Sound & Vibration

Tech Science Press

Integrated Condition Monitoring of Large Captive Power Plants and Aluminum Smelters

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Abstract: 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, Oil analysis and Thermography to diagnose ensuing problems of the Plant and Machinery at an early stage and plan to take corrective and preventive actions to eliminate the forthcoming breakdown and enhancing the reliability of the system. Nowadays, the most of the industries have adopted the condition monitoring techniques as a part of support system to the basic maintenance strategies. Major condition monitoring technique they follow is Vibration Spectrum Analysis, which can detect faults at a very early stage. However implementation of other techniques like Oil analysis or Ferrography, Thermography etc. can further enhance the data interpretation as they would detect the source of abnormality at much early stage thus providing us with a longer lead time to plan and take the corrective actions. In Large Captive Power Plants and Aluminium Smelters, Integrated Condition Monitoring techniques play an important role as stoppage of primary system and its auxiliaries (boiler, steam turbine, generator, coal and ash handling plants etc.) results into the stoppage of the entire plant, which in turn leads to loss of productivity. From economical and operational point of view, it is desirable to ensure optimum level of system availability.

Keywords: Condition monitoring; thermal power plant; vibration analysis; thermographs; maintenance

1 Introduction

Thermal Power Plants or Steam Power Plants generate more than 65% of the total electricity produced in the world. India is currently the 3rd largest producer of electricity in world and generation from coal based thermal power is about 85% of the country's power generation [1]. 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 [2].

In the recent years, there has been a trend to build Large 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 higher probability of fault occurrence in the system, when it is more complex. These faults are characterized by their slow pace of growth and can be detected by carefully monitoring the changes in the plant parameters. An early detection of these faults can allow time for preventive maintenance before a catastrophic failure occurs. This is vital for the control of ensuing damage. Similarly, when there is a chance of severe faults, it is necessary to detect them as early as possible and to take appropriate remedial measures to avoid shutdown of plant and ensuring safety. Large thermal power plants have highly complex but reliable instrumentation systems consisting of a variety of sensors for monitoring the process parameters. The utility of these systems is further enhanced when they are used for fault detection

A thermal power plant consists of main and auxiliary components as well as other systems. The critical components of a thermal power plant are Boiler and Auxiliaries, Steam Turbine and Auxiliaries and Generator and Auxiliaries.

Continuous generation of electricity of a power plant depends on the higher availability of its components and equipment's. Higher availability of the components and equipment is inherently associated with their higher reliability and maintainability.

Since its' genesis, the Maintenance culture has evolved down, through different types of maintenance techniques [3-6] 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 (breakdown) maintenance instead of predictive maintenance, 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 Based Maintenance

Condition Based Maintenance (CBM) or Condition Monitoring is determining the health and condition of equipment, machines and machinery systems by observing, checking, measuring, interpreting and monitoring certain parameters. CBM provides information on failures, much before system is going to fail [7]. The typical condition monitoring and fault diagnosis process usually consists of four phases i.e. (i) Data acquisition, (ii) Features extraction, (iii) Fault trend analysis, (iv) Decision making. There are different CBM techniques, such as: Vibration Analysis [8], Noise Analysis, Temperature Monitoring [9], Motor Current Signature Analysis (MCSA) [10] and Wear Debris Analysis etc.

The maintenance practice at 1215 MW, Captive Power Plant (CPP) of Vedanta Limited, Jharsuguda, Odisha, India shows that failure frequency of power unit components (Turbine, Induced Draft fan, Forced Draft fan etc) is many times higher than other components of the power system (overhead lines, transformers, switchgear, control systems, protections etc.). Intense wear and tear of machine elements as well as the necessity of maintenance works, affect the routine repairs of power units. The economic impact of power unit shut-down depends mainly on failure frequency, duration of repair and the period of the year in which the shut-down happens. A very important aspect is therefore is to optimize the values of these above said parameters to improve availability. The main reasons of power unit components failures can be classified as follows:

i) Defects in construction and design
ii) Material defects
iii) Assembly errors
iv) Operational wear and tear of material (corrosion, erosion, fatigue, strain, ageing)
v) Influence of external conditions (e.g., lack of fuel or water, power system disturbances, no external demand etc)
vi) Faulty repairs
vii) Mal-operation
viii) Insufficient care to keep installation in appropriate technical condition.

The first three groups mentioned above generally reveal during the early lifetime of power machinery and are corrected during the warranty repairs. Reasons belonging to the fourth reveal after a longer period of operation. However, particular attention should be paid to the last three groups of reasons which depend directly on skills of operators and maintenance staff working in a power plant.

Before implementing CBM in any industry, it is essential to perform a 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 & Criticality Analysis (FMECA)

FMECA is an extension of failure mode and effects analysis (FMEA). 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 components(s), systems(s) or process (es) to be analyzed.
b) Identify the function(s), failure modes(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 among the team members performing FMECA, 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 is a common tool, used to determine the degree of criticality of the machineries. i.e., Risk Priority Numbers (RPNs).

1.3 Risk Priority Numbers (RPNs)

The RPN is a result of a multiplication of three factors namely, severity (S) x occurrence (O) x difficulty to detect (D). With each on a scale from 1 to 10, the highest RPN is 10 x 10 x 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.

