Application of Online Intelligent Remote Condition Monitoring Management in Thermal Power Plant Maintenance: Study of ThermPower Plant in Zimbabwe

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Abstract: ***This research study investigated the application of Online Remote Condition monitoring system at a thermal power plant. Analysis was done on the current maintenance strategy at the plant and attributes of the maintenance system. The study helps to show how Online Remote Condition Monitoring helps to improve the maintenance system at the plant from mainly Predetermined and Corrective approach to Predictive Maintenance and, the resultant benefits of its adoption. The findings clearly indicate the various aspects of Online Remote condition monitoring system which thermal power plants can consider to improve on plant safety, reliability and availability to achieve world class power generation practices. The study can be a useful resource to thermal plant engineers and related practitioners on various thermal power generation aspects.***

Keywords: thermal, power plant, intelligent, condition monitoring, maintenance

1. Introduction

The study is based on a plant whose output is theoretically of 920MW. In the year 2011 it was reported that its generating capacity was only 400MW. Thus to say the plant had a plant load factor of 43%. The poor operating and maintenance approaches in use at the power plant were cited as main causes. Currently main forms of maintenance are predetermined and corrective instead of predictive maintenance system.

The predetermined or time based preventive approach has fixed maintenance intervals in order to prevent components, sub-systems or systems to degrade [1]. Corrective maintenance is performed after an obvious fault or breakdown has occurred. Both approaches have shown to be costly due to lost production, cost of keeping spare parts and quality deficiencies [3].

These challenges have given rise to Condition-Based Maintenance (CBM), which is a maintenance philosophy that actively manages the health condition of assets as maintenance work is only done when really needed [6]. CBM reduces operating costs and increases the safety of assets. Combining this approach to maintenance with an online system resulted in an online real time condition monitoring system [7].

2. Justification

Thermal power plants need to be adequately protected, particularly critical plant and heavy machinery, against costly breakdowns [4]. Lost production time results in hundreds of thousands of dollars of losses per day – until the problem is rectified.

The common trend is that maintenance team becomes reactive, fire-fighting problems around the thermal plant as they occur as they lack a predictive maintenance system.

Early warning from Online Intelligent Condition Monitoring Systems presents an attractive to post-failure reactive maintenance [5]. Proactive schedules and performance of maintenance on components forewarned to fail, the repairs can be completed efficiently and at the most optimal time given the current state of the plant. Component failures at power plants are extremely costly. Preventing one such failure per year would provide a return on the investment, through preventing or minimizing potential down-time. Additional benefits of online intelligent condition monitoring system, can be acquired through enhanced safety, reliability, and the knowledge gained through continuous assessment of critical plant components [9].

3. Power Generation Process

3.1 Thermal power plant

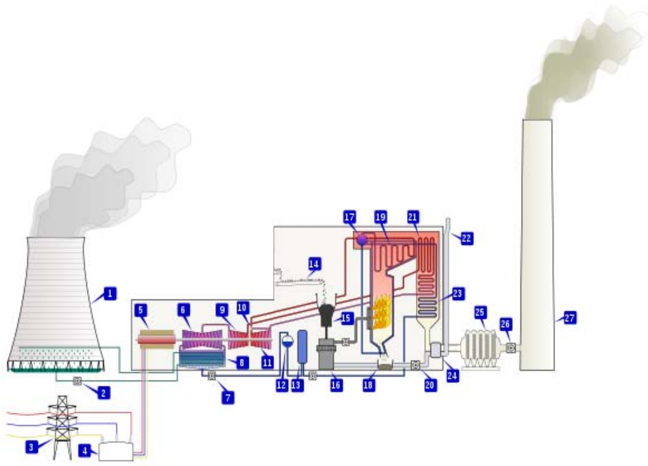


Figure 1: A typical coal-fired thermal power station [5]

