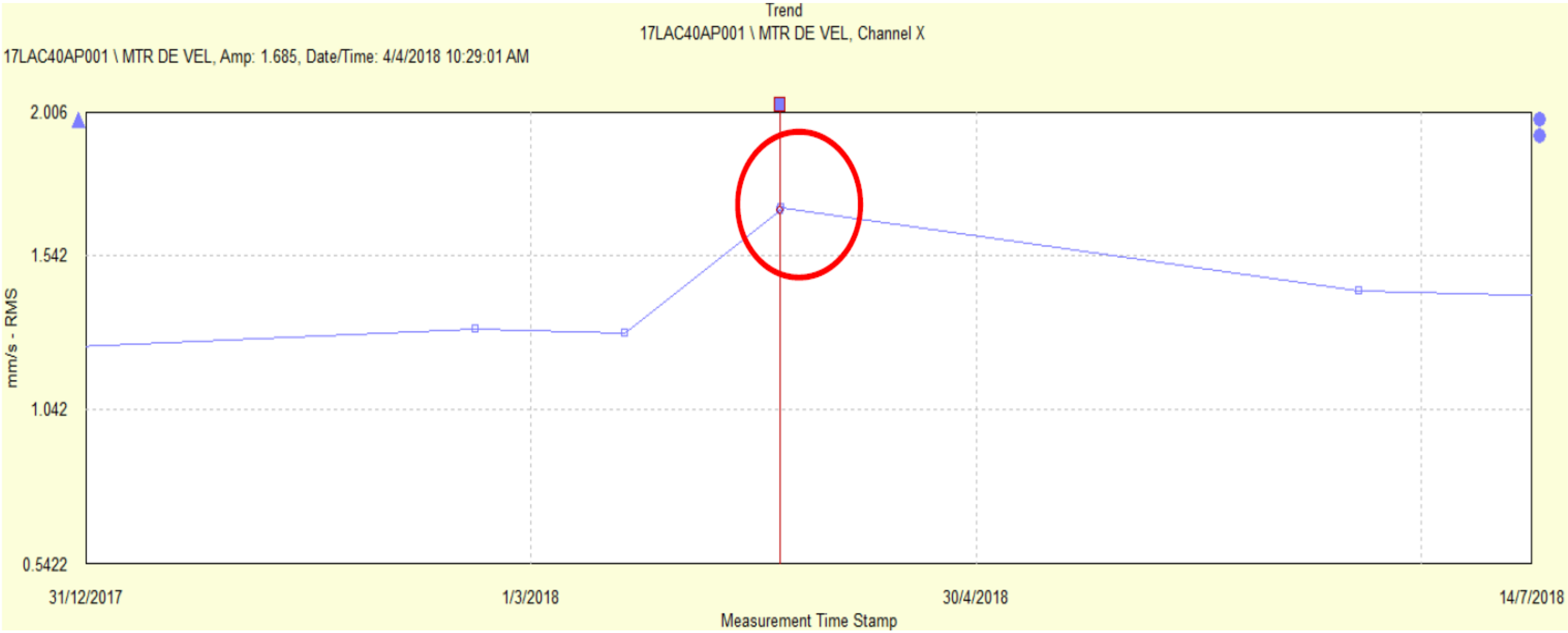

Figure 4.13 LPFW no.4 Motor DE Velocity Trend after maintenance

4.2.3 CT Fan Motor No.4 (before maintenance)

During the survey along the year 2018, an intermittent abnormal noise was detected at the motor side on 15 February 2018. Then the vibration readings were taken (full load 1485rpm) again on the same day and found abnormalities in the data.

I. CT Fan Motor no.4 NDE Enveloping Trend is shown in Figure 4.14, and on 15 February 2018 the motor NDE enveloping reading shot above 6gE which is 6.9gE as circled. This reflects that the motor is in abnormal condition. To further find the root cause, the spectrum was further analysed [48].

