Int J Syst Assur Eng Manag (June 2020) 11(3):583–599
https://doi.org/10.1007/s13198-020-00945-4

ORIGINAL ARTICLE

FMECA analysis and condition monitoring of critical equipments in super thermal power plant

J K. Mohanty[1] · P. R. Dash[1] · P. K. Pradhan[1]

Received: 16 July 2019 / Revised: 5 January 2020 / Published online: 21 January 2020

Abstract In the recent years, there is a trend to build super thermal power plants in order to have better economic viability. With the growth of the capacity and size, the complexities of these plants have also grown multifold. There is more chance of fault in the system, when it is more complex. An early detection of these faults can allow time for preventive maintenance before a severe failure occurs. Condition monitoring is implementation of the advanced diagnostic techniques to reduce downtime and to increase the efficiency and reliability. The research is for determining the usage of advanced techniques like Vibration analysis and Oil analysis and to diagnose ensuing problems of the plant and machinery at an early stage and plan to take corrective and preventive actions to eliminate the issue and enhancing the reliability of the system. Now days, most of the industries have adopted the condition monitoring techniques as a part of support system to the basic maintenance strategies. Failure Mode, Effect and Criticality Analysis (FMECA) is associated with condition monitoring to determine the criticality of such unit or machines. It is a design method used to systematically analyze probable component failure modes of product or process, assess the risk associated with these failure modes and find out the resultant effects on system operations. In this study, practical approach have been applied for the FMECA to determine the critical equipments in a super thermal power plant and condition monitoring of such equipments have been done.

✉ P. K. Pradhan
pkpradhan_me@vssut.ac.in

[1] Mechanical Engineering Department, VSSUT, Burla, Odisha, India

Keywords Condition monitoring · Thermal power plant · FMECA · Vibration analysis · FMEA

1 Introduction

Electricity is the only form of energy which is easy to generate, transmit, use and control. It is considered as the most usual form of energy transmission and distribution. There are various types of power plants from which electricity can be generated in a bulk manner. Thermal power plant is one of them.

Thermal Power Plants or Steam Power Plants generate more than 65% of the total electricity produced in the world (Mpoweruk). India is currently the 3rd largest producer of electricity in world and production of coal based thermal power is about 85% of the country's power generation (Power tech). The thermal power plant basically works on the principles of a Rankine cycle. The Rankine cycle is a process that is used to convert heat into mechanical work. The heat is supplied externally to a closed loop, which is used to convert water into steam. That steam runs the turbine, which is coupled with a generator and the generator produces the electricity. The heat sources used in thermal power plants are either combustion of fossil fuels like coal, oil and natural gas or the nuclear fission (Nag 2008).

There are hundred numbers of units, subunits, components, and parts in thermal power plant. The major components of a thermal power plant are; Turbine, Boiler, Generator, Condenser and Feed pumps.

In the recent years, there has been a developed trend to build thermal plants with higher efficiency in order to fulfill the requirements with better economic viability. With the growth of the capacity and size, the complexity of the plants is also growing. The more complex a system, the higher are the chances of occurrence of faults in it. These faults may lead to cause catastrophic failure and collapse of the system. The faults which are having slow pace of growth can be detected by carefully monitoring the changes in the process parameters.

Since its' genesis, the Maintenance culture has evolved down, through different types of maintenance techniques (Mohanty 2014; Williams et al. 1994; Jardine et al. 2006; Kim et al. 2014) like.

- Unplanned maintenance: Run to failure or breakdown maintenance
- Schedule maintenance
- Preventive maintenance
- Condition monitoring/predictive maintenance
- Reliability centered maintenance
- Total productive maintenance

In earlier days, the main form of maintenance was corrective maintenance instead of predictive maintenance system, resulting to high downtime with reduced generation, besides safety & environmental issues. These challenges gave rise to Condition Based Maintenance (CBM) that actively manages the health and condition of the assets; as maintenance work is only done when really needed through use of diagnostic tools.

1.1 Condition monitoring

Condition monitoring detect and diagnose of incoming defects in any equipment and plan the maintenance based on machine condition to prevent breakdown for better availability with cost optimization and reduction of secondary failures. Today condition monitoring is becoming essential for all the machines/equipment in a thermal power plant.

Types of condition monitoring techniques

The various condition monitoring techniques are used in industries. These are;

i. Visual, optical, tactile and aural monitoring
ii. Performance monitoring
iii. Temperature monitoring
iv. Vibration monitoring
v. Electrical current monitoring through MCSA (motor current signature analysis)
vi. Lubricant monitoring (through oil analysis)
vii. Shock pulse monitoring
viii. Leakage monitoring
ix. Crack monitoring and corrosion monitoring through NDT (Non destructive testing)
x. Noise monitoring (through acoustic analysis)
xi. Ultrasonic monitoring

Before going to implementation of CBM of any industry, it is essential to do FMECA (Failure Mode, Effect & Criticality Analysis) to identify the degree of criticality of various machineries and components of such industry. Based on these, application of CBM techniques can be decided.

1.2 Failure mode, effect and criticality analysis (FMECA)

FMECA is an extension of failure mode and effects analysis (FMEA). FMEA can be applying to recognize probable failure modes, conclude their effect (Würtenberger et al. 2014). FMEA is extended to FMECA (Chen et al. 2012; Catelani et al. 2018; Pancholi and Bhatt 2016; Srivastava and Mondal 2015; Zhou et al. 2014) to indicate that criticality analysis is performed too. It is a design method used to systematically analyze probable component failure modes of product or process, assess the risk associated with these failure modes and find out the resultant effects on system operations.

The basic steps for performing an FMEA/FMECA analysis include:

(a) Identify the machine(s), item(s) or process (es) to be analyzed.
(b) Identify the function(s), failure(s), effect(s), cause(s) and control(s) for each item or process to be analyzed.
(c) Evaluate the risk associated with the issues identified by the analysis.
(d) Prioritize and assign corrective actions.
(e) Perform corrective actions and re-evaluate risk.
(f) Distribute, review and update the analysis, as appropriate

Most analysis of this type also includes some method to assess the risk associated with the issues identified during the analysis and to prioritize corrective actions. There are two common tools used to determine the degree of criticality of the machineries. These are;

i. Risk priority numbers (RPNs)
ii. Criticality analysis/score

i. Risk priority numbers (RPNs)

The RPN is a result of a multiplication of detectability (D) × severity (S) × occurrence (O). With each on a scale from 1 to 10, the highest RPN is 10 × 10 × 10 = 1000. This means that this failure is not detectable by inspection, very severe and the occurrence is almost sure. If the occurrence is very sparse, this would be 1 and the RPN would decrease to 100. So, criticality analysis enables to focus on the highest risks.

ii. Criticality analysis

Criticality analysis is a systematic approach to identify potential risks and their consequences which can impact the business. It has well defined criteria that specify the potential consequences, so that they can be evaluated, categorized & prioritized.

Present study is focused on FMECA analysis and condition monitoring or predictive maintenance of equipments in super thermal power plants.

The current study is based on Captive Power Plant (CPP) of Vedanta Limited (VL), Jharsuguda, Odisha. It has 9 units having capacity of 1215 MW. With the commissioning of its first unit in August 2008, the plant has come a long way with all the nine units commissioned in 2010. The plant possesses world class technology supplied by Shanghai Electric Company, Sanghai. Technologies like High Concentration Slurry Disposal &Close-circuit cooling systems are environment friendly technologies and positive impact on reduction in water consumption.

The plant having capacity of 9 × 135 MW, is a sub critical, direct pulverized coal fired, corner tangential firing, natural circulation boiler and single reheat, double cylinder, double flow, single shaft, extraction and condensing steam turbine of 'Shanghai Electric' Make. It has adopted the state-of-art Digital Distributed Control System, High Concentration Slurry Disposal (HCSD) of fly ash & bottom ash, counter-flow forced draft Cooling Towers and multi-flue Stacks. It sources water from Hirakud Reservoir over a distance of 33 km. Coal is transported from Mahanadi Coal Fields having bottom discharge wagons and also by road from some of the nearer mines.

The Captive Power Plant supplies power to the power intensive Pot Lines of the 0.5 mMT Aluminium Smelter through a 220 kV Switchyard where the AC power is converted to DC power through a set of Transformer Rectifiers. The DC power is utilized for Electrolysis of Alumina in 608 no. of cells in pot lines to produce Aluminum.

The power plant along with Aluminium smelter is certified by ISO 9001, 14001 and OHSAS 18001 i.e. Integrated Management System from IRQS. Also both Captive Power Plant and Smelter of Vedanta Limited have been certified by SGS India Pvt. Ltd for ISO 50001 (Energy Management System) and ISO 55001 (Asset Management System).