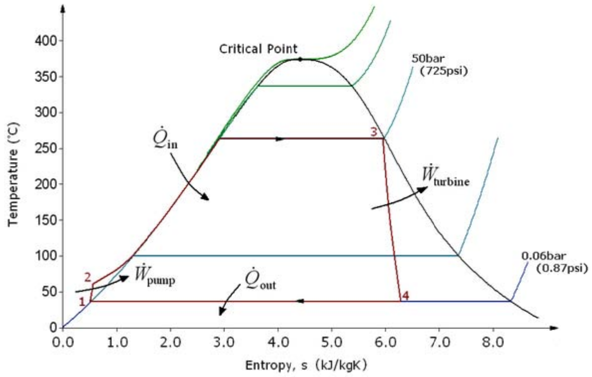
1. Cooling tower	10. Steam Control valve	19. Superheater
2. Cooling water pump	11. High pressure steam turbine	20. Forced draught fan
3. Transmission line (3-phase)	12. Deaerator	21. Reheater
4. Step-up transformer (3-phase)	13. Feedwater heater	22. Combustion air intake
5. Electrical generator (3-phase)	14. Coal conveyor	23. Economizer
6. Low pressure steam turbine	15. Coal hopper	24. Air preheater
7. Condensate pump	16. Coal pulverizer	25. Precipitator
8. Surface condenser	17. Boiler steam drums	26. Induced draught fan
9. Intermediate steam turbine 1	8. Bottom ash hopper	27. Flue gas stack

A thermal power plant basically works on Rankine cycle. The Rankine cycle is a cycle that converts heat into work. The heat is supplied externally to a closed loop, which usually uses water. The Rankine cycle closely describes the process by which steam-operated heat engines most commonly found in power generation plants generate power [5]. The heating process used in thermal power plants is combustion of fossil fuels in this case coal.

The Rankine cycle is sometimes referred to as a practical Carnot cycle because, when an efficient turbine is used, the TS diagram begins to resemble the Carnot cycle. The main difference is that heat addition (in the boiler) and rejection (in the condenser) are isobaric in the Rankine cycle and isothermal in the theoretical Carnot cycle. A pump is used to pressurize the working fluid received from the condenser as a liquid instead of as a gas. All of the energy in pumping the working fluid through the complete cycle is lost, as is most of the energy of vaporization of the working fluid in the boiler. This energy is lost to the cycle because the condensation that can take place in the turbine is limited to about 10% in order to minimize blade erosion; the vaporization energy is rejected from the cycle through the condenser. But pumping the working fluid through the cycle as a liquid requires a very small fraction of the energy needed to transport it as compared to compressing the working fluid as a gas in a compressor (as in the Carnot cycle).

The efficiency of a Rankine cycle is usually limited by the working fluid. Without the pressure reaching super critical levels for the working fluid, the temperature range the cycle can operate over is quite small: turbine entry temperatures are typically 565°C (the creep limit of stainless steel) and condenser temperatures are around 30°C. This gives a theoretical Carnot efficiency of about 63% compared with an actual efficiency of 42% for a modern coal-fired power station. This low turbine entry temperature (compared with a gas turbine) is why the Rankine cycle is often used as a bottoming cycle in combined-cycle gas turbine power stations [4].

One of the principal advantages the Rankine cycle holds over others is that during the compression stage relatively little work is required to drive the pump, the working fluid being in its liquid phase at this point. By condensing the fluid, the work required by the pump consumes only 1% to 3% of the turbine power and contributes to a much higher efficiency for a real cycle. The benefit of this is lost somewhat due to the lower heat addition temperature. Gas turbines, for instance, have turbine entry temperatures approaching 1500°C. Nonetheless, the efficiencies of actual large steam cycles and large modern gas turbines are fairly well matched.



T-s diagram of a typical Rankine cycle operating between pressures of 0.06bar and 50bar.

Figure 2: The four processes in the Rankine cycle [4]

There are four processes in the Rankine cycle. These states are identified by numbers in the diagram above.

Process 1-2: The working fluid is pumped from low to high pressure. As the fluid is a liquid at this stage the pump requires little input energy.