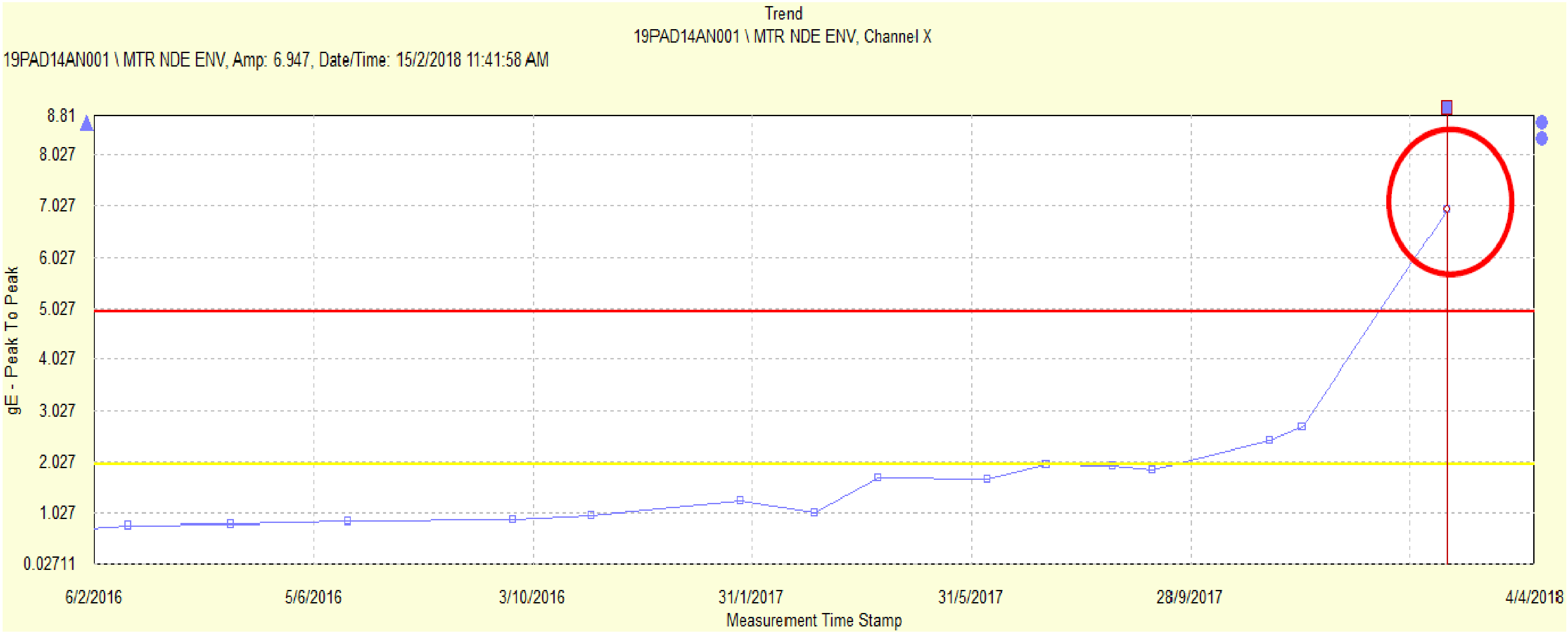

Figure 4.14 CT no.4 Motor NDE Enveloping Trend

II. CT Fan Motor no.4 NDE Enveloping Spectrum Amplitude is shown in Figure 4.15, which shows that the motor NDE enveloping spectrum readings were not satisfactory. The spectrum analysis shows that ball pass frequency outer (BPFO) start to fail where the highest amplitude at 1*BPFO is 1.4gE, 2*BPFO is 0.9gE and 3* BPFO is 0.8gE as shown in Figure 4.15 red marked. Based on the vibration diagnostics chart [48], this clearly indicates that the bearing is defected. Hence it is recommended to replace the NDE bearing.

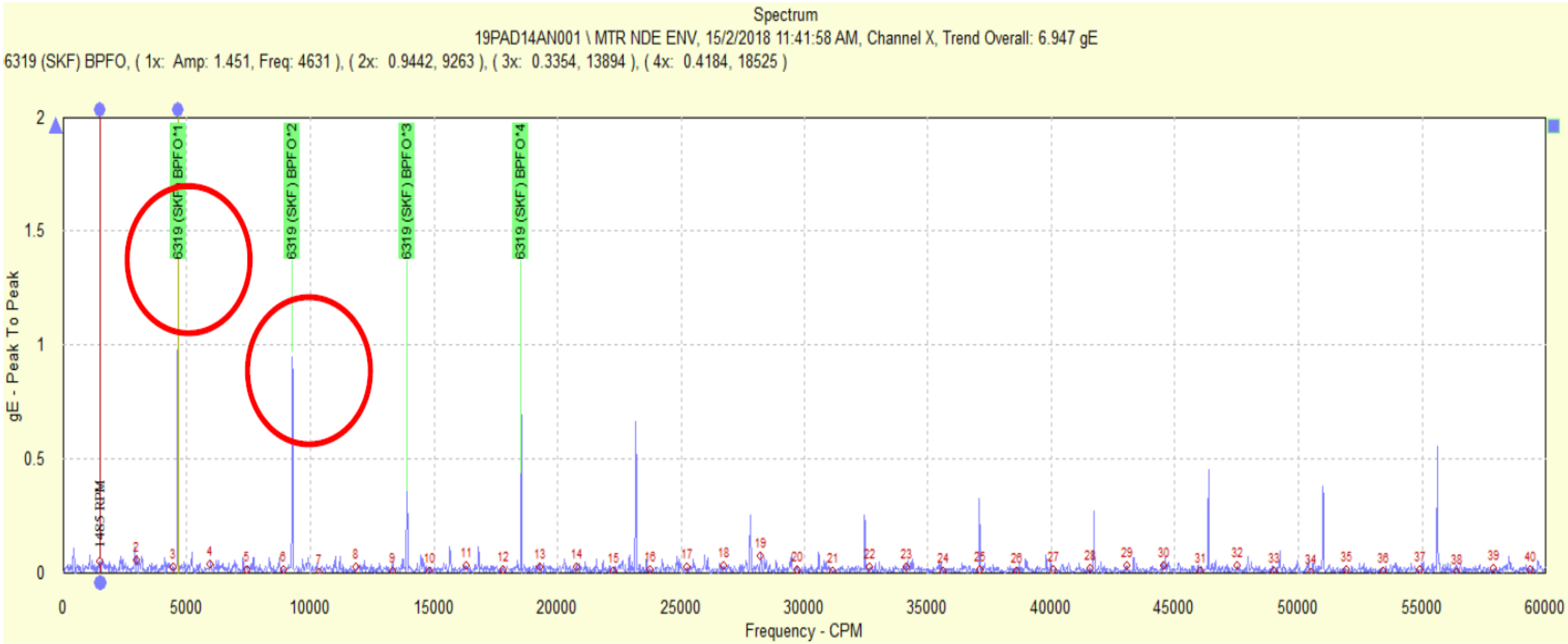

Figure 4.15 CT no.4 Motor NDE Enveloping Spectrum

III. CT Fan Motor no.4 NDE Velocity Trend is shown in Figure 4.16, which shows the motor NDE Velocity Trend data at 3.4mm/s as circled which is in the critical region (severity) [48]. Thus, the velocity spectrum must be analysed to find the root cause.