2 Methodology and experimentation

Present study is focused on FMECA analysis and condition monitoring or predictive maintenance of equipments in super thermal power plant, Vedanta Limited.

2.1 FMECA/criticality analysis of vedanta limited

Criticality Analysis is done for all individual equipment up to replaceable part and the same is to be reviewed once in a year in Captive Power Plant of Vedanta Aluminium Limited (VAL), Jharsuguda, India.

In the current study, the criticality score is taken as multiplication of seven numbers of distinct factors covering the entire functionality of the equipment. These factors are to be rated on a scale of 1 to 3 by considering the guideline briefed as below. The seven factors for calculating the Criticality analysis are:

(a) Consequence factors: CF
(b) Redundancy factor: RF
(c) Downtime factor: DF
(d) Cost of replacement factor: CrF
(e) Severity factor: SF
(f) Loading factor: LF
(g) Restoration/service factor: SF

Criticality score(CS) = CF × RF × DF × CrF × SF × LF × SF

The degree of criticality may be defined as

1. Most critical = Criticality score > = 450
2. Critical = 50 < Criticality score < 450
3. Non critical = Criticality score = < 50

The following guide lines have been followed for the present work;

The below factors are ranked on a scale of 1 to 3 based on their conditions as given.

A. Consequence factor (CF)
    1. Impacts production or quality: Neither P nor Q
    2. Impacts production or quality: Either P or Q
    3. Impacts production or quality: Both P & Q
B. Redundancy factor (RF)
    1. Whether it has dedicated stand by
    2. Whether it has conditional stand by
    3. Whether it has no standby

Dedicated standby means a separate unit, which is not operating. It is provided beside the working unit and is ready to start when the working unit stops. Exp: Boiler Feed Pumps

Conditional standby means a second unit is operating in parallel with the primary duty unit and both are sharing the demand. If the primary unit fails, the second unit takes the full service. Exp: Rectifier Units have conditional standby

C. Downtime factor (DF)

The Scoring is based on the percentage of downtime hours as compared to running hours.

1. Less than 1% of running time
2. 1–3% of the running time
3. Greater than 3% of the running time

Downtime = (Breakdown hours/Running hours) × 100%

In case running hour is equal to calendar hour i.e. no idle time is there for equipment then calendar hour is to be considered. The entire calculation is to be done on the basis of previous 1 year data.

D. Cost of replacement factor (CrF)

Scoring is based on the cost of the equipment/assembly/spare.

1. Less than Rs. 1 Lakh
2. Between Rs. 1 and Rs. 5 Lakh
3. Greater than Rs. 5 Lakh.

E. Severity factor (SF)

Scoring is based on whether it impacts safety or statutory requirements.

1. Impacts neither safety nor statutory
2. Impacts either safety or statutory
3. Affects both safety and statutory

F. Loading factor (LF)

Scoring is based on the utilization of the equipment against its rated capacity.

1. Less than 80% of rated capacity
2. Between 80 and 100% of rated capacity
3. More than 100% of the rated capacity

Based on the type of equipment, its load (average for the year) needs to be calculated (equipment wise) and compared against its rated capacity and kept as backup in the criticality assessment workbook.

G. Restoration/service factor (SF):

1. If spares and expertise are available within the plant
2. If spares and expertise are partly available within the plant and external help may be required
3. If availability of spares and/or expertise are completely dependent on external parties only

In this factor we need to consider the time required to repair the equipment in case of major failure. In case of replaceable part cause wise MTTR (Mean Time to Repair) data can be considered.

After taking care of all parameters, the criticality scores of all important equipments are evaluated and presented in Table 1.

The above criticality analysis has categorized some of the most important equipments of the Captive Power Plant. In this paper, we have considered three most critical equipments for the analysis. These are;

i. ID fan (induced draft fan)
ii. FD fan(forced draft fan)
iii. APH (air preheater)

Table 1 Equipment criticality analysis for CPP

SN	Equipments	CF	RF	SF	CrF	LF	DF	SF	CS = (CF × RF × DF × SF × CrF × LF × SF)	Degree of critical
1	Turbine	3	3	3	3	3	3	2	1458	Most critical
2	Air pre-heater	3	3	3	3	3	1	2	486	Most critical
3	ID fan	3	3	3	3	3	1	2	486	Most critical
4	FD fan	3	3	3	3	3	1	2	486	Most critical
5	CT fan	2	3	2	2	2	1	1	48	Non critical
6	BFP	2	3	2	2	2	1	1	48	Non critical
7	ESP	3	1	1	3	3	1	2	54	Critical
8	Boiler	3	3	3	3	3	1	2	486	Most critical
9	Generator	3	3	3	3	3	1	2	486	Most critical
10	PA fan	3	3	3	3	3	1	2	486	Most critical
11	Compressor	2	3	2	2	2	1	1	48	Non critical
12	CW pump	2	3	2	2	2	1	1	48	Non critical
13	High pressure heater	2	1	1	3	3	1	2	36	Non critical

Table 2 FMEA of ID fan

Primary parts	Component/sub-process	Potential failure mode	Potential causes
Impeller	Blade	Impeller damage	Ash erosion
		Impeller jam	Cone misalignment
Shaft		Shaft runout	Shaft misalignment
			Overload
			Overheating
			Bearing failure
		Shaft erosion	Erosion
			Bearing jamming due to oil quality
Bearing housing	Cooling water line	Bearing damage	High temperature
		Shaft damage	Bearing damage
		Housing damage	Shaft damage
	Locating ring	Sudden increase in RPM	Wrong operation
		Overheating	Rotation of bearing outer race
	Oil view glass	Oil view glass damage	High vibration
			Improper fitment of view glass
			Poor view glass quality
Variable speed turbo coupling (VOITH coupling)		Coupling Bearing damage	Oil contamination.
			Increase differential pressure on double oil filter
			Abnormal Speed variation
			Sudden Increase in oil level
			Increase in temperature of Coupling
			Variation in output speed
			Variation in Lube Oil pressure
Bellow		Bellow damage	Dust
			Increase in pressure
			Pricking due to support clamp
			Improper bolt tightening
Inlet cone	Uneven clearance	Increase in fan Vibration	Improper installation

2.2 FMEA analysis

The FMEA of the above most critical equipments have been done and presented as follows

i. Induced draft fan

Induced Draft Fan or ID fan is used to create a vacuum or negative pressure in steam boiler. ID Fan is also used to identify the combustion process used in large boilers. With mechanical ventilation inside the boilers, the heat transfer rate increases. ID fan is always located between dust collector and chimney. ID fan takes the hot flue gases from furnace via dust collector (ESP or dust separation system or Fume Extraction system) and delivers to chimney. It produces the pressure lower than atmospheric in the system or it may be said that ID fan produces a negative pressure in the furnace to remove the flue gases from furnace via multi cyclone and to push the flue gases to chimney. The FMEA of ID Fan is given as below (in Table 2).

ii. Forced draft fan

The main functionality of a Forced Draft Fan or FD fan is for providing the required quantity of hot pressurized air to the furnace for smooth and uniform combustion of fuel. In the case of a steam boiler assembly, this fan is of great importance. As we know, in a Boiler to generate steam, combustion must occur, be it with any fuel i.e. coal, LDO, Furnace oil etc. and for combustion to exist one of its' three main requirements is air. This requirement is compensated by a Forced Draft Fan. However, the total air requirement to the boiler is managed by both Primary Air (PA) Fan & Forced Draft (FD) Fan. PA fan is used to

Table 3 FMEA for FD fan

Primary parts	Component/Sub-process	Potential failure mode	Potential causes
Impeller	Blade	Impeller imbalance	High vibration
Shaft	Shaft	Shaft runout	High vibration/Wobbling of shaft
	Coupling	Coupling Misalignment	High vibration
			Bearing failure
		Shaft undercut	Foreign material ingress
			Oil seepage
Bearing housing	Cooling water line	Bearing damage	PA fan trip
		Shaft damage	
		Housing damage	
	Oil view glass	Oil view glass damage	Oil leakage
	DE & NDE Bearing	Impeller Imbalance	High vibration
		shaft runout	High vibration
Discharge damper	Fan discharge damper	Bearing seize	Remote operation Not possible
		Shaft damage	
Bellow	Suction bellow	Bellow damage	Abnormal sound
		Bellow damage	Reduction in header pressure
Inlet cone	Inlet cone	Uneven clearance	Reduction in discharge pressure

transport the pulverized coal from mills to the furnace for the combustion. While primary air is supplied to the burner with the fuel that controls the rate of combustion as well as the amount of fuel that can be burnt, Secondary air is supplied to the combustion process that controls combustion efficiency to ensure complete combustion of the fuel. FD fan supplies air to the Air-preheater, where it captures the heat from the flue gases coming from the boiler outlet. The FMEA for FD Fan is enumerated in Table 3.