2 Methodology and Experimentation

The current study is based on Captive Power Plant (CPP) of Vedanta Limited (VL), Jharsuguda, Odisha, India. It has nine units having a total 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 (HCSD) and close circuit cooling systems installed in VL CPP are environment friendly technologies with positive impact on reduction in water consumption.

The captive power plant supplies power to the Aluminum Smelter (capacity of 0.5 mMT). The power is utilized for electrolysis of Alumina in 608 numbers of cells in pot lines to produce Aluminum hot metal. The hot metal in turn is transported to Cast House for production of Aluminum Ingots, Wire Rods & Billets.

The Power plant along with Aluminum Smelter is certified with ISO 9001, 14001 and OHSAS 18001 i.e., Integrated Management System from IRQS. Also both these plants of Vedanta Limited has been certified by SGS India Pvt Ltd for ISO 50001 (Energy Management System) and ISO 55001 (Asset Management System).The plant has adopted the state-of-art digital distributed control system. It strives to be at the fore front of technological innovation and establish itself as a leading player in both the domestic and global aluminum industry.

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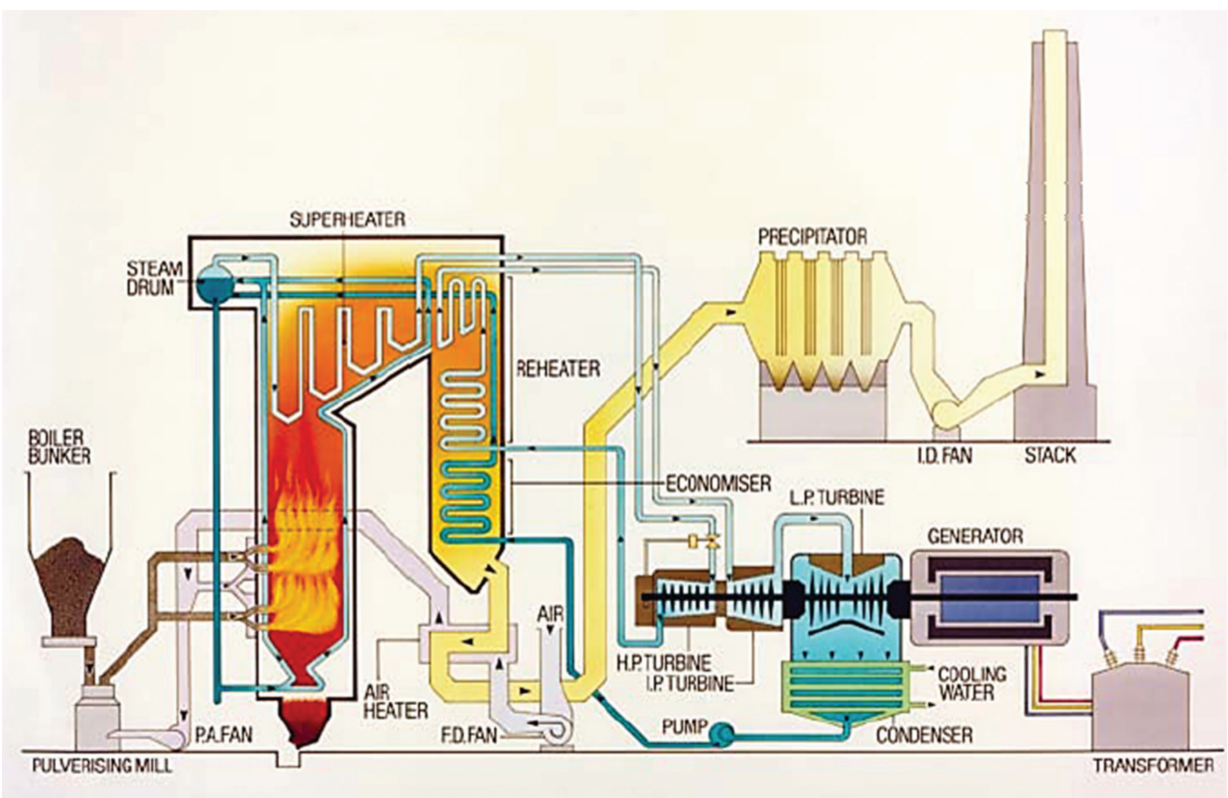

Figure 1: Line diagram of a large thermal power plant

Table 1: Equipment criticality analysis for CPP

SN	Equipments	S	O	D	RPN	Remark[see note]
1	Turbine	9	4	5	180	Most Critical
2	Wire rod mill	7	5	6	210	Most Critical
3	ID Fan	6	6	5	180	Most Critical
4	FD Fan	6	6	5	180	Most Critical
5	Air Pre-heater	7	5	4	140	Critical
6	CT Fan	4	4	3	48	Non Critical
7	BFP	4	3	4	48	Non Critical
8	ESP	3	6	3	54	Non Critical
9	Compressor	3	4	4	48	Non Critical
10	CW Pump	4	3	4	48	Non Critical
11	High Pressure Heater	4	3	3	36	Non Critical

Note: For this analysis, (i) RPN ≥ 150 is considered as most critical (ii) RPN in between 100 and 150 is considered as critical and (iii) RPN ≤ 100 is considered as non critical.

CBM has been currently adopted in VL and it covers 2500 number of equipments monitored through vibration analysis, 7500 number of equipments monitored through thermography and 1821 number of equipments monitored through oil analysis.