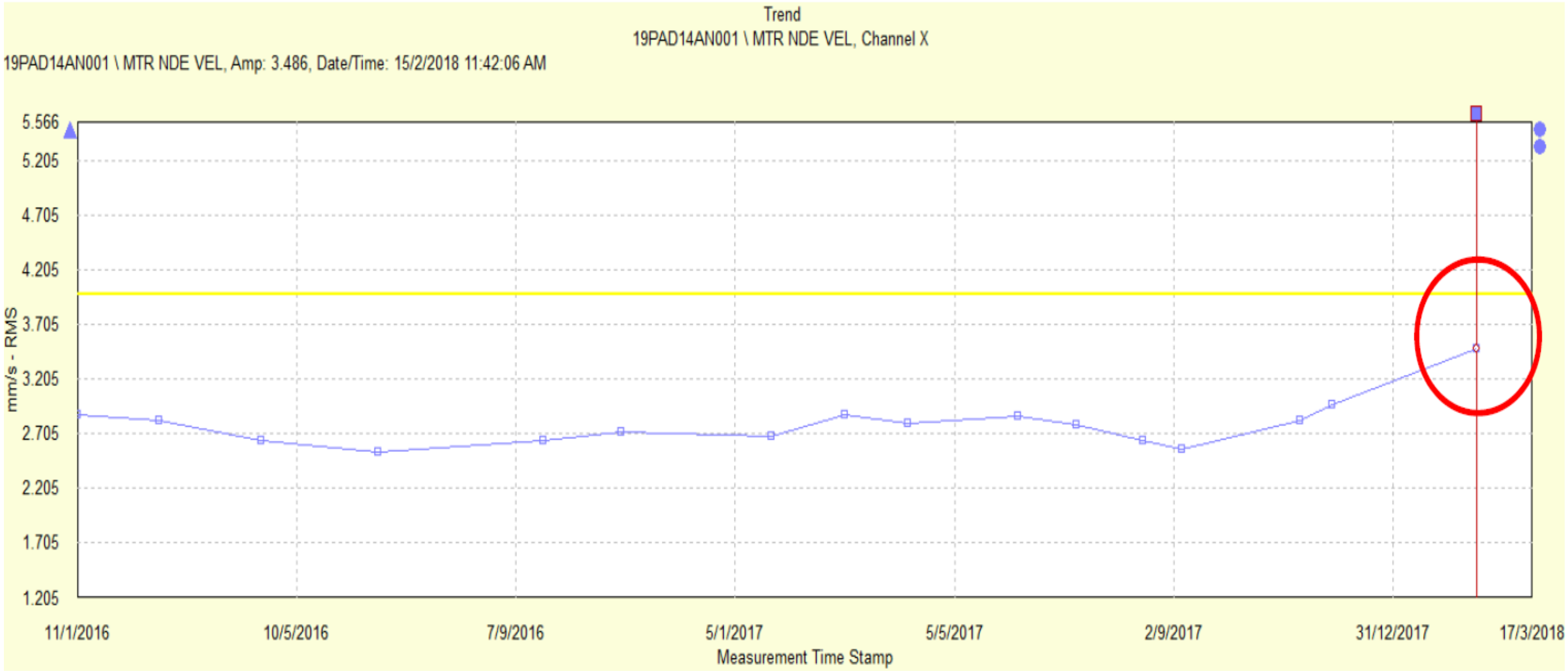

Figure 4.16 CT no.4 Motor NDE Velocity Trend

IV. CT Fan Motor no.4 NDE Velocity Spectrum is shown in Figure 4.17, which shows that the amplitude is 2.244mm/s RMS which is above 1mm/s RMS. Comparing with the vibration spectrum diagnostic chart [48], this spectrum indicates there is a minor looseness within the motor. It is recommended to check the motor base frame for any cracks or damages [48].

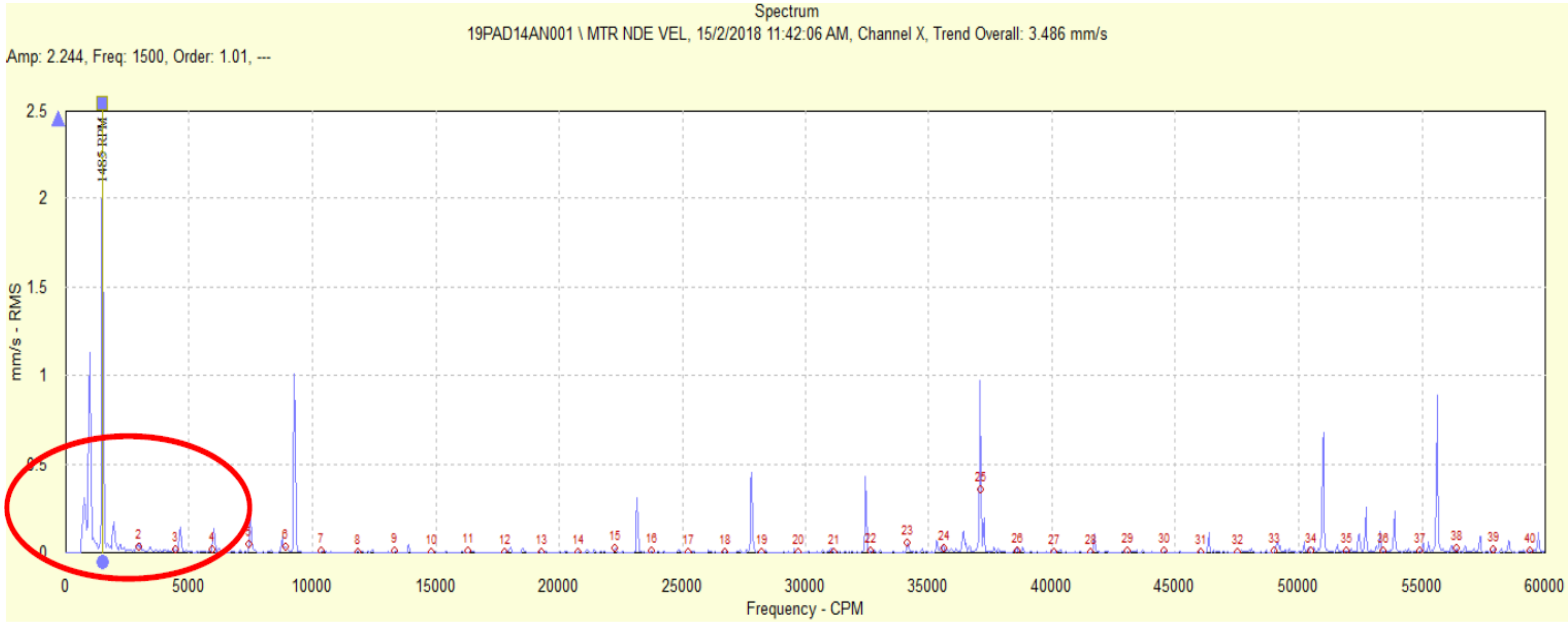

Figure 4.17 CT no.4 Motor NDE Velocity Spectrum Amplitude

4.2.4 CT Fan Motor No.4 (after maintenance)

After taking the vibration reading and analysing by referring to [48], it was found that the main root cause of the abnormal sound and vibration was due to two reasons. First, the bearing was defective on the NDE side only. Second, the motor base frame was damaged. Therefore, the proper timing was selected to shut down the machine. For this CT fan motor, usually 1 out of 10 fans will be shut down during power plant low load profile (where plant generating only 40-60% plant capacity). This opportunity will be utilized by the maintenance team to perform their maintenance job. This time is the best to optimize the plant maintenance time and cost. During this time the motor no.4 was shut down and isolated. KLPP Mechanical and Electrical Team Members performed the preventive maintenance. First the motor bearings were changed on both the NDE, the DE side and lubricated sufficiently. Secondly, the motor base frame shim was found to be broken, was also replaced with a new shim and motor alignment was performed. After 1 hour of motor running, the vibration data was collected to verify whether the problem has been solved. The vibration data collected were shown in Figure 4.20 to Figure 4.23 (page 71 – page 74).

Figure 4.18 CT Fan Motor Bearing Replacement at KLPP Workshop

Figure 4.19 CT Fan Motor Base Frame Shim Replaced

Figure 4.18 and 4.19 show that the bearing and shield problem has been resolved as recommended. Thus, the new vibration data should be normal.

I. CT Fan Motor no.4 NDE Enveloping Trend is shown in Figure 4.20, which shows the motor NDE enveloping reading drops from 6.9gE previously to 0.52gE peak to peak currently. This indicates that the bearing replacement is very critical [48].