iii. Air preheater

An Air Preheater (APH) is any device designed to heat air before another process (for example, combustion in a boiler) with the primary objective of increasing the thermal efficiency of boilers. These may be used as a single unit in small capacity boilers where air is indirectly heated by steam externally and supplied to boilers. However, in bigger units it is a regenerative one, which is installed in the flue gas path prior to ESP in order to reduce the flue gas exit temperature, while increasing the air temperature required for combustion in furnace. So the purpose of the air preheater is to recover the heat from the boiler flue gas which increases the thermal efficiency of the boilers by reducing the useful heat lost in the flue gas. As a consequence, the flue gases are also conveyed to the flue gas stack (or chimney) at a lower temperature, allowing simplified design of the conveyance system and the flue gas stack. It also allows control over the temperature of gases leaving the stack to meet emissions regulations. It is installed between the economizer and chimney. The FMEA for APH is enumerated in Table 4.

From the above FMEA analysis it is observed that the most of the failures are due to vibration and due to lack of lubrication. So in this work, some case studies, which are related to vibration analysis and oil analysis for these "Most Critical" equipments i.e. ID Fan, FD Fan and APH are studied and analyzed.

3 Case studies and observations

Condition monitoring of the above critical equipments are done through vibration analysis and oil analysis, which are presented as follows;

3.1 Case study 1: Condition monitoring of ID Fan #4A, VOITH coupling

A VOITH Coupling is a hydraulic coupling or fluid coupling manufactured by VOITH GmbH, Germany. Fluid Coupling is a device used for transmitting power from one shaft to another shaft by means of acceleration and deceleration of a hydraulic fluid. In Fluid couplings, the output speed is always less than the input speed. There are two types of fluid coupling namely.

1. Constant fills/fixed speed type:
2. Variable speed/Scoop type:

The VOITH Coupling used in ID Fans in this case is a Scoop control type. VOITH coupling is an important component of ID fan, which is monitored by means of vibration analysis. Also oil analysis or patch test is done for

Table 4 FMEA for APH

Primary parts	Component/sub-process	Potential failure mode	Potential causes
Guide bearing	Guide bearing	Bearing seize	Oil leakage from guide bearing
			Oil contamination
			Seal tube damage
			Improper oil circulation
			Rotor misalignment
			Guide bearing cap bolt damaged
			Rise in oil temperature
			Bearing material quality
Support bearing	Support bearing	Bearing seize	Oil leakage from support bearing
			Oil contamination
			Seal tube damage
			Improper oil circulation
			Rotor misalignment
			Rise in oil temperature
			Bearing material quality
Gear box	Gear	Gear damage	Improper backlash
			Poor gear material
			Misalignment of main shaft
			Misalignment of trunion shaft
		Deformation of rotor	Oil leakage
			Oil contamination
			Oil level low
			GB and motor misalignment
			APH sudden stop
			bearing material quality
Lub oil pump	Oil cooler	APH bearing damage	Seal damage
			Spider coupling damage
			Oil contamination
			Pump damage
APH rotor	Heating elements	Rotor deformation	Flow and velocity of flue gases
	Radial/axial/bypass/post seals	Improper seal setting	Ash erosion
		Erosion	Flue gas erosion of APH internals
			Leakages in APH
			Chocking in scarph
	Diaphragm plates	Erosion and corrosion and aging	Loose tightening
			Improper seal setting
	Sector plates	Erosion and aging	Flue gas
	(HE and CE)		
	Rack and pinion assy	Teeth damage	Shearing of teeth
		Gear box failure	Improper lubrication
			Bearing failure
			overload
	Air seal assy(Seal tube)	Line chokage	Ash
		Gland packing failure	Ageing
	Main shaft and trunion shaft	Trunion bolt looseness	Improper fitting
		Misalignment	Support bearing failure
		Locking cap looseness	Sleeve and shaft clearance
	Support grating	Erosion and corrosion	Ash erosion
		Weld looseness	Poor welding

the cross verification. A patch test is oil analysis, which enables to identify abnormal levels of contamination and wear debris present in the working fluid. The term '4A' stands for Unit-4, A-side Fan. The schematic diagram of an ID fan is shown in Fig. 1.

3.1.1 Specification and equipment details

Motor KW-1700, RPM-991, Motor NDE (Non Drive End) Bearing: NU240ECM, Motor DE (Drive End) Bearing: 23044CC/C3W33. Driving end bearing of VOITH Coupling: NU 1040, Bearings inside VOITH Chamber: 7322 = Two nos., NU 230 = One no., Output bearing of VOITH Coupling: 7230 = Two nos. Fan DE & NDE Bearings: 22232EASMC3. Class: IV Machine (i.e. 300 KW and no rigid foundation).

Vibration velocity limit (as per ISO-2372/ISO-10816):

Normal: 7.1 mm/s, Marginal: Above 7.1 mm/s, Critical: 11.2 mm/s & Above

Vibration gravitational spike energy (gSE) Limit ISO standards: Max. 1.0 m/s^2 for a good bearing.

3.1.2 Machine diagnosis symptoms during operation

The condition monitoring of VOITH coupling is done through vibration analysis. The vibration data are taken and analyzed using Emerson make- CSI-2140 Vibration Data Logger with accelerometer and AMS Suite Software.

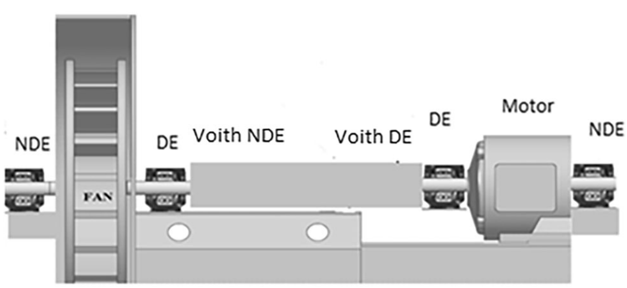

Fig. 1 Schematic diagram of an ID fan

Measurement of vibration readings are done at horizontal, vertical and axial directions, over the VOITH Chamber, just above the inside bearing of VOITH chamber. A typical case study, which was carried out during November, 2018-January, 2019, has been taken for consideration. The time-domain data as well as spectra of vibration signal have been captured and analyzed. The RMS value of vibration and spike energy (gSE) are presented on Table 5. The vibration spectra are presented in Figs. 2 and 3.

After the inspection and analyzing the time-domain data and vibration spectra, it is observed that

1. The vibration spectra of VOITH chamber bearing show the peak at 387.7 Hz, which is a non-synchronous bearing frequency i.e. 38.15 × RPM. The harmonics of this frequency are also observed. Those indicate there is impact in bearing.
2. Spike energy (gSE) is 1.9 m/s^2 at VOITH coupling Non drive end side.
3. Little abnormal noise observed from the VOITH coupling.
4. Metallic particles (of smaller sizes) are found during oil analysis.

After analyzing the abnormal vibration spectrum, it is confirmed that there is defect in the internal bearings of VOITH coupling. As per the recommendation, the VOITH coupling was replaced on 25th December 2018. After replacing the Voith coupling, following spectra (i.e. Figs. 4 and 5) were taken.