Process 2-3: The high pressure liquid enters a boiler where it is heated at constant pressure by an external heat source to become a dry saturated vapor. The input energy required can be easily calculated using mollier diagram or h-s chart or enthalpy-entropy chart also known as steam tables.

Process 3-4: The dry saturated vapor expands through a turbine, generating power. This decreases the temperature and pressure of the vapor, and some condensation may occur. The output in this process can be easily calculated using the Enthalpy-entropy chart or the steam tables.

Process 4-1: The wet vapor then enters a condenser where it is condensed at a constant temperature to become a saturated liquid.

In an ideal Rankine cycle the pump and turbine would be isentropic, i.e., the pump and turbine would generate no entropy and hence maximize the network output. Processes 1-2 and 3-4 would be represented by vertical lines on the T-S diagram and more closely resemble that of the Carnot cycle. The Rankine cycle shown here prevents the vapor ending up in the superheat region after the expansion in the turbine, which reduces the energy removed by the condensers.

Variables

$\dot{Q}$ Heat flow rate to or from the system (energy per unit time)

$\dot{m}$ Mass flow rate (mass per unit time)

$\dot{W}$ Mechanical power consumed by or provided to the system (energy per unit time)

η_{therm} Thermodynamic efficiency of the process (net power output per heat input, dimensionless)

η_{pump}, η_{turb} Isentropic efficiency of the compression (feed pump) and expansion (turbine) processes, dimensionless

h_1, h_2, h_3, h_4 The "specific enthalpies" at indicated points on the T-S diagram

h_{4s} The final "specific enthalpy" of the fluid if the turbine were isentropic

p_1, p_2 The pressures before and after the compression process

Equations

In general, the efficiency of a simple Rankine cycle can be defined as:

$$\eta_{therm} = \frac{\dot{W}_{turbine} - \dot{W}_{pump}}{\dot{Q}_{in}} \approx \frac{\dot{W}_{turbine}}{\dot{Q}_{in}}$$

The following equations are derived from the energy and mass balance for a control volume. η_{therm} defines the thermodynamic efficiency of the cycle as the ratio of net power output to heat input. As the work required by the pump is often around 1% of the turbine work output, it can be simplified.

$$\frac{\dot{Q}_{in}}{\dot{m}} = h_3 - h_2$$

$$\frac{\dot{Q}_{out}}{\dot{m}} = h_4 - h_1$$

$$\frac{\dot{W}_{pump}}{\dot{m}} = h_2 - h_1$$

$$\frac{\dot{W}_{turbine}}{\dot{m}} = h_3 - h_4$$

3.2 Milling Plant

The coal is put in the boiler after pulverization. A pulverizer is a mechanical device for grinding coal for combustion in a furnace in a power plant. Pulverizing coal for a boiler is a key factor in overall cycle efficiency. This helps in reduction of carbon-dioxide emission per million units of electricity generated, as well as removing moisture in coal to an acceptable level for firing in boiler [4]. The higher the moisture, the lower the output.

The hot primary air is used for drying the coal and to transport the milled coal to the furnace. The exhauster is used for lifting the milled coal from the pulverizer to the furnace through a cyclone. The control systems are well made to understand the requirement of ball charge and the output from the mill. Ball mills can be designed for a very high capacity like 75 tons per hour output for a specific coal.

3.3 Boiler Plant

The pulverized coal is put in boiler furnace. Boiler is an enclosed vessel in which water is heated and circulated until the water is turned in to steam at the required pressure. The high temperature combustion gases vaporize the water inside the boiler to steam. The higher the steam pressure and temperature the greater efficiency the engine will have in converting the heat in steam into mechanical work. Steam is used as a heating medium to convert thermal energy to mechanical work, which in turn is converted to electrical energy. Water is most commonly used because of its economy and suitable thermodynamic characteristics. Fire tube boilers and water tube boilers are used as shown in Figure 3 [5].