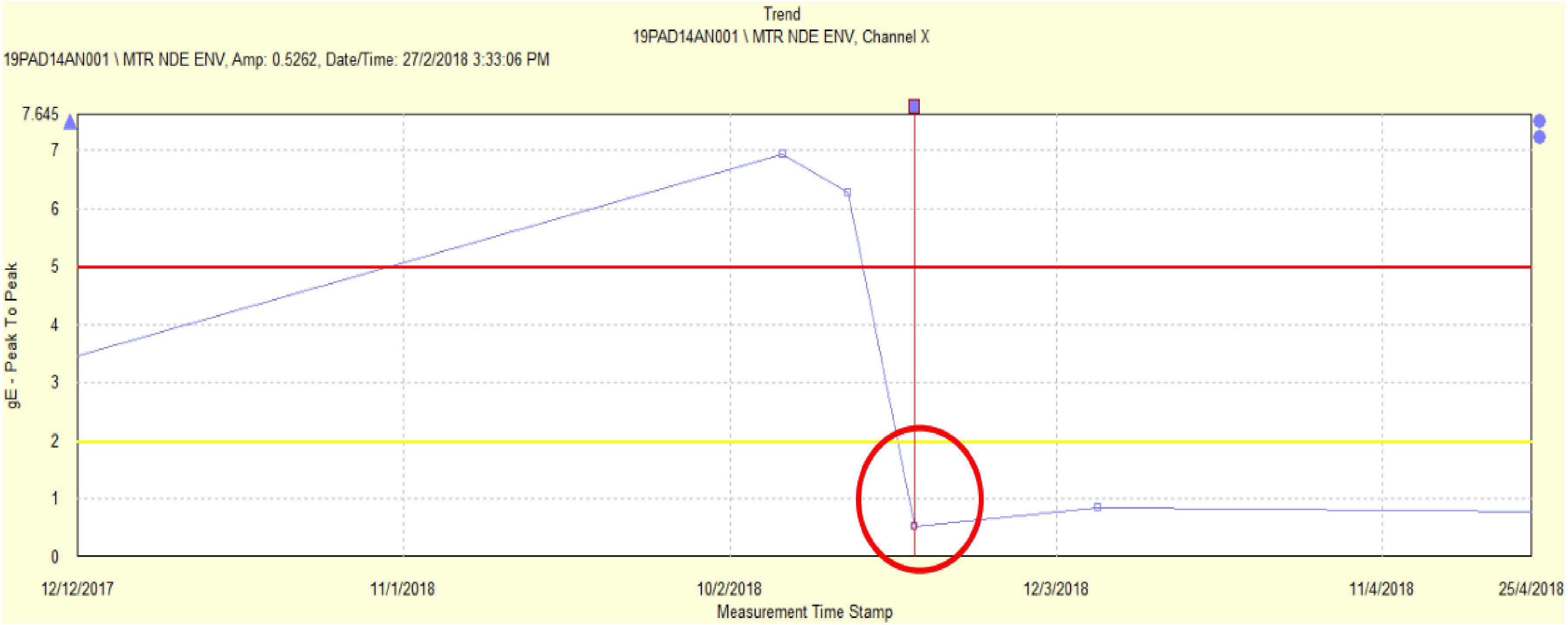

Figure 4.20 CT no.4 Motor NDE Enveloping Trend after maintenance

II. CT Fan Motor no.4 NDE Enveloping Spectrum Amplitude is shown in Figure 4.21, which shows that the bearing defect seen previously had been rectified. The 4 fundamentals and its significant harmonic frequencies spectrum amplitude are lower than 1gE. The 4 fundamental and its significant harmonic frequencies are 1785, 2x1785=3570, 3x1785= 5355 and 4x1785=7140. This clearly indicates that the bearing is in normal condition [48].

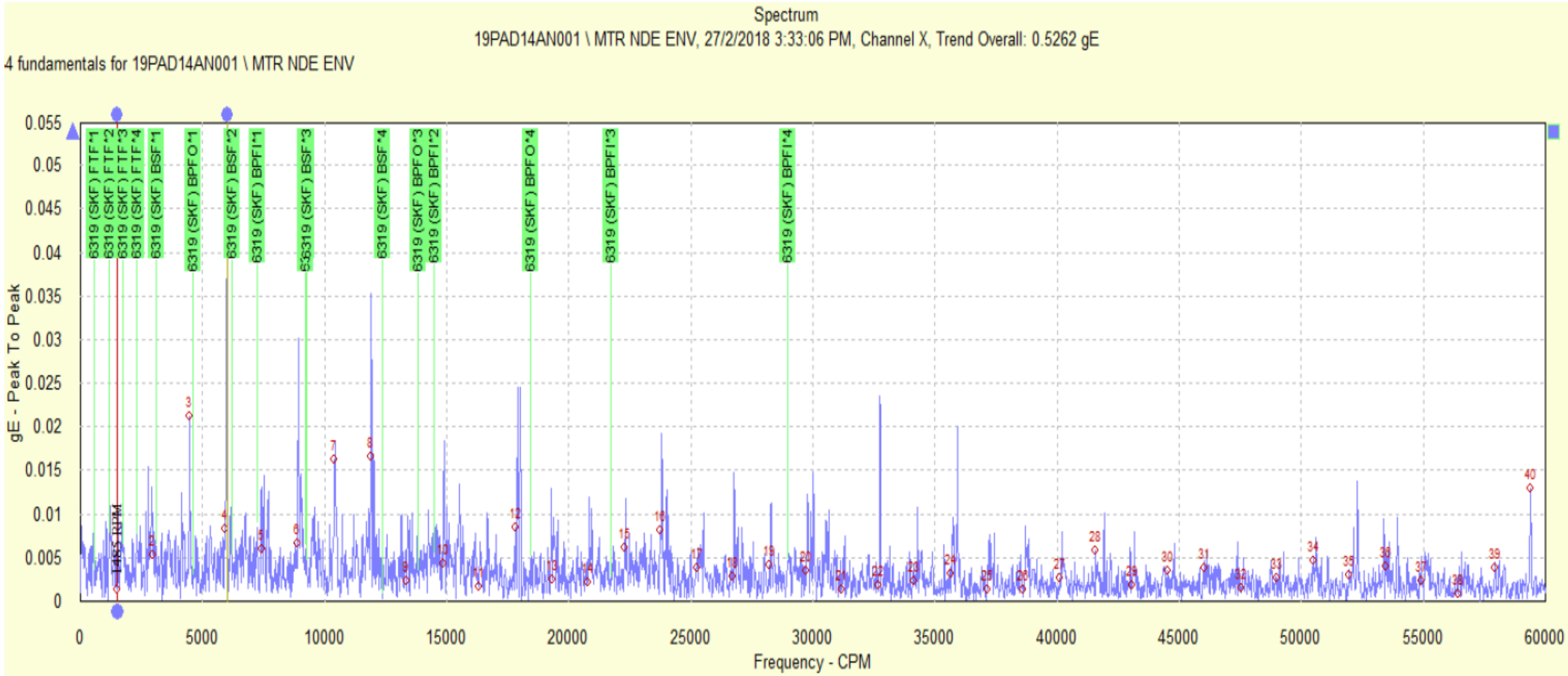

Figure 4.21 CT no.4 Motor NDE Enveloping Spectrum after maintenance

III. CT Fan Motor no.4 Velocity Trend is shown in Figure 4.22, which shows that the velocity trend drops from 3.4mm/s to 1.7mm/s currently [48]. This also clearly indicates that after resolving the motor base frame shim issue, the velocity trend was reduced. This is because, previously the shield was cracked and cause looseness [48].