Power units are complicated thermal and mechanical installations consisting of several components with a different level of redundancy. Basic power unit components (boiler, turbine, and generator) are singular. However, auxiliary devices like ID fans (Induced draft fans), FD fans (Forced draft fans), coal mills, feed pumps, condensate pumps, cooling water pumps, ash handling units, coal handling plants etc. have inbuilt standbys. The characteristic feature of reliability of power unit is directly dependent on the redundancy of its' auxiliary system in order to increase reliability of operation.

2.1 FMECA in Vedanta Limited

FMECA Analysis is currently done for all individual equipment up to replaceable part and the same is to be reviewed once in a year. After taking care of all three parameters, the RPN of all the important equipments are evaluated and presented in Tab. 1.

The above FMECA analysis has categorized some of the most important equipments of the captive power plant and smelter unit. In this paper, we have considered three critical equipments for the analysis. These are;

i) ID Fan (Induced Draft Fan)
ii) FD Fan(Forced Draft Fan)
iii) WRM (Wire Rod Mill)

3 Observations and Case Studies

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 FD Fan

Sufficient air is required for complete combustion in boiler, which is supplied by two numbers of forced draft fans. The quantity of combustion air is varied by controlling the blade angle using pitch control mechanism. Two sections of steam coil air preheater are installed in the discharge of each forced draft fan. Steam drawn from auxiliary steam header is used to preheat the cold air during initial start up to minimize cold end corrosion. The schematic diagram of a FD fan set up is shown in Fig. 2.

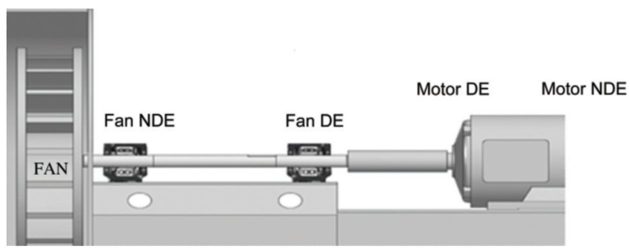

Figure 2: Schematic diagram of a FD fan set up

3.1.1 Specification Details of FD Fan:

Motor: 400 KW, 992 RPM, MNDE (Motor Non Drive bearing):6326, MDE (Motor Drive end bearing), NU 228EC3, FAN DE (Drive end): 6232MC3, FAN NDE (Non drive end): 6238, Vibration limit ≤3 mm/sec (as per Original Equipment Manufacturer, i.e. Sanghai Blowers).

3.1.2 Machine Diagnosis Symptoms during Operation

The condition monitoring of FD Fan 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. A typical case study, which was carried out during April 2018, has been taken for illustration. The time-domain data as well as spectra of vibration signal have been captured and analyzed. These are described as follows.

i) Vibration (RMS value) of 5.9 mm/s is observed at NDE of Fan on 15th April 2018 which was higher than allowable limit of 3.5 mm/s.
ii) The amplitude of vibration is 5.0 mm/s at 1x RPM, which was prominent in vibration spectrum (Fig. 3). That indicates unbalance in the impeller, which may be due to ash deposit.
iii) By taking the cross phase readings in both horizontal & vertical directions of Fan NDE & Fan DE bearings, it is confirmed that there is force unbalance in the system as phase difference is 90 degrees [11-12].

As per the recommendation [11], the impeller and its hub were cleaned to remove the ash deposit. Fan Impeller balancing has been done by installing 185 gm of balancing weight @ 64 degree, which has been put on 7th blade out of 11blades in the impeller. After balancing, the amplitude of vibration reduced to 1.4 mm/s at fan NDE, which is shown in Fig. 4. Also, the RMS value of vibration reduced to 1.5 mm/s.

3.2 Case Study 2: Condition Monitoring of ID Fan

Flue gas traveling upwards from the combustion zone in the boiler transfer heat to super heaters, re-heaters etc., in the upper elevation of the furnace and through economizers arranged in the second pass of the boiler and then enter the duct for the downward travel to Air Pre-heater. After transferring some of its heat to air heaters, flue gas travels in two independent streams through Hybrid ESP (ESP and bag houses) where 99% of fly ash is separated. Subsequently the flue gas is drawn by two radial flow ID fans, thus to