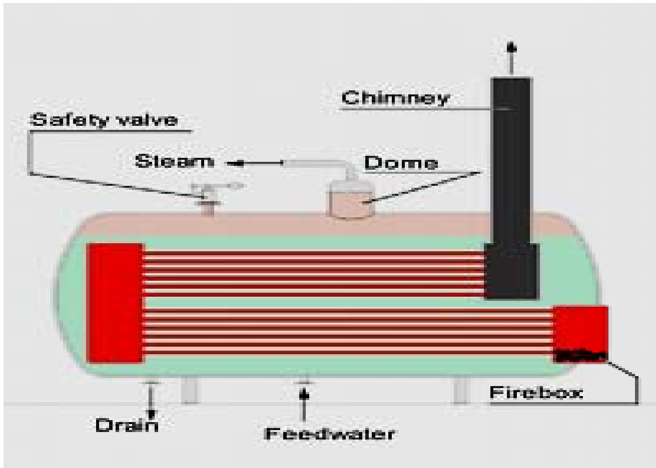


Figure 3: Fire tube boiler

3.4 Condenser

Steam after rotating steam turbine comes to the condenser unit. It is a shell and tube heat exchanger installed at the outlet of every steam turbine in thermal power station to convert steam from its gaseous to liquid. The purpose is to condense the outlet steam from turbine to obtain maximum efficiency and to get the condensed steam back to steam generator(boiler) feed water [4].

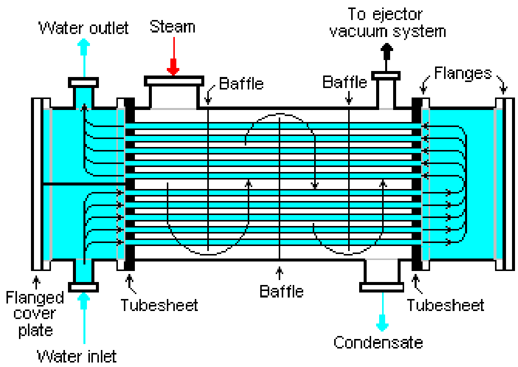


Figure 4: Condenser

3.5 Cooling Towers

Hot water from the condensers is passed to cooling towers in which atmospheric air circulates in direct contact with warmer water (the heat source) and the water is thereby cooled. Water, acting as the heat-transfer fluid, gives up heat to atmospheric air, and thus cooled, is re-circulated through the system, affording economical operation of the process. Evaluation of cooling tower performance is based on cooling of a specified quantity of water through a given range and to a specified temperature.

3.6 Electrostatic precipitator

The device removes dust or other finely divided particles from flue gases by charging the particles inductively with an electric field, then attracting them to highly charged collector plates. It has the ability to handle large volumes of gas, at elevated temperatures with a reasonably small pressure drop, and the removal of particles in the micrometer range.

3.7 Steam turbine generator

The turbine generator consists of a series of steam turbines interconnected to each other and a generator on a common shaft. There is a high pressure turbine at one end, followed by an intermediate pressure turbine, two low pressure turbines, and the generator. As steam moves through the system and loses pressure and thermal energy it expands in volume, requiring increasing diameter and longer blades at each succeeding stage to extract the remaining energy. The entire rotating mass is over 200 metric tons and 30 m long. It is so heavy that it must be kept turning slowly even when shut down (at 3 rpm) so that the shaft will not bow even slightly and become unbalanced. To minimize the frictional resistance to the rotation, the shaft has a number of bearings. The bearing shells, in which the shaft rotates, are lined with a low friction material like Babbitt metal [7]. Oil lubrication is provided to further reduce the friction between shaft and bearing surface and to limit the heat generated.

3.7 Transformers

A transformer is a device that transfers electrical energy from one circuit to another through inductively coupled conductors—the transformer's coils. A varying current in the first or primary winding creates a varying magnetic flux in the transformer's core and thus a varying magnetic field through the secondary winding. This varying magnetic field induces a varying electromotive force (EMF), or "voltage", in the secondary winding. This effect is called inductive coupling [5].