After corrective action i.e. replacing the VOITH coupling, following things are observed

1. RMS value of vibration is reduced.
2. Vibration amplitude at non synchronous frequency (i.e. 387.7 Hz) decreased significantly from 0.5 to 0.1 mm/sec.
3. Spike energy value reduced from 1.9 to 0.8 g.
4. No such abnormal noise observed from the VOITH coupling.
5. In patch test for oil analysis, no particle was found

Table 5 RMS of vibration (in mm/s) and spike energy, *gSE*' (in m/s^2) of VOITH Coupling

		16th Nov. 2018	06th Dec. 2018	13th Dec. 2018	25th Dec. 2018	25th Dec. 2018	04th Jan. 2019
Voith DE	H (*gSE*)	1.12	0.90	1.14	Coupling replaced	0.8	1.01
		(*gSE* = 1.2)	(*gSE* = 1.3)	(*gSE* = 1.3)		(*gSE* = 0.8)	(*gSE* = 0.7)
	V	1.48	1.58	1.18		0.9	1.38
	A	2.73	2.93	2.10		2.0	1.94
Voith NDE	H (*gSE*)	1.42	1.59	1.77		1.0	1.40
		(*gSE* = 1.2)	(*gSE* = 1.4)	(*gSE* = 1.9)		(*gSE* = 0.9)	(*gSE* = 0.8)
	V	1.85	1.95	1.37		1.6	1.49
	A	1.91	1.97	1.89		2.2	2.30

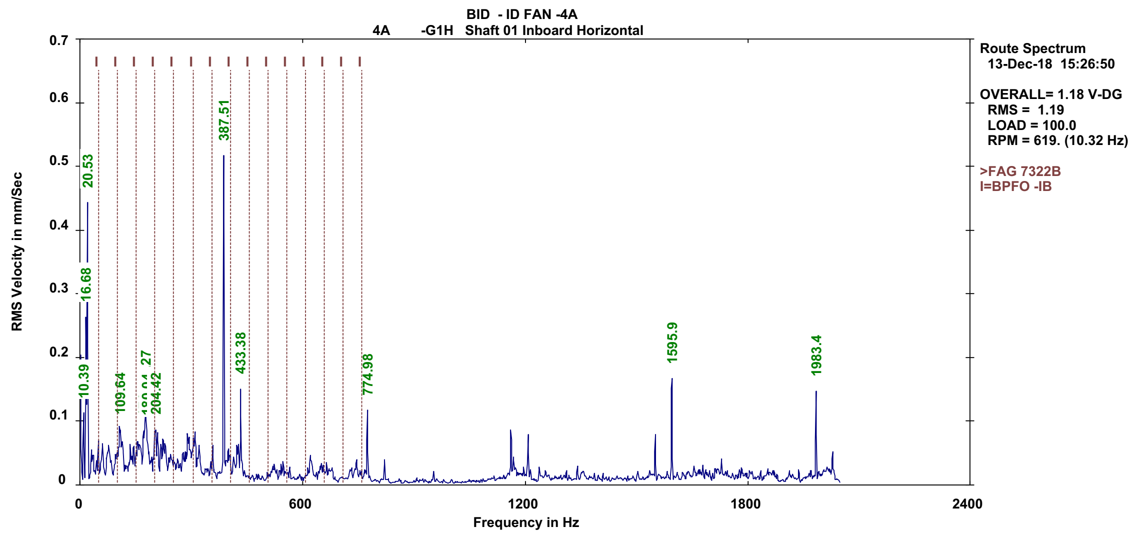

Fig. 2 Vibration spectrum of VOITH Input (Horizontal direction)

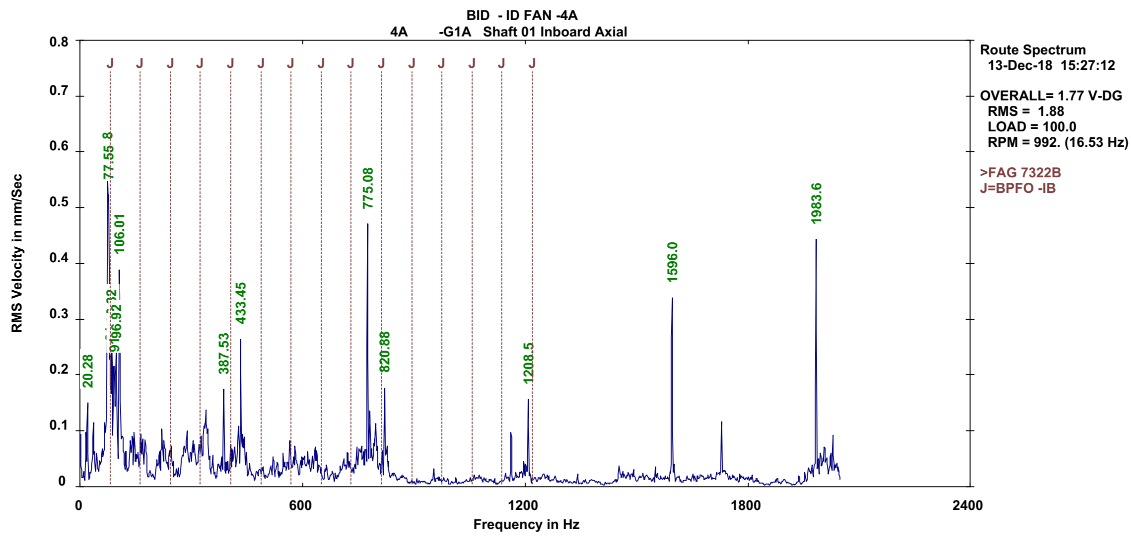

Fig. 3 Vibration spectrum of VOITH Input (Axial direction)

3.2 Case study 2: Condition monitoring of FD fan #7A

FD Fan health monitoring is done by means of vibration analysis. Also oil analysis or patch test is done for the cross verification. The term '7A' stands for Unit-7, A-side Fan. The schematic diagram of a FD fan set up is shown in Fig. 6.

3.2.1 Specification and equipment details

Motor: KW-400, RPM-992, Motor Non Drive end (NDE) bearing:6326; Motor Drive end(DE) bearing: NU 228EC3; Fan Drive end(DE) bearing:6232MC3, Fan Non Drive end(NDE) bearing:6238

Vibration velocity limit ISO standards

Normal: 7.1 mm/s, Marginal: Above 7.1 mm/s, Critical: 11.2 mm/s & Above

Vibration gravitational spike energy (gSE) Limit ISO standards: Max. 1.0 m/s^2 for a good bearing.

3.2.2 Machine diagnosis symptom during operation

The condition monitoring of FD Fan is done through vibration analysis. The vibration data were taken and analyzed. Measurements of vibrations are done in horizontal, vertical and axial directions of both DE and NDE of the Fan as well as of the Motor. A typical case study, which was done during June–September, 2018, has been taken for considerations. The time-domain data as well as spectra of

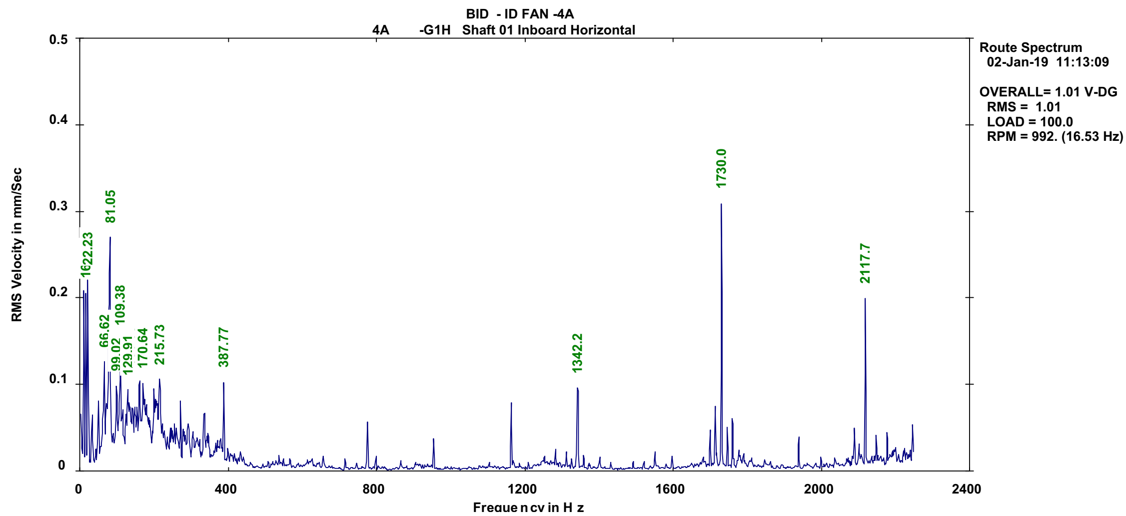

Fig. 4 Vibration spectrum of VOITH Input, (Horizontal direction)