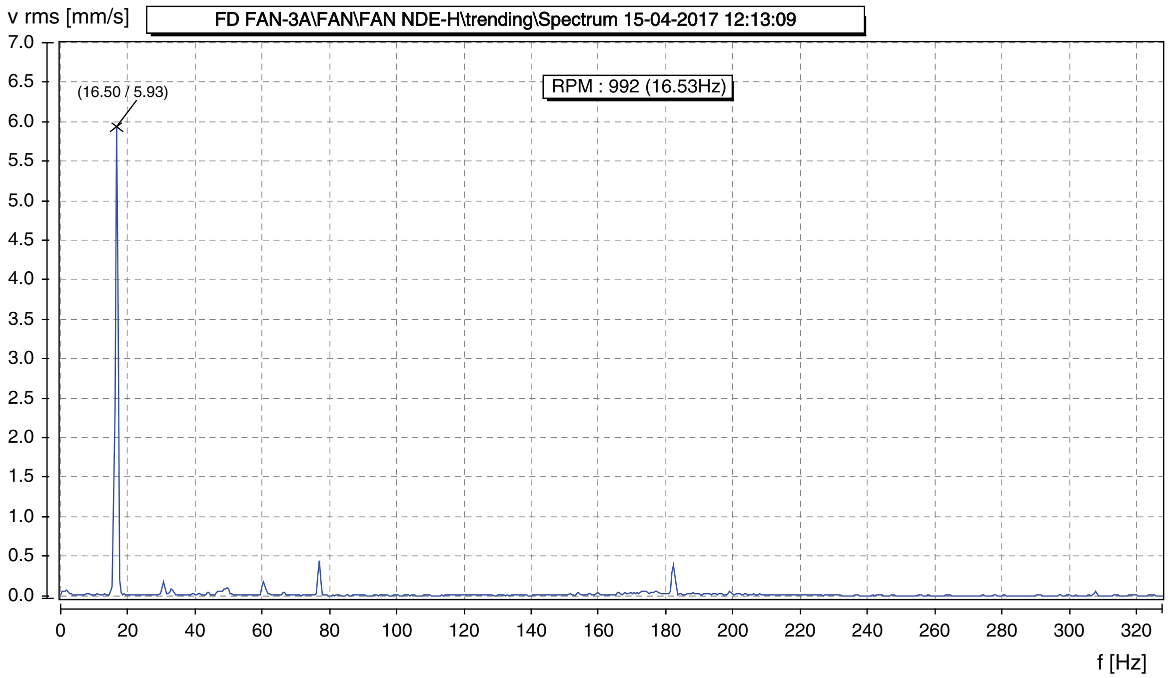

Figure 3: Vibration spectrum of NDE of FD fan

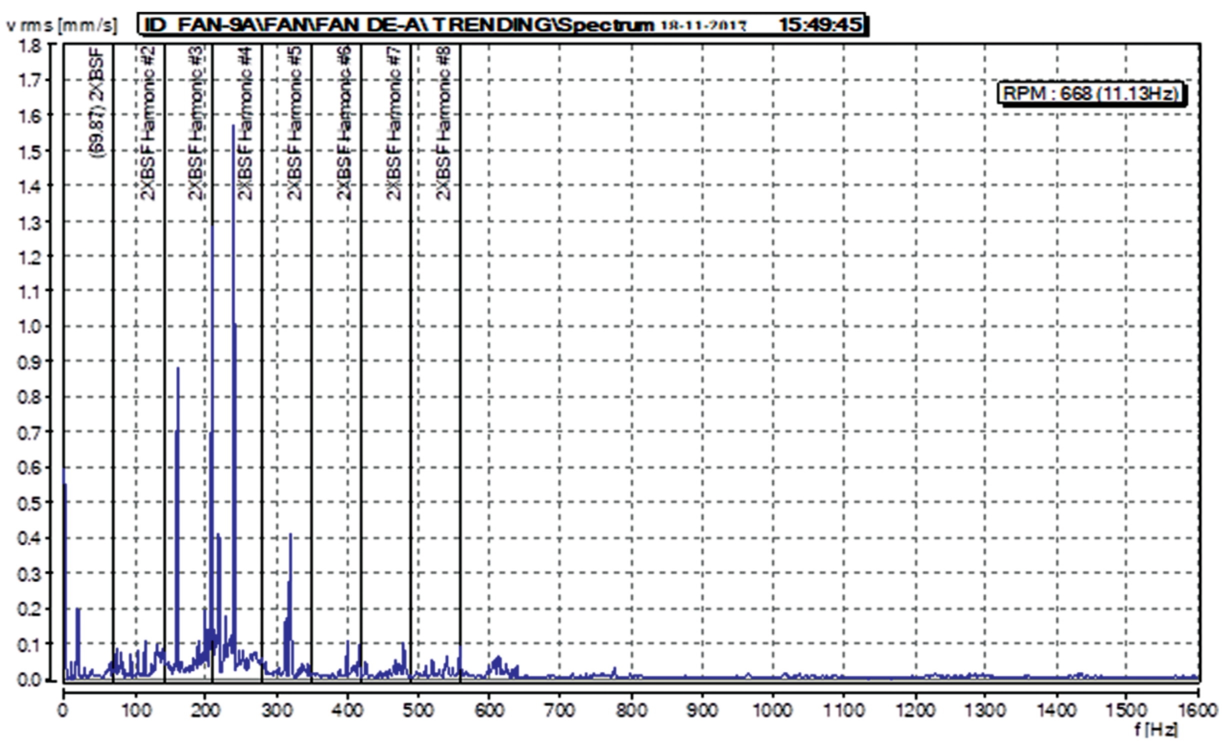

Figure 4: Vibration spectrum of NDE of FD fan (after removing of ash deposit)

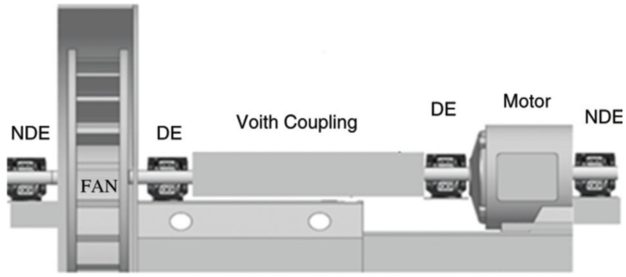

Figure 5: Schematic Diagram of an ID fan set up

have balanced draft. The fan is provided with variable speed control through a Hydraulic coupling (VOITH make) for regulation of the quantity of flue gases handled. Flue gas is finally discharged through a 275 M high stack. The schematic diagram of an ID fan set up is shown in Fig. 5.