In an ideal transformer, the induced voltage in the secondary winding (Vs) is in proportion to the primary voltage (Vp), and is given by the ratio of the number of turns in the secondary (Ns) to the number of turns in the primary (Np) as follows:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

By appropriate selection of the ratio of turns, a transformer thus enables an alternating current (AC) voltage to be "stepped up" by making Ns greater than Np, or "stepped down" by making Ns less than Np.

Transformers are essential for high-voltage electric power transmission, which makes long-distance transmission economically practical.

4. Performance problems of power plant

The performance of a power plant can be expressed through some common performance factors as: heat rate (energy efficiency), thermal efficiency, capacity factor, load factor, economic efficiency and operational efficiency [5].

4.1 Heat Rate (Energy Efficiency)

Overall thermal performance or energy efficiency for a power plant for a period can be defined as

$\varphi_{hr} = H / E$

where,

φ_{hr} = heat rate (Btu/kWh, kJ/kWh)

H = heat supplied to the power plant for a period (Btu, kJ)
E = energy output from the power plant in the period (kWh)

4.2 Thermal Efficiency

Thermal efficiency of a power plant can be expressed as

$\mu_{te} = (100)\ (3412.75) / \varphi$

where

μ_{te} = thermal efficiency (%)

4.3 Capacity Factor

The capacity factor for a power plant is the ratio between average load and rated load for a period of time and can be expressed as

$\mu_{cf} = (100)\ P_{al} / P_{rl}$

where

μ_{cf} = capacity factor (%)
P_{al} = average load for the power plant for a period (kW)
P_{rl} = rated capacity for the power plant (kW)

4.4 Plant Load Factor

Load factor for a power plant is the ratio between average load and peak load and can be expressed as

$\mu_{lf} = (100)\ P_{al} / P_{pl}$

where

μ_{lf} = load factor (%)
P_{pl} = peak load for the power plant in the period (kW)

4.5 Economic Efficiency

Economic efficiency is the ratio between production costs, including fuel, labor, materials and services, and energy output from the power plant for a period of time. Economic efficiency can be expressed as

$\varphi_{ee} = C / E$

where

φ_{ee} = economic efficiency (cents/kW, euro/kW, ...)
C = production costs for a period (cents, euro, ..)
E = energy output from the power plant in the period (kWh)

4.6 Operational Efficiency

Operational efficiency is the ratio of the total electricity produced by the plant during a period of time compared to the total potential electricity that could have been produced if the plant operated at 100 percent in the period.
Operational efficiency can be expressed as

$\mu_{oe} = (100)\, E / E_{100\%}$

where

μ_{eo} = operational efficiency (%)
E = energy output from the power plant in the period (kWh)
$E_{100\%}$ = potential energy output from the power plant operated at 100% in the period (kWh)

These performance indexes are affected by several plant components, whereby failure of a component will result in the performance indexes deviating from the desired results.

The technical problems areas encountered at the power plant are [5]:

- Poor condition of boiler pressure parts with high erosion, overheating, external corrosion, oxide deposits, weak headers and pressurized furnace etc.
- Poor water chemistry has affected the condition of boiler and turbine in many cases. The water treatment plant is often in a dilapidated condition.
- Poor performance of air pre-heaters due to blocked elements and high seal leakage
- Poor performance of the milling system resulting in high unburnt carbon, a result of lack of preventive or scheduled maintenance.
- Poor condition of Electrostatic Precipitators (ESPs) resulting in high emissions.
- Problems of high axial shift, vibrations and differential expansion in Turbine.
- Low vacuum in condenser due to dirty / plugged tubes, air ingress and tube leakages
- High vibrations in Boiler Feed Pumps and Condensate Pumps and passing of recirculation valves, resulting in low discharge
- High pressure heater not in service in most power plants, directly impacting the energy efficiency performance.
- Deficiencies in electrical systems including High HT and LT motor failures, poor condition of DC system, non-availability of Unit Auxiliary Transformer e.t.c
- Poor condition of Balance of Plant (BoP) resulting in under-utilization of capacities