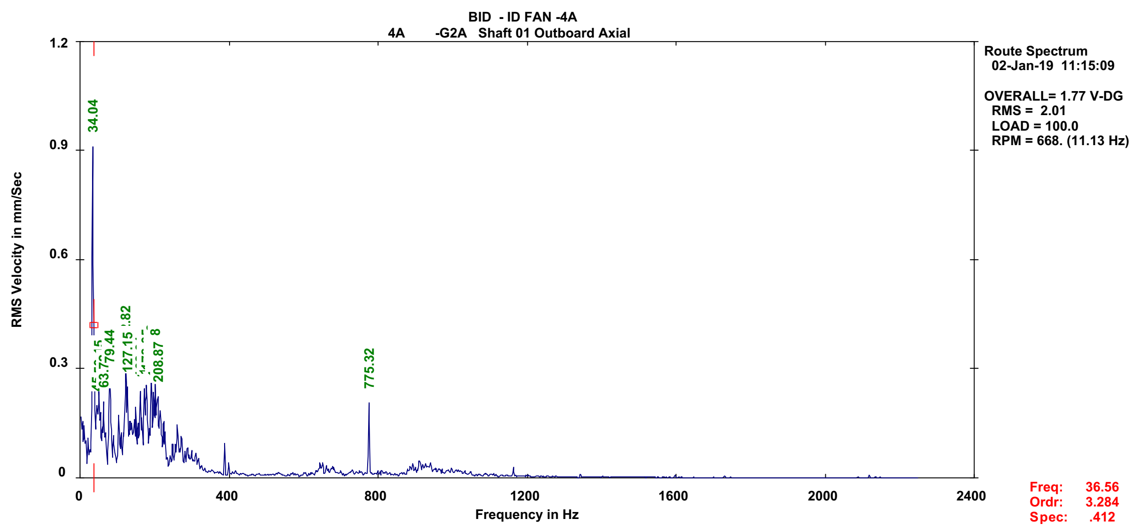

Fig. 5 Vibration spectrum of VOITH input (Axial direction)

Fig. 6 Schematic diagram of a FD fan

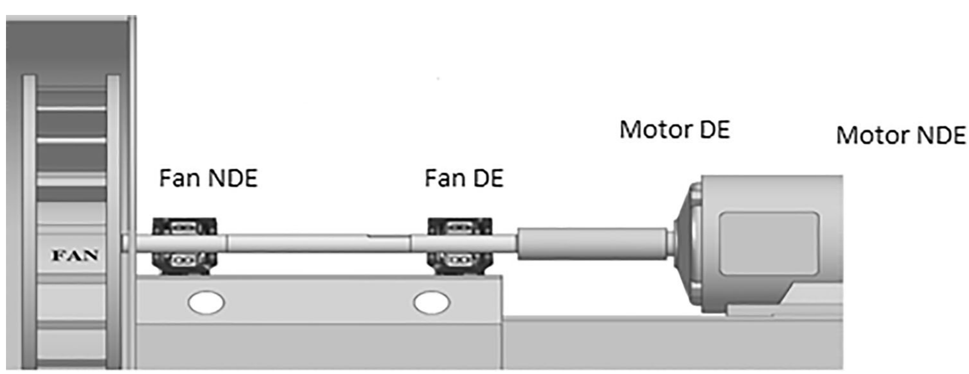

Table 6 RMS value of vibration (in mm/s)

Position		12th June 2018	26th June 2018	24th July 2018	04th Aug. 2018	18th Aug. 2018	10th Sept. 2018
Motor NDE	H	0.80	0.80	0.50	0.50	0.50	0.60
	V	0.60	0.60	0.20	0.40	0.30	0.70
	A	0.60	0.70	0.20	0.30	0.40	0.30
Motor DE	H	0.70	0.70	0.50	0.50	0.50	0.60
	V	0.60	0.50	0.20	0.30	0.20	0.30
	A	0.50	0.60	0.30	0.40	0.30	0.40
Fan DE	H	1.00	1.20	1.60	1.60	1.30	2.40
	V	1.40	1.30	0.90	1.40	1.40	2.10
	A	1.10	1.20	1.10	1.10	0.90	1.30
Fan NDE	H	1.20	1.00	1.30	1.40	1.30	1.50
	V	1.20	1.10	1.00	1.00	1.20	1.40
	A	0.90	0.80	1.00	1.20	1.30	1.40
		26th Sept. 2018	05th Oct. 2018	10th Oct. 2018	01st Nov. 2018	12th Nov. 2018	19th Nov. 2018
Motor NDE	H	1.60	1.70	1.70	Fan bearing replaced	0.55	0.68
	V	0.40	0.60	0.50		0.50	0.65
	A	0.60	0.70	0.70		0.46	0.40
Motor DE	H	0.40	0.50	0.60		0.60	0.63
	V	0.80	0.90	0.40		0.49	0.21
	A	0.30	0.40	0.60		0.40	0.38
Fan DE	H	2.50	2.60	2.70		0.90	0.81
	V	2.10	2.20	3.30		0.60	0.44
	A	2.50	2.60	2.00		0.46	0.20
Fan NDE	H	1.70	1.80	2.20		0.90	1.07
	V	1.50	1.60	2.80		0.30	0.34
	A	1.80	1.90	1.90		0.46	0.50

vibration signal have been captured and analyzed. These are described as follows. The RMS values of vibration are presented in Table 6. The vibration spectra are presented in Figs. 7, 8, 9 and 10.

After analyzing the time-domain data and vibration spectra, the following are the observations:

1. The vibration spectra depict a peak at 170 Hz, which was dominant and is 2 × BPFO (Fan DE bearing). Also, the peaks at BPFO and its harmonics were observed.
2. Peaks at non-synchronous frequency, i.e. 936 Hz were observed.
3. Abnormal noise observed at fan bearings.
4. Metal particles (of small size) were found during oil analysis.

As per the recommendation, both the bearings of the Fan are e replaced on 01st November 2018. After replacing the bearings, following spectra (i. e Figs. 11, 12, 13 and 14) were taken.

After replacement of bearing, the follwing points are observed:

1. The RMS value of vibration was reduced.
2. Vibration amplitude at 2 × BPFO was drastically reduced.
3. Vibration amplitude at non-synchronous frequency was also reduced significantly.
4. There were no metal particles have been detected during oil analysis.
5. No abnormal noise is felt.

3.3 Case study: 3: Condition monitoring of air preheater, # 5B

Air pre-heater (APH) absorbs waste heat from flue gas and transfers this heat to the incoming cold air by means of continuously rotating heat transfer element of specially formed metal plates. Thousands of these high efficiency elements are spaced and compactly arranged within sector-shaped compartments of radially divided cylindrical shell, called the rotor. The housing surrounding the rotor is provided with duct connections at both ends, and is adequately sealed by radial, axial and circumferential sealing

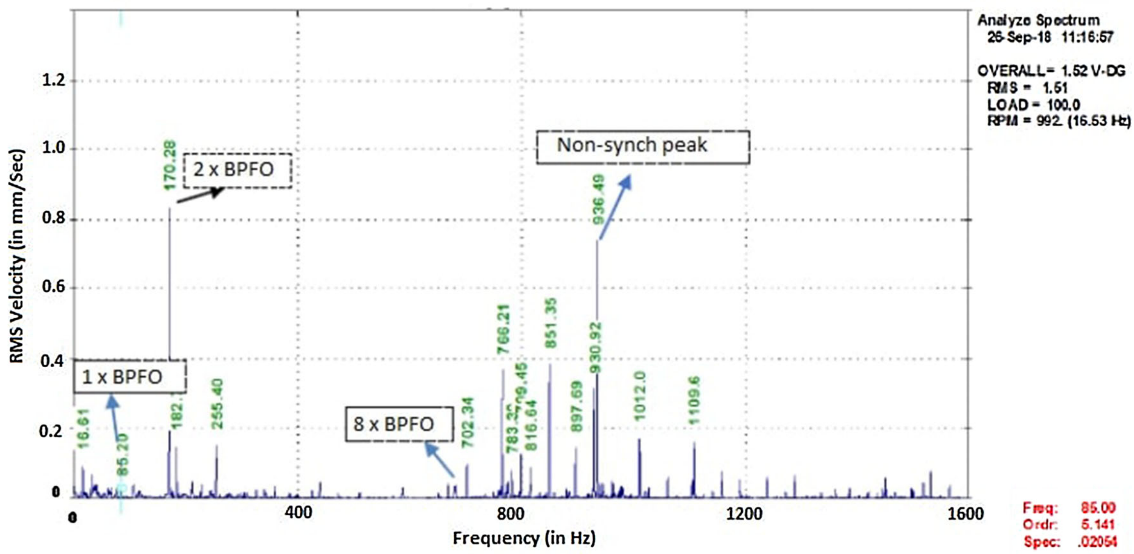

Fig. 7 Vibration spectrum of fan DE, (Horizontal direction)