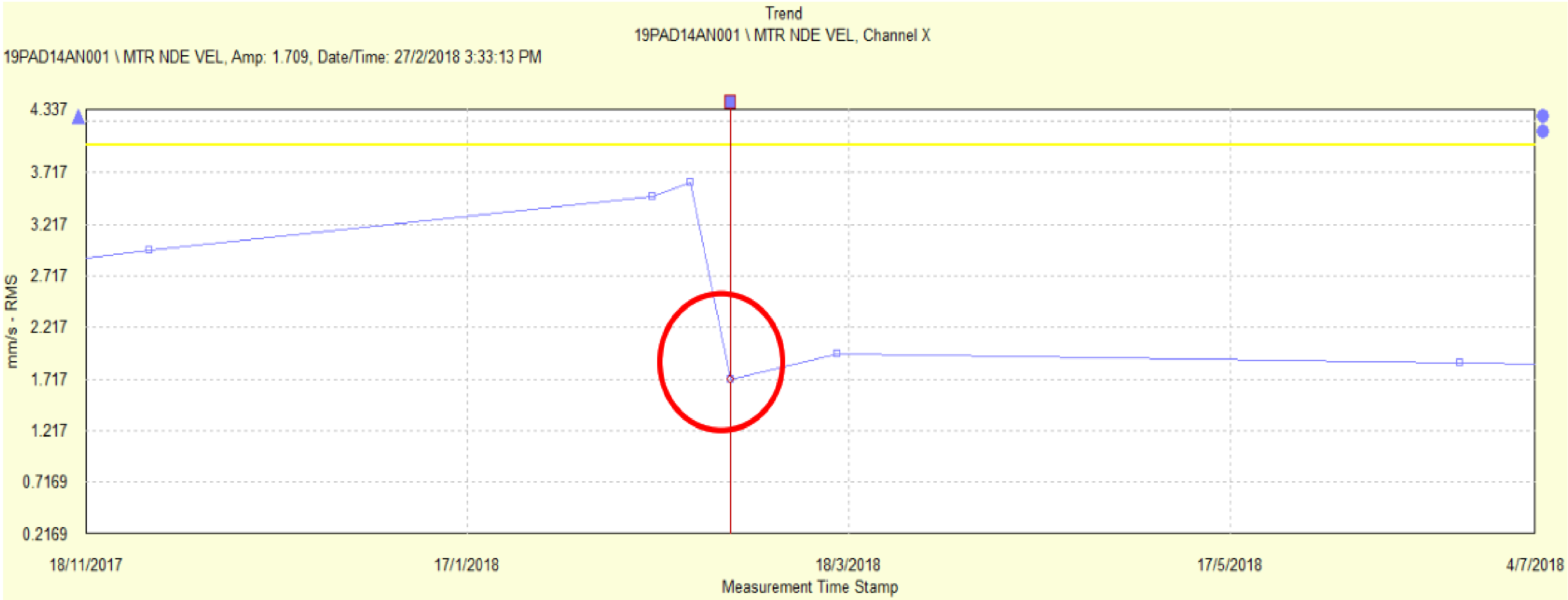

Figure 4.22 CT no.4 Motor NDE Velocity Trend after maintenance

IV. CT Fan Motor no.4 Velocity Spectrum is shown in Figure 4.23, which shows that the spectrum amplitude is slightly high at lower frequency, but it is still within the acceptable range. It is recommended to continue monitoring the vibration data. However, the major bearing problem was eliminated and currently the vibration is within the acceptable range [48].