5 On line remote condition monitoring management system

5.1 Online intelligent remote predictive maintenance system

The system provides early anomaly detection to identify an emergent equipment fault, state of degradation, or failure before it reaches plant break down level and is addressed immediately. The system uses a self-learning algorithm that creates a knowledge base of operational data of the plant. Each knowledge base consists of a set of clusters that characterize behavior at plant, system and component level for different operational states including transients. Learning is predominantly based on historical data but some systems can learn on the fly from real time data [8].
Condition based maintenance involves data collecting, analysis, trending, and using it to project equipment failures. Once the timing of equipment failure is known, action can be taken to prevent or delay failure. In this way, the reliability of the equipment can remain high. Process parameters (e.g. pressure, temperature, vibration, flow) and material samples (e.g. oil and air) are used to monitor conditions and give indications of plant equipment health, performance, integrity and provides information for scheduling timely correction action.

5.2 Targets and benefits of condition based maintenance

Condition based maintenance is a valuable addition to comprehensive, total plant maintenance program. It is a form of predictive maintenance as it seeks to reduce the number of unexpected failures and provide a more reliable scheduling tool for routine preventive maintenance tasks.

5.3 Benefits of condition based maintenance

The ability to predetermine the specific repair parts, tools and labor skills required provided the dramatic reduction in both repair time and costs. The ability to predict machine parts requirements and equipment failures as well as specific failure mode provided the means to reduce spare parts inventories. Rather than carrying repair parts in inventory, plants have sufficient lead-time to order repair or replacement parts as needed in many cases.

6. Condition monitoring technologies [9]

These technologies are used to handle problems such as misalignment, unbalance, deteriorating bearings, worn gears or couplings, lack of lubrication, oil deterioration or contamination, loose electrical connections, electrical shorting, or poor insulation. The significant economic benefits come from long term improvements in maintenance or operating practices. Operators need also to be trained observers, since that will provide the most complete and knowledgeable coverage of plant machinery. The mostly used diagnostic techniques include: vibration monitoring, acoustic analysis, motor analysis technique, thermography, process parameter monitoring etc.

6.1. Vibration monitoring

Vibration analysis detects repetitive motion of a surface on rotating or oscillating machines. The repetitive motion may be caused by unbalance, misalignment, resonance, electrical effects, rolling element bearing faults, or many other problems. The various vibration frequencies in a rotating machine are directly related to the geometry and the operating speed of the machine. By knowing the relationship between the frequencies and the types of defects, vibration analysts can determine the cause and severity of faults or problem conditions. The history of the machine and the previous degradation pattern is important in determining the current and future operating condition of the machine [9]. Thermography also detects any overheating of bearings due to insufficient lubrication, misalignment, and other causes.

Table 1. Vibration and Oil Analysis Correlation

Equipment Condition	Oil Analysis	Vibration Analysis	Correlation
Oil lubricated anti-friction bearings	Strength	Strength	Oil analysis can detect an infant failure condition. Vibration analysis provides late failure information
Oil lubricated journal/ thrust bearings	Strength	Mixed	Wear debris will generate in the oil prior to a rub or looseness condition
Unbalance	N/A	Strength	Vibration analysis can detect unbalance. Oil analysis will eventually detect the effect of increased bearing load
Water in oil	Strength	N/A	Oil analysis can detect water in oil. Vibration analysis is unlikely to detect this.
Greased bearings	Mixed	Strength	Some labs do not have adequate experience with grease analysis. Vibration analysis can detect greasing problems.
Greased motor operated valves	Mixed	Weak	It can be difficult to obtain a good grease sample and some labs do not have adequate experience with grease analysis. Vibration data is difficult to obtain when the valves are operating.
Shaft cracks	N/A	Strength	Vibration analysis is very effective in diagnosing a cracked shaft.
Gear wear	Strength	N/A	Oil analysis can determine inadequate lubrication.
Alignment	N/A	Strength	Vibration analysis can detect resonance. Oil analysis will eventually see the effect.