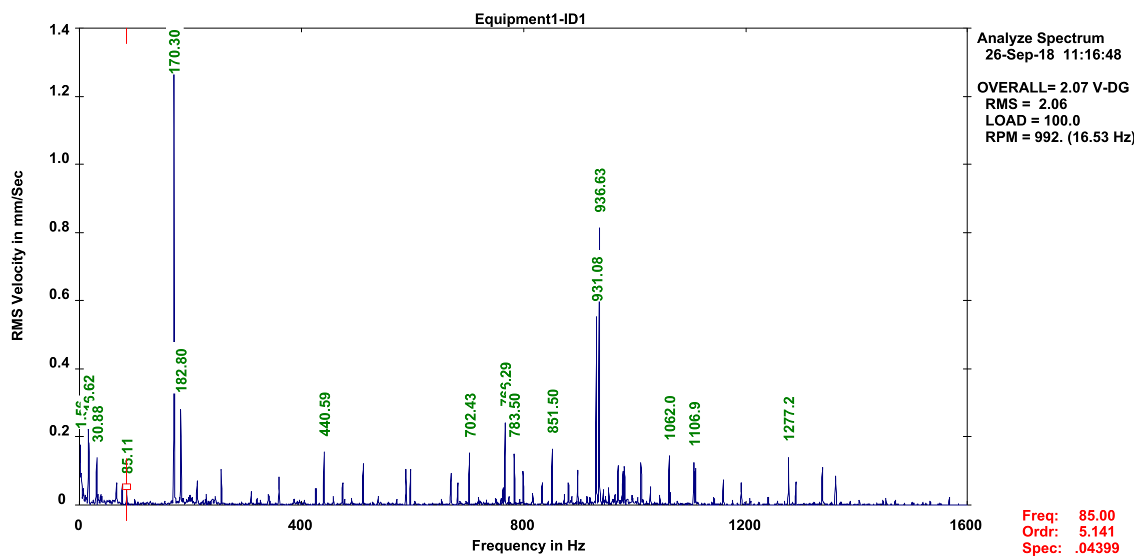

Fig. 8 Vibration spectrum of fan DE, (Axial direction)

members—forming an air passage through one half of the preheater and a flue gas passage though the other. As the rotor slowly revolves, the mass of elements passes alternately through the gas and air passages. Heat is absorbed by the element surface passing through the hot gas stream; then, these same surface are carried through the air stream, where they release the stored up heat, thus increasing the temperature of the incoming cold air. The Air Pre-heater is supported by a support bearing at the bottom and a guide bearing on the top. The schematic diagram of an APH set up is shown in Fig. 15.

3.3.1 *Specification and equipment details*

Heating element

(a) Hot end layer depth: 1000 mm element configuration 0.5 mm thick DU3(Double Undulated) COR-TEN Steel
(b) Hot intermediate layer depth: 880 mm element configuration 0.5 mm thick DU3 COR-TEN Steel
(c) Cold end layer depth: 305 mm element configuration 1.0 mm thick NF6(Notched Flat)corrosion resistance steel

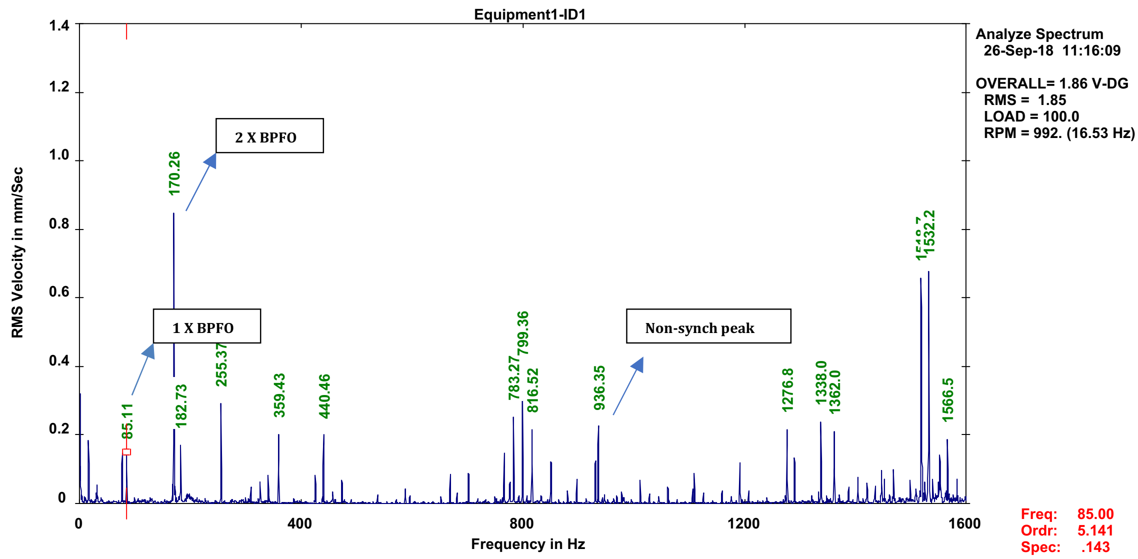

Fig. 9 Vibration spectrum of fan NDE, (Horizontal direction)

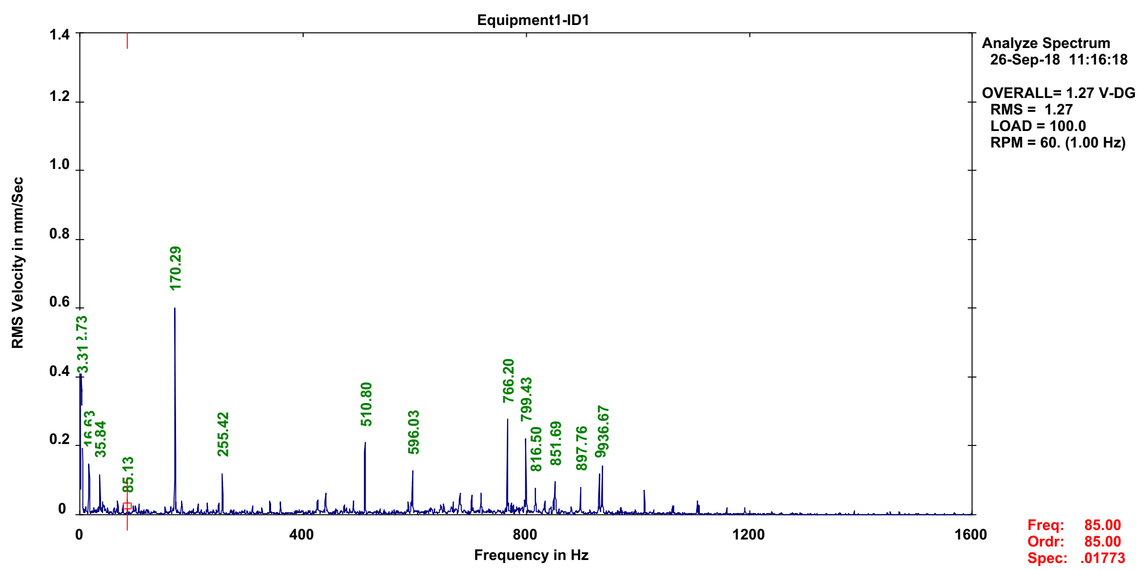

Fig. 10 Vibration spectrum of fan NDE, (Axial direction)

Rotor seals

Radial Seal, Rotor Post Seal, Axial Seal & By-Pass Seal(The forms are of seal leaves on both hot and cold end)

Rotor drive

Main motor: Type Y160M-6B3 7.5KW, 970 rpm (415VAC, 50 Hz), Auxiliary Air Motor: Type Z2-62 Double output shafts 7.5KW 1000 rpm, 415VAC, 50 Hz., Speed Reducer: SGW90A, Main Speed Ratio: 96.04, Auxiliary Speed Ratio: 0 $\sim$ 99.01, Output R.P.M. of Main motor: 10.1 rpm, auxiliary motor: 0 $\sim$ 10.1 rmp, output torque: 7000 N.m

Rotor support bearing: Spherical roller thrust bearing 90394/500

Rotor guide bearing: Two-way spherical roller bearing type 3153160

Oil capacity: Support bearing housing about 105 L, Guide bearing housing about 25 L, Oil grade: Servo mesh SP 680

Output RPM of APH: 1.5 RPM

Bearing outer race diameter: 870 mm

Problem description: In running condition, the Air Pre-heater Unit was tripped suddenly during August-2018.