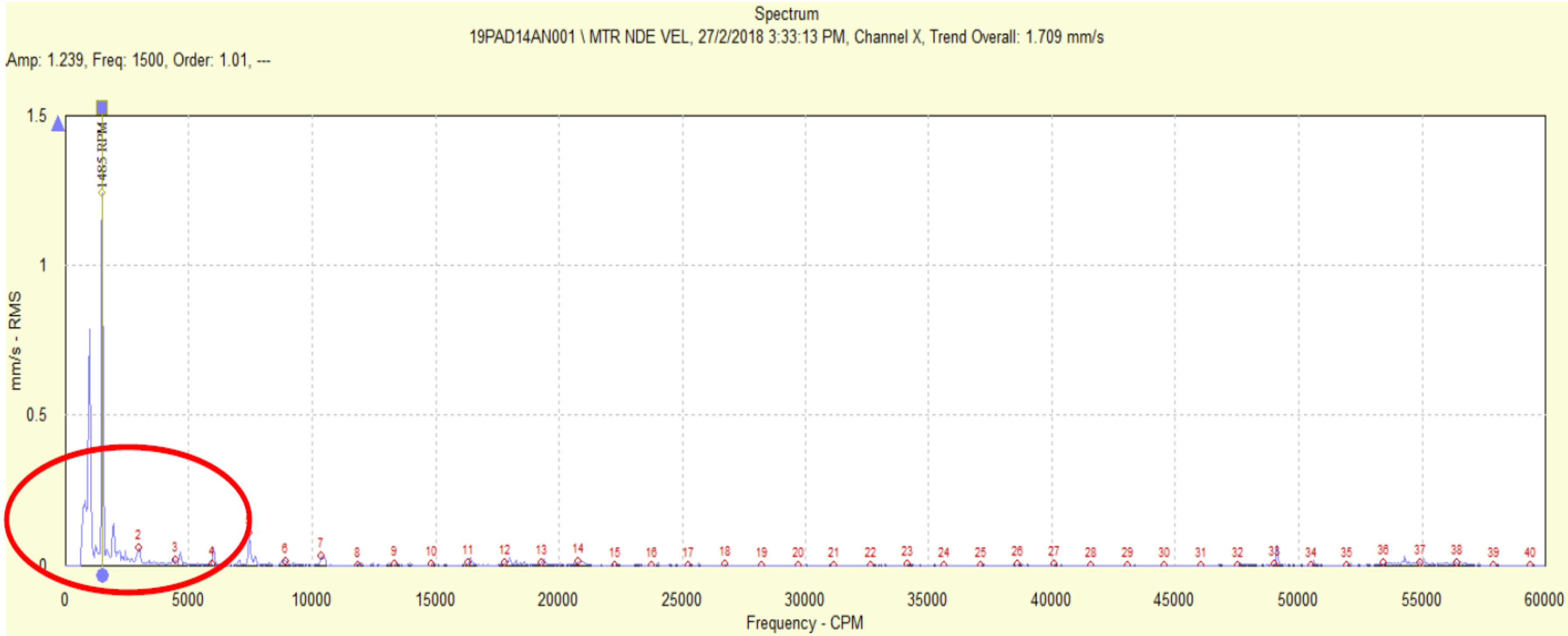

Figure 4.23 CT no.4 Motor NDE Velocity Spectrum after maintenance

4.3 Effect and Cost of Maintenance Comparison

As discussed, the vibration data has reduced significantly after the maintenance job was carried out as recommended. The data is again tabulated in Table 4.1.

Table 4.1 Vibration Record Before and After Maintenance.

	Before Maintenance	After Maintenance
LPFW no.4 Motor	Abnormal Sound/Noise	Normal Running
NDE Enveloping Trend	6.2gE	2.7gE
NDE Velocity Trend	2.2mm/s	1.69mm/s
DE Enveloping Trend	5.2gE	2.0gE
DE Velocity Trend	1.69mm/s	1.69mm/s
	Before Maintenance	After Maintenance
CT no.4 Motor	Abnormal Sound/Noise	Normal Running
NDE Enveloping Trend	6.9gE	0.52gE
NDE Velocity Trend	3.4mm/s	1.77mm/s
DE Enveloping Trend	0.6gE	0.6gE
DE Velocity Trend	0.5mm/s	0.5mm/s

Table 4.1 clearly indicates that the precision maintenance worked exactly as analysed. If the precision maintenance were not carried out, this early problem detection would not have been able to be identified. For example, the vibration data were not collected and the LPFW Motor no.4 was continued to run without vibration analysis This may lead to severe damage as the grease will dry out. Lack of lubrication will cause overheating of the LPFW Motor no.4 bearing. As the temperature increase, at certain temperature the bearing will be stuck and jammed. This may lead to catastrophic failure. On the worst-case scenario, once the bearing is jammed the overdrawn current will cause the motor winding to burn causing short circuit and tripping the breaker. Thus, the maintenance cost would be higher as compared to when precision maintenance is applied.

The same scenario applies to the CT Fan Motor no.4, if bearing change and base shim replacement were not carried out. The same consequences will also occur. The motor bearing will be jammed, and motor winding will burn. The cost for maintenance and downtime will be even higher.

4.4 Cost Analysis

Table 4.2 Cost Comparison with and without vibration analysis for LPFW [51].

Maintenance Cost	Repair Type	Cost (RM)	LPFW Motor no.4 (90kW)
With vibration analysis applied	Shell High Temperature Grease	60.00	
	Total	60.00	**60.00**
Without vibration analysis applied	Bearings	800.00	
	Rewinding (class F)	6000.00	
	Thermistor and Heater	300.00	
	Balancing	1500.00	
	Metal Spray Bearing Housing (set)	800.00	
	Metal Spray Bearing Seat (set)	800.00	
	General Service	200.00	
	Electrical Testing	100.00	
	Overhaul & Labour Cost	100.00	
	Transportation	200.00	
	Total	10800.00	**10,800.00**

Table 4.3 Cost Comparison with and without vibration analysis for CT [51].

Maintenance Cost	Repair Type	Cost (RM)	CT Motor no.4 (180kW)
With vibration analysis applied	Shell High Temperature Grease	60.00	
	Bearings	1000.00	
	Base Frame Repair and Shim	200.00	
	Alignment Cost	600.00	
	Total	1860.00	**1,860.00**
Without vibration analysis applied	Rewinding (class F)	9000.00	
	Thermistor and Heater	300.00	
	Balancing	1800.00	
	Metal Spray Bearing Housing (set)	800.00	
	Metal Spray Bearing Seat (set)	800.00	
	General Service	200.00	
	Electrical Testing	100.00	
	Overhaul & Labour Cost	100.00	
	Transportation	200.00	
	Total	13300.00	**13,300.00**

Table 4.2 and 4.3 clearly indicates that with vibration analysis approach, the maintenance cost will be much lower compared to maintenance cost without vibration analysis. Although at the initial stage, vibration analysis equipment may be expensive, but for the long-term run, it will be very helpful to identify the problem at an early stage to be rectified.

The total amount of cost saved from this vibration analysis approach is: -

Cost Saved = Maintenance Cost without vibration analysis – Maintenance Cost with vibration analysis

LPFW = RM 10,800.00 - RM 60.00 = **RM 10,740.00**

CT = RM 13,300.00 – RM1,860.00 = **RM11,440.00**

Total cost saved in one Year = RM 10,740.00 + RM11,440.00 = **RM22,180.00**

4.5 Pay Back Period (PBP)

Firstly, the simple Pay Back Period (PBP) [49] [52], is the financial metric of profitability which is used to calculate the return or gain from the investment. In simple term, PBP is the duration taken to get back what the investors have invested. With this simple PBP calculation only, investors able to invest on certain projects. Therefore, investing in buying the vibration analysis equipment is also not exemption. This simple PBP calculation is used to see the feasibility or profitability of buying the vibration tools and equipment.

A simple PBP cost is calculated below in Table 4.4, this table shows how long the duration required to recover the investment cost for this vibration analysis equipment. The electrical motor maintenance cost that has been saved is estimated for 2 units of motor only for each year.

Vibration Analysis Equipment Cost = **RM 45,000.00 (first year only)**
(include training and software license)

Vibration Analysis Equipment Maintenance Cost = **RM 1,000.00/year**

Vibration Analysis Equipment Calibration Cost = **RM 800.00/year**

Saving in Maintenance Cost with Vibration Analysis = **RM22,180.00**

Table 4.4 Breakeven for PBP Cost Estimation by Year [49].