There are five characteristics of rotating machine vibration are frequency, displacement, velocity, acceleration and phase angle.

6.2. Thermography

This measures absolute temperatures of key equipment parts or areas being monitored. Abnormal temperatures indicate developing problems. Temperature and thermal behavior of plant components are the most critical factors in the maintenance of plant equipment. Contact methods of temperature measurement using thermometers and thermocouples are still commonly used for many applications [8]. Non-contact measurement uses infrared sensors.

6.3 Lubricant analysis

Lubricant reduces friction, heat, and wear when introduced as a film between solid surfaces. The secondary functions of a lubricant are to remove contaminants and protect the solid surfaces. The oil analysis is a very effective tool for providing early warning of potential equipment problems. The goals of oil monitoring and analysis are to ensure that the bearings are being properly lubricated. This occurs by monitoring the condition of both the lubricant and the internal surfaces that come in contact with the lubricant.

The outside laboratories produce a very comprehensive report, in a very short turn-around time, and at a modest cost. Lube oil sampling intervals should be based on operating history, operating time, oil condition, etc.

As lubricant and machine conditions degrade, the physical properties of the oil and wear/contaminant levels will change [6]. By monitoring and trending these changes over time, and establishing useful limits for acceptable operation, lubricant and equipment problems can be quickly identified and resolved. A key element in determining the root cause of oil-related problems, is the ability to classify the types of wear and contaminants present (both chemical and particulate) and their potential source(s). This requires an understanding of chemical properties of the lubricants being used, the metallurgy of the internal components within the bearing reservoir, and the sources of contamination that can enter the system.

Table 2: Correlation of lubricant and wear particle analysis with other technologies

Technology	Correlative method	Indication	When used
Vibration	Time sequence	Wear particle build up precedes significant vibration increase in most instances.	Routinely (monthly)
Thermal analysis	Time coincident	With major wear particle production (near end of bearing life) occurs as the bearings fail.	When bearing degradation is a problem.

6.4 Acoustic analysis

This is the testing of generation, transmission, reception and effects of sound. It is air-borne sound that can manifest itself as a signal on mechanical objects, the pressure waves associated with leaking vapors or gasses, or the humming of electrical equipment. Acoustics technology includes frequencies as low as 2 Hz and as high as the mega-Hertz range [6]. Acoustic work can be performed in either the non-contact or in the contact mode. In either case, it involves the analysis of wave shapes and signal patterns, and the intensity of the signals that can indicate severity.

Because acoustic monitors can filter background noise, they are more sensitive to small leaks than the human ear, and can detect low-level abnormal noises earlier than conventional techniques. They can also be used to identify the exact location of an anomaly. They provide a digital indication of the sound intensity level and can locate the source of the sound. If it is necessary to know the wave shape and the frequency content of the signal, a more sophisticated portable waveform analyzer type is needed. When it is necessary to monitor critical equipment on a continuous basis, the sensors are permanently attached to the equipment and the signals are transmitted to an on-line acoustic monitoring system.

Most machines emit consistent sound patterns under normal operating conditions. These sonic signatures can be defined and recognized; and changes in these signatures can be identified as components begin to wear or deteriorate. This enables technicians to identify and locate bearing deterioration, compressed air or hydraulic fluid leaks, vacuum leaks, steam trap leaks and tank leaks.

Evaluation of long term ultrasonic analysis trends can identify poor maintenance practices such as improper bearing installation or lubrication, poor steam trap maintenance, and improper hydraulic seal or gasket installation. Long term ultrasonic analysis can also identify machines that are being operated beyond their original design limitations, inadequately designed machines, or consistently poor quality replacement parts.

Table 3: Correlation of leak detection with other technologies.