3.2.1 Specification Details of ID Fan

Rated KW: 1700 KW, Speed: 995 RPM, Bearing at Motor DE: 23044CC/C3W33, Bearing at Motor NDE: NU240ECM/C3, Bearing at FAN DE: 22232EASMC3, Bearing at FAN NDE: 22232EASMC3

Vibration Limit: 6.5 mm/sec (as per Original Equipment Manufacturer, i.e., Sanghai Blowers)

3.2.2 Machine Diagnosis Symptoms during Operation

The condition monitoring of ID Fan 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. A typical case study, which was carried out during December 2016–November 2017, has been taken for illustration. Measurement of vibration readings are done at horizontal, vertical and axial directions (shown in Tab. 2). The time-domain data as well as spectra of vibration signal have been captured and analyzed. These are described as follows.

i) The vibration level of Fan Bearing (DE axial) was increasing gradually. The impending growth rate indicates the probability of the system.
ii) From vibration spectra (Fig. 6), it is observed that high peaks at BSF (69.87 Hz) and its harmonics indicate there is defect in bearing [11, 12]. The vibration amplitudes are 0.18 mm/s at BSF and 2.5 mm/s at 3x BSF.

As per the recommendation [11], the Fan DE bearing was replaced. After that the amplitude of vibration reduced to 0.4 mm/s from 3.8 mm/s. Also vibration amplitude at BSF and its harmonics were decreased, which is shown in Fig. 7.

3.3 Condition Monitoring of Gear Boxes for WRM-1 in Smelter

Wire Rod Mill is designed for production of aluminum rods of 9 mm diameter at the speed of 8 ton/hour by the rolling process. Hot metal from the furnaces at around 700^{o} C temperature is poured through the precast launders to the casting area which is carried over to the rolling stands by the help of casting wheel supported by idler wheels. The cast bar taken by the casting wheel passes through the entry shear and then comes to the roughing mills (3 stands with low speeds and high reduction ratio) and finishing mills (7 Stands with high speed and low reduction ratio), which is shown in Fig. 8. The required diameter is achieved at the end of 10th stand and rod is then quenched by cold water after which it enters the coiler area where coils of 2.5 MT are produced. This is finally packaged and handed over. Each stand consists of a set of motor –gear box-roll modules- for the rolling process. Motors are VFD (Variable Frequency Drive) driven with highest one is of 80 KW rating. Every alternate stand is of similar construction. All odd number stands (stand1, 3, 5, 7, 9) are having horizontal arrangement of motor-gear

Table 2: Vibration (RMS Value, in mm/s)

Date Parts		7th Dec. 2016	3rd June 2017	7th July 2017	17th Aug. 2017		18th Nov. 2017
Motor NDE	H	0.8	0.9	0.5	0.7	Bearing replaced on 12th Nov. 2017	0.3
	V	0.5	0.6	0.4	0.5		0.3
	A	0.7	0.7	0.6	0.7		0.6
Motor DE	H	0.6	0.6	0.4	0.6		0.3
	V	0.3	0.4	0.3	0.4		0.4
	A	0.8	0.9	1.1	1.2		1.4
VOITH DE	H	1.4	1.0	1.1	1.1		1.4
	V	1.0	0.8	0.7	0.7		0.6
	A	2.3	1.9	2.0	1.9		1.8
VOITH NDE	H	1.6	1.7	1.7	1.9		1.2
	V	2.5	2.6	2.6	2.1		1.3
	A	2.0	2.1	1.8	2.0		1.7
Fan DE	H	2.3	2.4	2.1	2.3		0.3
	V	2.2	2.7	2.1	2.2		0.2
	A	2.2	2.3	2.8	3.8		0.4
Fan NDE	H	1.4	1.4	0.7	1.1		0.3
	V	1.6	1.5	0.8	1.4		0.2
	A	0.9	0.8	0.7	0.8		0.6

Note: H = Horizontal direction, V = Vertical direction and A = Axial direction. DE = Driving end, NDE = Non driving end.

box- module while even number stands are having vertical arrangement of gear box. The vertical stands are having bevel gear arrangements inside gear boxes with input of 1180-2100 rpm (Revolution per minute) and output rpm is as low as 20 rpm. All these gear boxes are lubricated by individual self-contained lube units with Servo mesh 320 gear oil. Each of these stands are monitored by the help of vibration analysis on weekly basis and oil analysis on monthly basis.

3.3.1 Machine Diagnosis Symptoms during Operation

The WRM-1 roughing stand 2 is driven by a 30 KW motor with 1180-2100 rpm VFD drive. The gear box is with bevel arrangement of gears in 3 stages. This is quite critical as it is single line equipment. The condition monitoring of WRM is done through vibration analysis along with oil analysis. The vibration data are taken and analyzed using Emerson make- CSI-2140 Vibration Data Logger with accelerometer and AMS Suite Software. Vibration measurements are done at all bearing points in motors and input side bearings of gear box. The output side bearing points of gear box are not accessible and accelerometer cannot be mounted on it. As per ISO 10816 it is class-2 equipment with vibration (rms) limits of 4.2 mm/s (alert) and 7.1 mm/s (alarm).