Year	Investment + Equipment Maintenance Cost (RM)	Saving Cost (RM)
1	45000.00	22180.00
2	**45000.00+1000.00+800.00 = 46800.00**	**22180.00+22180.00 = 44360.00**
3	**46800.00+1800.00 = 48600.00**	**44360.00+22180.00 = 66540.00**
4	48600.00+1800.00 = 50400.00	66540.00+22180.00 = 88720.00
5	50400.00+1800.00 = 52200.00	88720.00+22180.00 = 110900.00

48600/22180 = <u>2.19 years</u>

0.19*12months = <u>2.28 months approximate to 3 months</u>

Based on Table 4.4, the breakeven of PBP can be achieved within the year 2 and 3. To be exact the payback period is achieved in 2 years and 3 months. This proves that, investing in vibration analysis equipment is a profitable for long-term maintenance.

4.6 Chapter Summary

As a summary, this chapter began with the analysis of the vibration data that were collected for the LPFW Pump Motor no.4 and CT Fan Motor no.4. The motor DE and NDE enveloping trend, enveloping spectrum, velocity trend and velocity spectrum were presented in the form of graphs. The root cause for the motor abnormalities were analysed based on the vibration data and best recommended solutions were described. The preventive maintenance based on the recommendation were carried out. At the same time, the cost for the motor maintenance with and without vibration analysis were studied. This also shows that the maintenance cost with vibration analysis is much lower compared to maintenance cost without vibration analysis. Finally, the simple PBP for the vibration equipment investment was studied. Based on the PBP calculation also process that the vibration equipment investment can be recovered within the second year after the investment. This is because the maintenance cost with vibration analysis approach is very much cheaper than without the vibration analysis. Thus proves, precision maintenance is very cost effective and reliable.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The main objectives of this research work were achieved. Condition of critical motor in combined cycle power plant using vibration analysis with SKF Microlog GX Series CMXA 75 were evaluated. Precision maintenance schedule subject to maintenance time and cost for critical motor was presented. Comparison between precision maintenance and predictive maintenance cost of critical motor were presented.

Electrical motor is a very critical equipment for a CCPP. Therefore, best maintenance approach must be implemented for the motor to avoid any catastrophic failure. Precision maintenance will be the best solution especially the vibration survey. The vibration survey will detect the motor fault at an early stage and with best analysis the root cause can be found. Therefore, once the root cause is eliminated or rectified as of this project. The electrical motor will be healthy to run.

As for this thesis, the LPFW Pump Motor no.4 and CT Fan Motor no.4 was found with some abnormalities during routine vibration survey. The vibration readings taken show abnormalities. The readings were then analysed with the aid of chart from [48], then the root cause was identified and eliminated. The maintenance cost with vibration analysis is very much lower compared to maintenance cost without vibration analysis. Besides that, investing in any vibration equipment for maintenance purpose will be profitable in long run as proven in the PBP calculation for this SKF Microlog GX Series CMXA 75 equipment. The PBP is 2 years and 3 months.

5.2 Recommendations

As a future recommendation, this precision maintenance will be much effective if analysed along with thermography survey (infrared camera) to check temperature abnormalities for an electrical motor. For example, this thermography survey is done for the motor power terminal side and motor breaker supply terminal side and power cables. This thermography survey may show some additional abnormalities by reflecting it in term of temperature.

REFERENCES

[1] R. Williams, "A Guide to the Condition Monitoring of Machinery," *Tribology International*, vol. 13(2), p. 91, 1980.

[2] M. Irfan, N. Saad, R. Ibrahim and V. See, "An intelligent diagnostic system for the condition monitoring of AC motors," in *IEEE 8th Conference on Industrial Electronics and Applications, ICIEA*, 2013.

[3] H. Toliyat, S. Nandi and M. Hajjaghaiani, Electric Machines - Modeling Condition Monitoring and Fault Diagnosis, Taylor Francis, 2013 (1-266).

[4] M. Rad, M. Torabizadeh and A. Noshadi, "Artificial neural network-based fault diagnostics of an electric motor using vibration monitoring," in *International Conference on Transportation, Mechanical, and Electrical Engineering, TMEE*, 2011.

[5] J. Penman and C. Yin, "Feasibility of using unsupervised learning, artificial neural networks for the condition monitoring of electrical machines," *IEE Proceedings: Electric Power Applications*, vol. 141 (6), pp. 317-322, 1994.

[6] A. Murray and J. Penman, "Extracting useful higher order features for condition monitoring using artificial neural networks," *IEEE Transactions on Signal Processing*, vol. 45(11), pp. 2821-2828, 1997.

[7] S. Wildermuth, U. Ahrend, C. Byner, P. Rzeszicinki, D. Lewandowski and M. Orman, "Condition monitoring of electric motors based on magnetometer measurements," in *IEEE International Conference on Emerging Technologies and Factory Automation, ETFA*, 2015.

[8] P. J. Tavner, "Review of condition monitoring of rotating electrical machines," *IET Electric Power Applications*, vol. 2(4), pp. 215-247, 2008.

[9] F.C.Trutt, J.Sottile and J.L.Kohler, "Condition monitoring of induction motor stator windings using electrically excited vibrations," in *IAS Annual Meeting (IEEE Industry Applications Society)*, 2002.

[10] P.Vas, "Artificial Intelligence based Electrical Machines and Drives," *Bookcraft Ltd, Midsomer Norton, Great Britain*, 1999.

[11] S. P. S. Bhowmik, "Fault diagnostic and monitoring methods of induction motor," *International Journal of Applied Control, Electrical and Electronics Engineering (IJACEEE),* vol. 1, pp. 01-18, 2018.

[12] J. Mitchell, "An introduction to machinery analysis and monitoring," *PennWell Pub Co,* 1981.

[13] A. Stoynova and B. Bonev, "Infrared survey in electrical preventive maintenance," in *26th International Scientific Conference Electronics, ET,* 2017.

[14] R. Bris, E. Chatelet and F. Yalaoui, "New method to minimize the preventive maintenance cost of series-parallel systems," *Reliability Engineering and System Safety,* vol. 82 (3), pp. 247-255, 2003.

[15] K. Loparo, M. Adams, W. Lin, F. Abdel-Magied and N. Afshari, "Fault detection and diagnosis of rotating machinery," *IEEE Transactions on Industrial Electronics,* vol. 47(5), pp. 1005-1014, 2000.

[16] M. Grida, A. Zaid and G. Kholief, "Optimization of preventive maintenance interval," in *Annual Reliability and Maintainability Symposium*, 2017.

[17] X. Liang, "Temperature estimation and vibration monitoring for induction motors and the potential application in electrical submersible motors," *Canadian Journal of Electrical and Computer Engineering,* vol. 42(3), pp. 148-162, 2019.

[18] J. Echeverría-Villar, J. Martínez-Román and L. Serrano-Iribarnegaray, "Transient harmonic torques in induction machines: Measurement and impact on motor performance," *Electrical Engineering,* vol. 94(2), pp. 67-80, 2012.