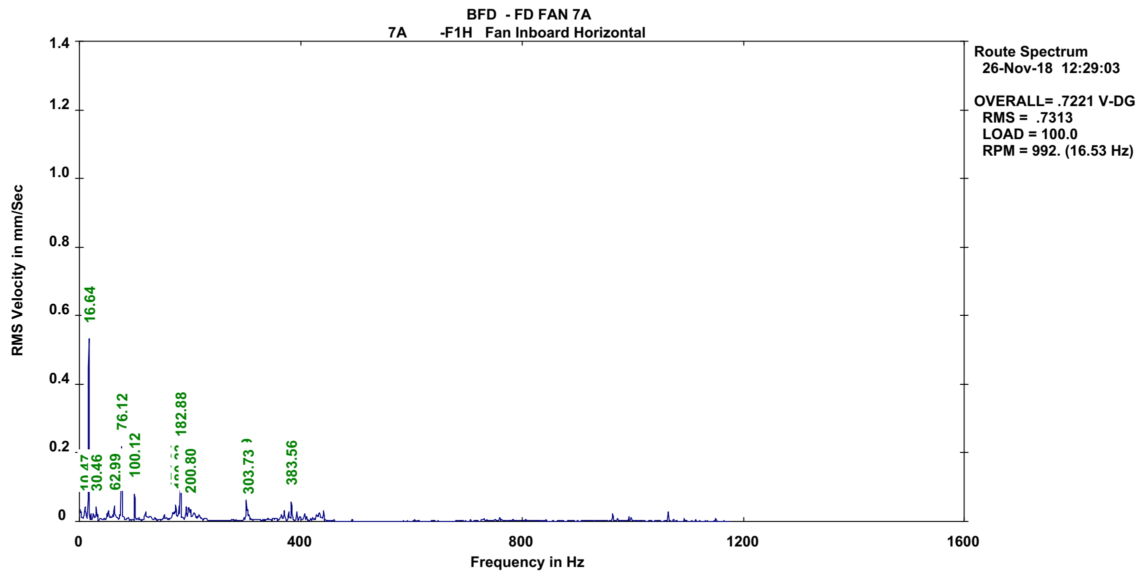

Fig. 11 Vibration spectrum of fan DE, (Horizontal direction)

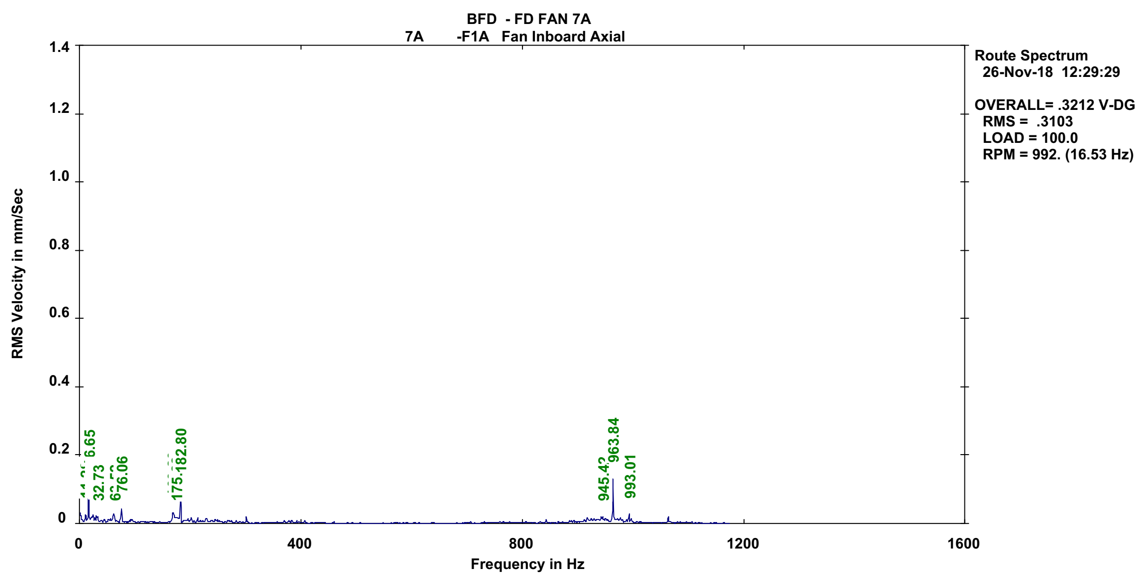

Fig. 12 Vibration spectrum of fan DE, (Axial direction)

3.3.2 Machine condition report

On inspection, it is found that the bearing has failed with roller & cage which have completely displaced out of position. Outer race was completely broken. Oil was completely black in color and lot of sludge deposition was found in chamber of bearing housing. Also minor dents have been found on the surface of Roller and lower race. No indication of high current & noise observed from the APH prior to failure. The breakdown has happened abruptly.

After dismantling we found visually that the oil quality is in poor condition, which was completely black & thick with lot of sludge deposition inside the chamber, although the entire oil had been changed during the annual overhauling just 6 months before. For oil replacement this degraded oil was required to be completely drained off and the oil chamber was needed to be cleaned with low viscosity flushing oil. However, complete draining was not possible and still a good amount of sludge was remaining inside the oil chamber which could not be removed by gravity because of unusual position of drain point at end of

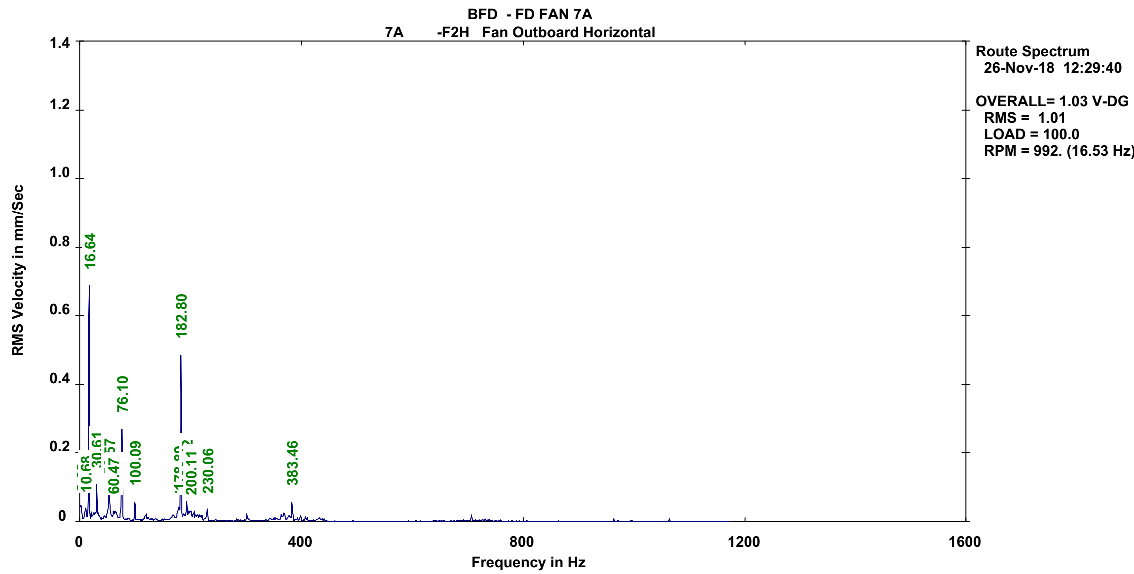

Fig. 13 Vibration spectrum of fan NDE, (Horizontal direction)

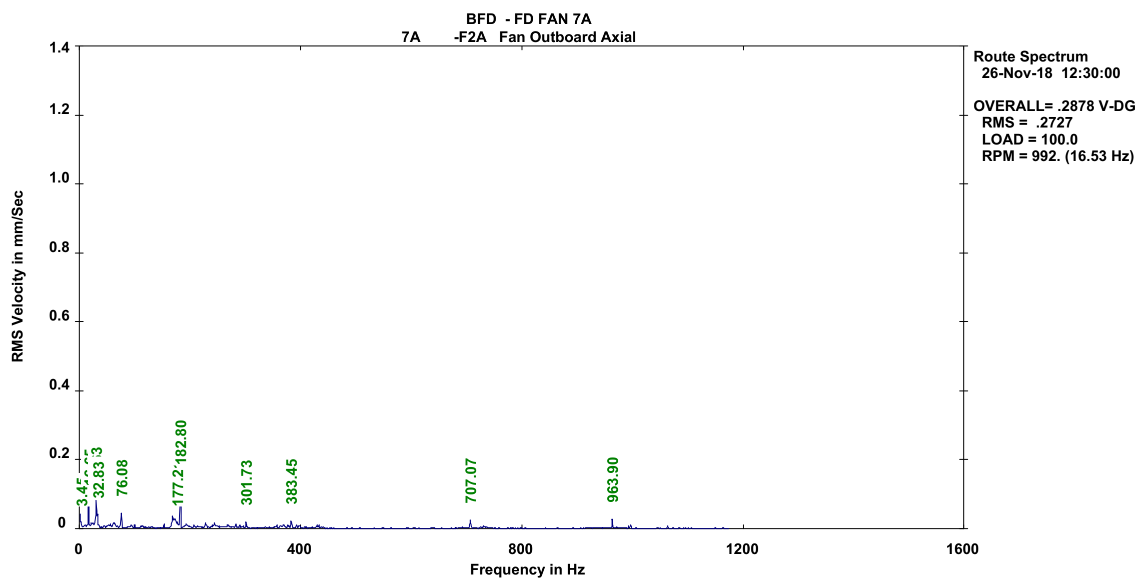

Fig. 14 Vibration spectrum of fan DE, (Axial direction)

housing instead of at centre position and also at a height of 10 mm from bottom of the housing. This resulted into the deposition and accumulation of sludge during the 6 years of operation.