A typical case study, which was carried out during January-November 2017, has been taken for illustration. The time-domain data as well as spectra of vibration signal have been captured and analyzed. These are described as follows.

i) In the month of April 2017 during oil analysis it was detected that high amount of wear was observed in gear box. But vibration trends (RMS value) were around 1.8 mm/s with no such abnormality at

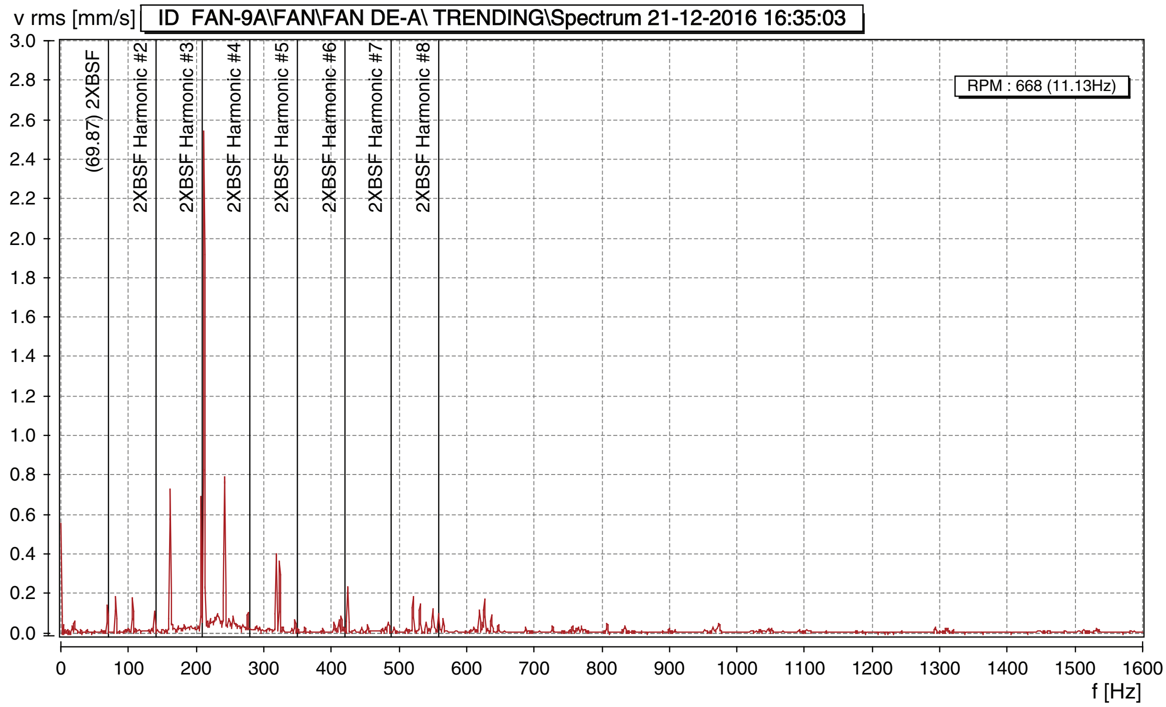

Figure 6: Vibration Spectrum of Fan DE (Axial) with high peaks at BSF and harmonics