[19] F. Dalvand, A. Kalantar, S. Shokoohi and H. Bevrani, "Time-domain bearing condition monitoring in induction motors using instantaneous frequency of motor voltage," in *Institute of Electrical and Electronics Engineers (IEEE),* 2015.

[20] A.Barkov and J. Mitchel, "Condition assessment and life prediction of rolling element bearings - part 1," *S V Sound and Vibration, IEEE,* pp. 10-31, 1995.

[21] S. Sunder, K.Satyakrishna and S. Sharma, "Computer Aided Online Fault Diagnosis of Induction Motors," *9th International Conference Electrical Power Quality and Utilization,* pp. 9-11, 2007.

[22] M. Orman and C. T. Pinto, "Usage of acoustic camera for condition monitoring of electric motors," in *IEEE Region 10 Annual International Conference*, 2013.

[23] J. Kamarainen, J. Lindh, T. Ahola, J. Kalvianien and H. Ilonen, "Diagnosis Tool for Motor Condition Monitoring," *IEEE Transactions on Industry Applications,* vol. 41, pp. 963-971, 2005.

[24] P. J. Tavner and J. Penman, Condition Monitoring of Electrical Machines, John Wiley and Sons, 1987.

[25] A. Jezzini, M. Ayache, L. Elkhansa, B. Makki and M. Zein, "Effects of predictive maintenance(PdM), Proactive maintenace(PoM) & Preventive maintenance(PM) on minimizing the faults in medical instruments," in *2nd International Conference on Advances in Biomedical Engineering, ICABME*, 2013.

[26] P.Tanver, "Electrical Power Application," *Institute of Engineering and Technology (IET),* vol. 2, p. 215, 2008.

[27] D. Mutia, K. John and S. Maranga, "Maintenance Management of Medical Equipment in Hospitals," *Industrial Engineering Letters,* vol. 2(3), pp. 9-19, 2012.

[28] M. Eti, S. Ogaji and S.Probert, "Reducing the cost of preventive maintenance (PM) through adopting a proactive reliability-focused culture," *Applied Energy,* vol. 83(11), pp. 1235-1248, 2006.

[29] Y. Tsai, K. Wang and L. Tsai, "A study of availability-centered preventive maintenance for multi-component systems," *Reliable Engineering and System Safety,* vol. 84, pp. 261-270, 2004.

[30] F. Trutt, J. Sottile and J. Kohler, "Online condition monitoring of induction motors," *IEEE Transactions on Industry Applications,* vol. 38(6), pp. 1627-1632, 2002.

[31] T. Habetler and R.Schoen, "A new method of current-based condition monitoring in induction machines operating under arbitrary load conditions," *Electrical Machines and Power Systems,* vol. 25, pp. 141-152, 1997.

[32] E. Bana, M. Carnero and M. Oliveira, "A multi-criteria model for auditing a Predictive Maintenance Programme," *European Journal of Operational Research,* vol. 217(2), pp. 381-393, 2012.

[33] M. A. Cash, T. Habetler and G. Kliman, "Insulation failure prediction in induction motors using line neutral voltages," *Moscow Power Engineering Institute,* vol. 202, pp. 57-60, 1989.

[34] A. Boudiaf, A. Djebala, H. Bendjma, A.Balaska and A.Dahane, "A summary of vibration analysis techniques for fault detection and diagnosis in bearing," in *8th International Conference on Modelling, Identification and Control, ICMIC*, 2017.

[35] Y. Chaudhari, J. Gaikwad and J. Kulkarni, "Vibration analysis for bearing fault detection in electrical motors," in *1st International Conference on Networks and Soft Computing, ICNSC*, 2014.

[36] R. Wald, T. Khoshgoftaar and J. Sloan, "Fourier transforms for vibration analysis: A review and case study," in *IEEE International Conference on Information Reuse and Integration, IRI*, 2011.

[37] P. Kripakaran and B. Reddy, "Diagnosis of bearing fault in induction motor by zero sequence current," in *International Conference on Innovative Research in Electrical Sciences, IICIRES, pp.1-6*, 2017.

[38] X. Song, Z. Wang and J. Hu, "Detection of Bearing Outer Race Fault in Induction Motors using Motor Current Signature Analysis," in *22nd International Conference on Electrical Machines and Systems, ICEMS*, 2019.

[39] B. Bajpeyee and S. Sharma, "Detection of bearing faults in induction motors using short time approximate discrete Zolotarev transform," in *Institution of Engineering and Technology (IET)*, 2018.

[40] S. Devendiran and K. Manivannan, "Vibration based condition monitoring and fault diagnosis technologies for bearing and gear components-A review," *International Journal of Applied Engineering Research*, vol. 11(6), pp. 3966-3975, 2016.

[41] S. Nandi and H. A. Toliyat, "Condition monitoring and fault diagnosis of electrical machines - a review," in *IAS Annual Meeting (IEEE Industry Applications Society)*, 1999.

[42] J. Hooper and J. Marco, "Defining a representative vibration durability test for electric vehicle (EV) rechargeable energy storage systems (RESS)," *World Electric Vehicle Journal (2016) 8(2) 327-338,* vol. 8(2), pp. 327-338, 2016.

[43] H. Helmi and A. Forouzantabar, "Rolling bearing fault detection of electric motor using time domain and frequency domain features extraction and ANFIS," *IET Electric Power Applications,* vol. 13(5), pp. 662-669, 2019.

[44] S. Gopinath, "Study on electrical motor mass unbalance based on vibration monitoring analysis technique," in *International Conference on Mechanical and Electrical Technology*, 2010.

[45] P. Tavner, L. Ran, J. Penman and H. Sedding, Condition monitoring of rotating electrical machines, Institution of Engineering and Technology, (2008), 1-250, 2008.

[46] C. D. SIlva, Vibration monitoring, testing, and instrumentation, CRC Press, (1-681), 2007.

[47] J. N. Eshleman and R. L. Eshleman, Basic Machinery Vibration : An Introduction to Machine Testing, Analysis, and Monitoring, 1999.

[48] SKF USA Inc. - SKF Group, User Manual SKF Microlog GX Series, Data Collector/Analyzer, Revision C, USA: SKF Group, 2014.

[49] A. Mazaraki and O. Fomina, "Tools for management accounting," *Economic Annals - XXI*, *Institute of Society Transformation*, 20 July 2016.

[50] H. J. Hau, M. W. Haziq and Satheswaraan, "Kuala Langat Power Plant Sdn Bhd - Condition Monitoring Report," KLPP, 2018.

[51] Y. Loong, "Electrical Motor Repair and Rewinding Price Guide," 2018.

[52] J. King, "Purchasing industrial equipment and calculating the return on investment," March 2017.