It is worthwhile to note that the sludge is mainly the oxidized form of the oil settled at the bottom and was not able to drain out completely. Topping up of new oil in the system during every overhauling was leading to further carbonization of new oil too, which resulted into increase in oil temperature further and oil pump found running intermittently till temperature subside below the alarm value.

With the prolonged running of bearing with high concentration of carbonized sludge led to erosion of the weakest part of bearing assembly i.e. cage and race ways, resulting to failure of cage, inner race and outer race causing bearing failure. The gap between upper race of bearing and adopter plate should be zero during loading condition. This is shown in Fig. 16. The damaged bearing (inner race) is shown in Fig. 17.

From the analysis the reasons for the damage may be enumerated as follows

- Poor oil quality: Carbonized Sludge in the oil that can lead to damage of bearing resulting to sudden stoppage of APH due to jamming.

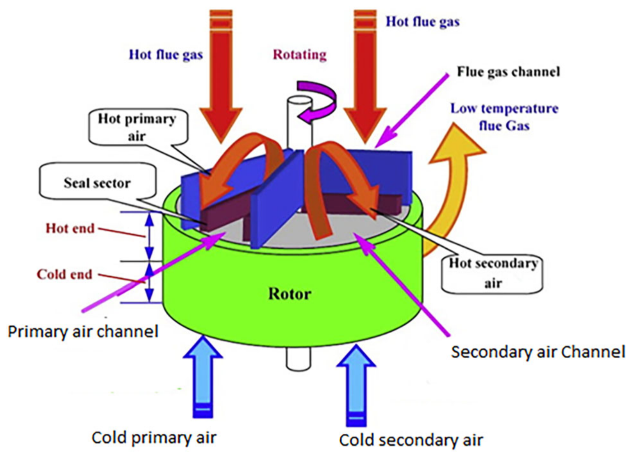

Fig. 15 Schematic diagram of an air preheater

- Fatigue failure: Wear out of outer race and inner race may damage the bearing due to prolonged running with higher load on it.
- Ingress of foreign particles from the APH rotor to bearing housing.

The following corrective and preventive actions were taken to make it normal.

1. Contaminated oil was drained completely. Housing with the oil circulating system flushed with a low viscosity flushing oil. Few quantity of sludge which could not be drained was removed through a portable vacuum pump.
2. The oil drain point was extended outside through proper tubing and a level gauge was installed.
3. Support bearing was replaced with a new one with proper leveling and gap setting. Centering of the rotor was done with respect to both support and guide bearing to make their axes are collinear.
4. Oil sump and the bearing housing were filled up with fresh oil.
5. New Gland rope was put just above the support bearing housing (between cover plate & rotor) to prevent any dust ingress.
6. The bearing base is perfectly leveled and its own axis is perfectly centered with axis of rotor. So that, the bearing and rotor are co-axial.

3.3.3 Future recommendation and horizontal implementation

During annual overhauling, both support and guide bearing housings along with the oil circulating system are to be cleaned with low viscosity flushing oil. Sludge deposit has to be completely removed by a portable vacuum pump. The inaccessible oil drain points of other units of the Power station have to be extended outside with installation of an oil gauge for easy oil filling and level monitoring. Both Support and guide bearings are to be inspected in every annual overhauling and are to be replaced with new one in case of any defect. Alignment of rotor shaft to be done along with guide bearing and support bearing in every overhauling and proper sealing on the rotor shaft to prevent ash dust ingress to the bearing housing is to be ensured. Patch test along with microscopic examination is to be done every month to find out oil quality degradation/contamination due to carbonization and/or metallic particles. In case of change in oil colour and contamination, oil has to be

Fig. 16 On load condition, there is gap between bearing upper race & adapter plate, which should be zero

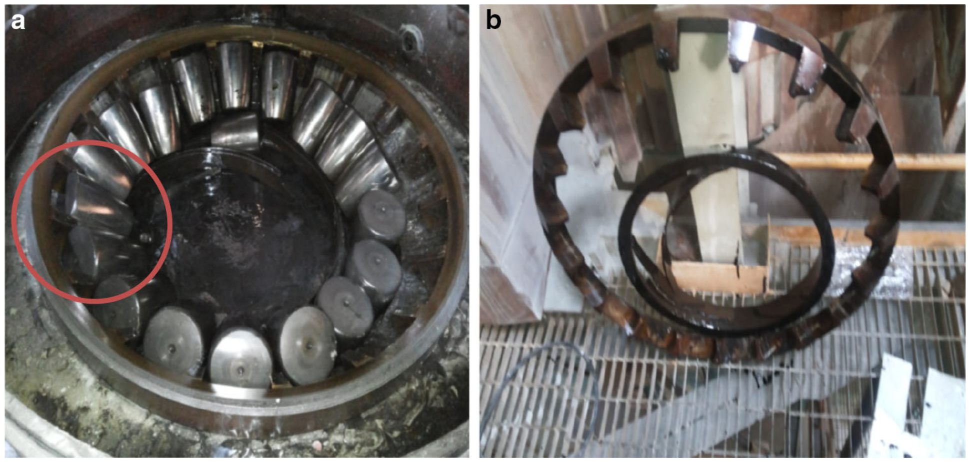

Fig. 17 Cracked bearing inner race **a** with one roller broken **b** with broken cage

drained from the oil sump & the bearing housing and replaced with fresh oil proactively.

4 Summary

These examples of equipment diagnostics indicate the vibration analysis is a very sensitive and strong technique to trace the developments of the defects. Condition monitoring of plant and machineries not only decrease the downtime but also improve the efficiency and reliability of the system. It decreases the probability of sudden failure and accident. FMECA is an important tool to implement the condition monitoring technique. Equipping auxiliary machinery of power plants and suitable condition monitoring, ensure reliable, safe resource-saving maintenance of power plants.

References

Catelani M, Ciani L, Venzi M (2018) Failure modes, mechanisms and effect analysis on temperature redundant sensor stage. Reliab Eng Syst Saf 180:425–433

Chen Y, Ye C, Liu B, Kang R (2012) Status of FMECA research and engineering application, 2012 prognostics & system health management conference, (PHM-2012 Beijing)

Jardine AKS, Lin D, Banjevic D (2006) A review on machinery diagnostics and prognostics implementing condition-based maintenance. Mech Syst Signal Process 20:1483–1510

Kim H, Na MG, Heo G (2014) Application of monitoring, diagnosis, and prognosis in thermal performance analysis for nuclear power plants. Nucl Eng Technol 46(6):737–752

Mohanty AR (2014) Machinery condition monitoring: principles and practices. CRC Press, London

Mpoweruk. https://www.mpoweruk.com/fossil_fuels.htm. Accessed on 20 May 2019

Nag PK (2008) Power plant engineering. Tata Mc Hill Publishing Co. Ltd, New Delhi

Pancholi N, Bhatt MG (2016) Multi criteria FMECA based decision-making for aluminium wire process rolling mill through COPRAS-G. J Qual Reliab Eng. Article ID 8421916

Power tech. https://www.power-technology.com/features/feature-the-top-10-biggest-thermal-power-plants-in-india/. Accessed on 20 May 2019

Srivastava NK, Mondal S (2015) Predictive maintenance using modified FMECA Method. Int J Prod Qual Manag 16(3):267–280

Williams JH, Davies A, Drake PR (1994) Condition-based Maintenance and Machine Diagnostics. Springer, New York

Würtenberger J, Kloberdanz H, Lotz J, Von Ahsen A (2014) Application of the FMEA during the product development process—dependencies between level of information and quality of Result. International design conference, Dubrovnik, Croatia, May 19–22, 2014

Zhou A, Yu D, Zhang W (2014) A research on intelligent fault diagnosis of wind turbines based on ontology and FMECA. Adv Eng Inf 29(1):115–125