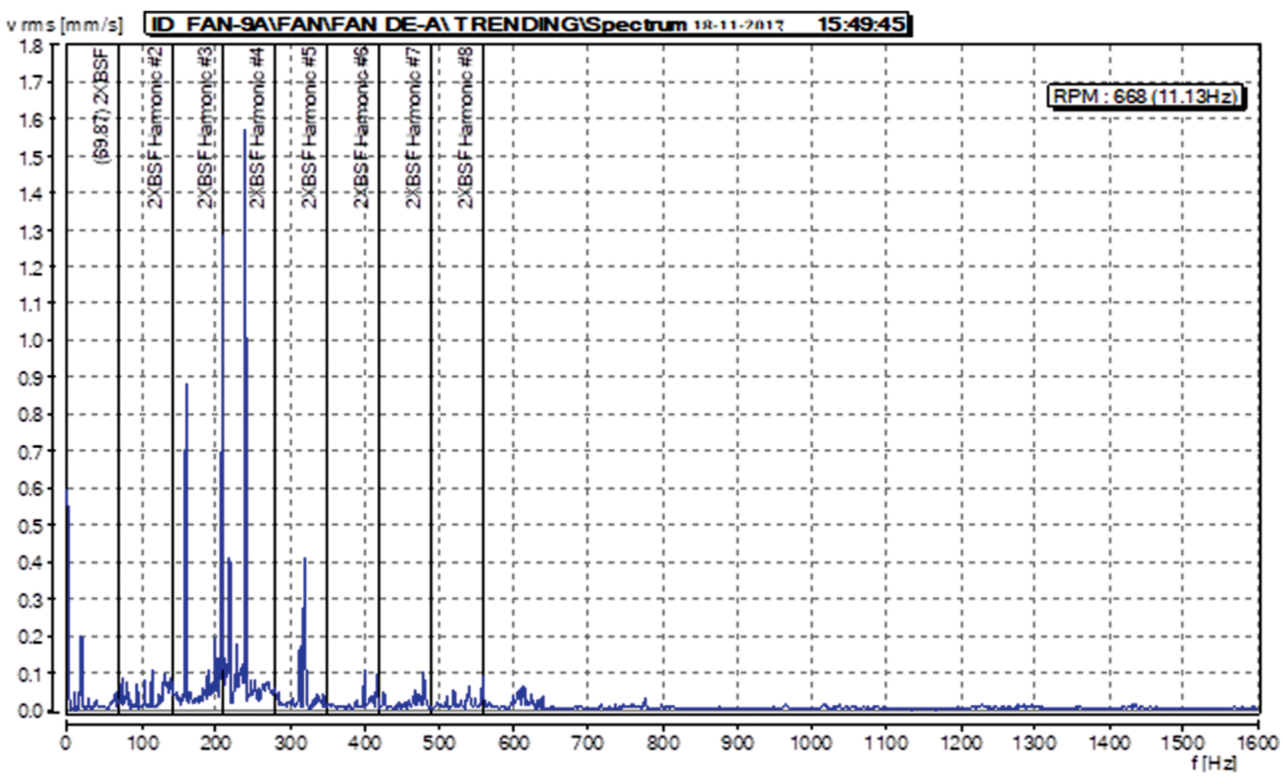

Figure 7: Vibration spectrum of fan DE (Axial), showing smaller BSF peaks (after replacing fan DE bearing)

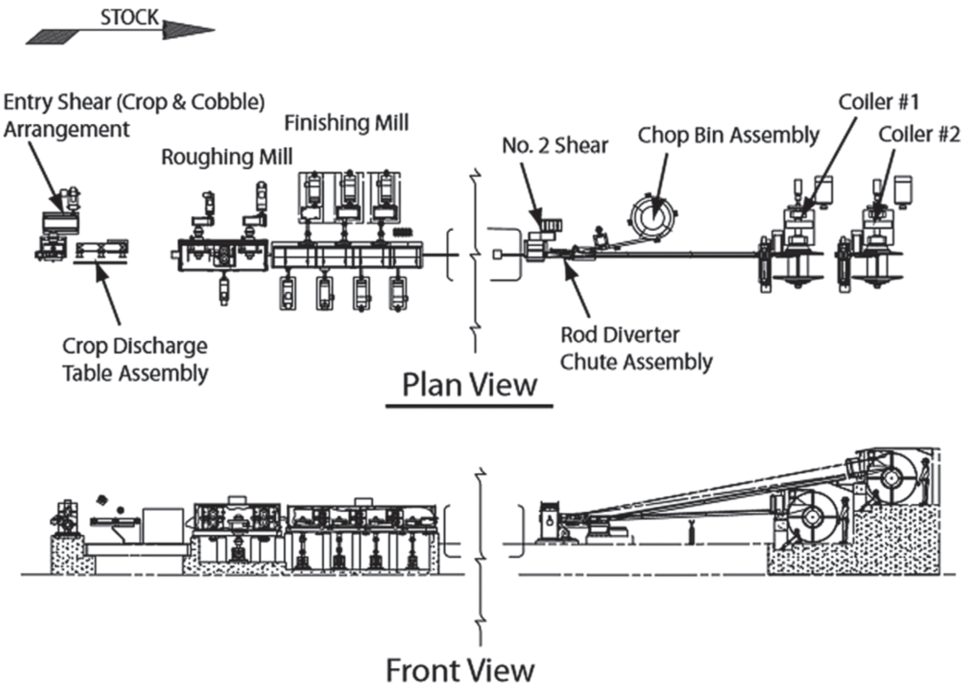

Figure 8: General arrangements of wire rod mill stands

spectrum analysis. There is no indication of bearing fault in vibration spectrum, as there is no peak at BPFO, BPFI and BSF.

ii) So it was suspected to be a case of sediments deposit at gear box base and was recommended to change the oil. Oil replacement was done.

iii) Same observations (i.e high amount of wear were also found) in oil analysis during May 2017. Then it was recommended to flush the gearbox and further fill the gear box with clean oil. As per recommendations the flushing was done by a flushing agent having 32 grade viscosity. It was observed that fine shiny particles along with small amount of sediments were received at drain points. After oil replacement with clean Servo mesh-320, the system was restored and vibration measurements were about 1.5 mm/s.

iv) After that, again in June 2017, the wear amount was still present even after flushing the gear box. So, it was suspected to be generated due to abnormal wear of some internal components. It was suggested to inspect the internal of gear box.

v) Vibration spectrum was again analyzed and no such abnormalities of bearing faults (BPFO, BPFI etc.) were observed. Spectrum indicated a peak at gear meshing frequency with very low amplitudes of noise floor indicating a healthy spectrum.

vi) Since there is no peak at fault frequencies, the chance of bearing abnormalities was eliminated. Again oil was replaced in gear box and the system was put back to operation.

vii) Subsequently, on 09th July 2017 the oil sample indicated high wear without any significant change in vibration levels. Vibration (RMS) values were in similar trend. But now spectrum analysis (Fig. 9) indicates the prominent peak at gear meshing frequency (i.e. 19.760 kHz.) and it's harmonics along with side bands which indicates gear meshing inaccuracies. It was recommended to check the gear conditions.

viii) In the month of Sept 2017, the gear box was removed and it was inspected. A crack had been developed in one teeth and it was broken, which has led to wear in the system. Moreover, the gear has further pitting marks due to the abrasive action of wear out particles.

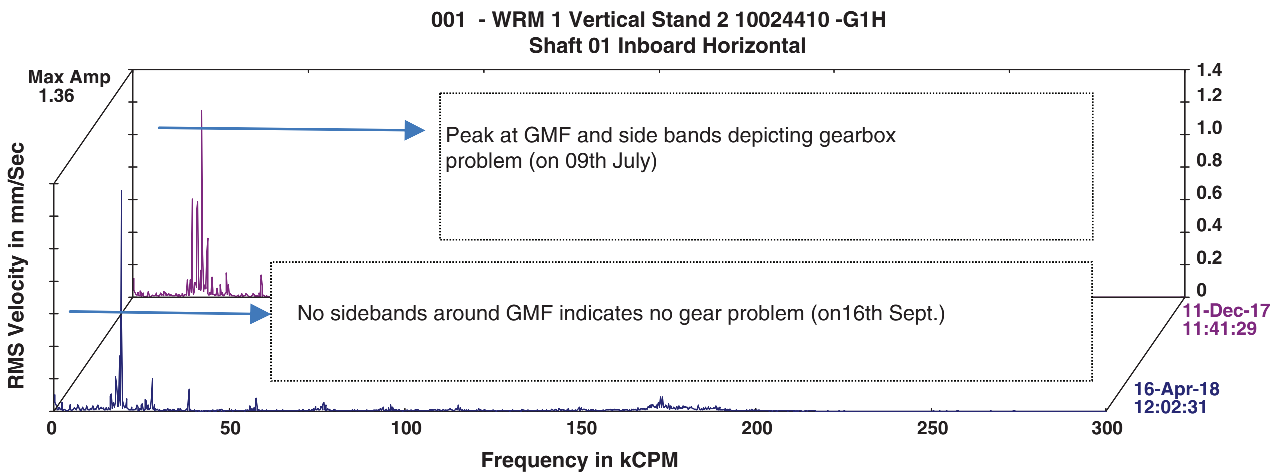

Figure 9: Waterfall spectrums before and after gear box replacement

ix) As per recommendation [11] the gear box was replaced with a new one. Readings after the actions were completed indicated a clear spectrum depicting a healthy gear box (shown in Fig. 9).

x) After the gear box was replaced, oil analysis was conducted and the oil condition was in acceptable limit without any wear particle indicating the broken tooth was the cause of the problem earlier.

3.4 Case Study 4: CBM of Hot Spot through Thermography in Phase # 1 Rectifier in Smelter.

Pot Lines in Smelter are power intensive. AC power from CPP switchyard is received by Smelter switchyard and rectified to DC power utilized by pot lines. Smelter switchyard consists of two phases with 5 nos. of Rectifier-Transformers and one no of auxiliary transformer each. The auxiliary transformer feeds power to 6.6 kV bus bar of both the phases of switchyard. All area substations avail power from 6.6 kV bus bar of Phase 1 and phase 2. The current carrying capacity of incoming lines of rectifier is 2500 Ampere and voltage rating is 220 kV. If there any flash over occurs on the line, entire power system becomes unbalanced and both Smelter and CPP may trip and collapse.

3.4.1 Machine Diagnosis Symptoms during Operation

The condition monitoring of Hot spot is done through thermographs using IR camera. Unit-13, 221 Bus Bar Joint indicated hot spot at R phase with 110^{o}C with red hot indication in the IR camera (as shown in Fig. 10). The high temperature of 110^{o}C in the bus bar joint might have led to electrical flash over

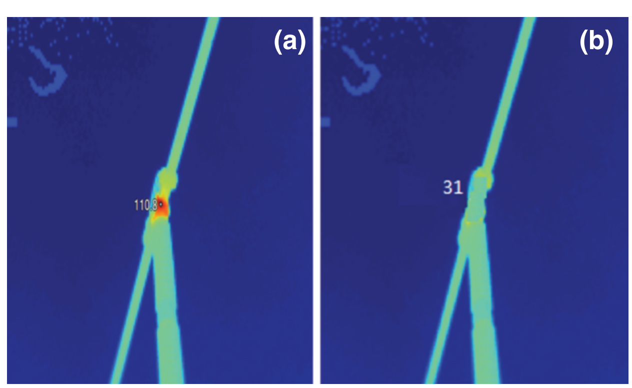

Figure 10: Thermograph image, (a) before replacement, (b) after replacement

leading to tripping of rectifiers. This in turn would have resulted in stoppage of Pot line, impacting the Metal production directly.

It was suspected that the Clamp/Jumper might be rusted needing cleaning or replacement if necessary. As per recommendation, the clamp was replaced and the temperature reduced to 31^{o}C in R- phase and was equivalent to the one in Y and one in B phase indicating a healthy connection.

4 Summary

Condition based maintenance improves the reliability and capability of the system. It eliminates the accidents and so-called 'sudden failures'. Though there are several conditions monitoring techniques, vibration analysis is considered to be a very sensitive and strong technique to trace the developments of the defects. However, in some cases, one or more technique should be applied in combination to enhance the reliability. Like in case study-3, the combination of oil analysis with a detailed vibration analysis was able to detect the defect in gear box, which might not have been possible to detect by using single technique. Equipping auxiliary machinery and suitable condition monitoring techniques ensure the reliable, safe and resource-saving maintenance of power plants.

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