Technology	Correlation method	Indication	When used
Thermal analysis	Time coincident	Abnormal temperature coincident with acoustic signals indicating leak of fluid	On condition of suspected leak especially in systems with many potential leak points.
Non-intrusive flow	Time coincident	Flow downstream of shut valve giving acoustic indication of internal leakage	On condition of suspected leak and many choices of valves to open for repair
Visual inspection	Time sequence	Visual indication of valve disks or seal damage sufficient to cause internal leakage.	Use for confirmation before valve disassemble. Use after removal for correlation between acoustic signal and visual observed degree of leak causing damage

6.5 Motor analysis techniques

Monitoring electric motor condition involves determining the extent of electrical insulation deterioration and failure. Traditional insulation tests have concentrated on the ground wall, with a common test being insulation resistance. Less attention is paid to turn-to turn or phase-to-phase insulation, yet there is evidence that deterioration of this thin film is also a major cause of motor failures [7].

7. Research Design

In this study several key variables are considered to determine the relevance of installing a condition based maintenance system at ThermPower plant. Key plant performance measures, including heat rate (energy efficiency), thermal efficiency, capacity factor, load factor, economic efficiency and operational efficiency are looked at. They are dependent on the performance of plant equipment, which are: grinders, boilers, water treatment plant, turbine, generators, etc. which are all monitored by this condition based maintenance system study.

8. ThermPower plant analysis

8.1 Problems at each unit of the plant

Preventive maintenance which is done at a predetermined time period is the most common; that is to say it is a time depend maintenance strategy which is carried out weekly, monthly, yearly, etc. Corrective maintenance is maintenance which is used when an unplanned failure occurs, sometimes it is intentional whereby the component works at a run to fail basis. It is a costly approach to maintenance whereby resources will have to be scrambled to tackle the unforeseen failure which can occur at the most inopportune of times. Condition based is used is only for the turbine at ThermPower plant, whereby most of its parameters are monitored and when they go beyond the set limits it will automatically trip. The power plant currently uses vibration monitoring technology in condition based maintenance.

The plant also uses a maintenance management system (MMS) to monitor its maintenance work, recording failures, planned outages, forced outages and reasons for those failures and outages.

Table 4: Problems at ThermPower plant: UNIT – 1

No.	Equipment	Problem
1	Turbine	Turbine Axial thrust running high
2	Milling plant	Poor performance of mills. Mills have completed long running hours and are overdue hauling.
3	Spray water by-pass valves	Spray-water by-pass valves are passing badly disturbing the control of Boil parameters.
4	Burner management system	Burner availability is very poor & more time is taken for starting the unit.
5	Feed regulation station	Heavy passing through the feed regulating values of A & B lines.
6	UPS(uninterruptible power supply)	UPS Backup supply is not available due to following problems: 24V Battery chargers require serving/ repair of cards. 110V AC UPS needs replacement. 220V AC UPS for DCS needs to be refurbished.
7	O measurement system	O Analyzers are not in service; hence excess air cannot be assessed for proper fuel combustion.
8	Pyrometer Hoses	Most of the hoses are leaking.
9	Seal Oil Pump	Standby Seal oil Pump is not available
10	Generator Transformers	Winding Temperature is running high
11	Condenser	Fouling of condenser tubes resulting in drop in vacuum.

Table 5: Problems at ThermPower plant: UNIT – 2

1	Turbine	Turbine end thrust & shaft position is running high.
2	Milling Plant	Poor performance of mills, mills have completed long running hours & are overdue for overhauling.
3	Air-heaters	There is excessive Air-heater leakage.
4	Feed regulation station	Heavy passing through the feed regulating valves of A & B lines.
5	Condensate Extraction Pump	There is no standby condensate extraction pump.
6	Spray-water by-pass valves	Spray water by-pass valves are passing badly disturbing the control of boiler parameters
7	Burner management system	Burner availability is very poor
8	UPS	UPS Backup supply is not available due to following problems: 24V Battery Chargers require servicing/repair of cards 110V A.C needs replacement 220V AC UPS for DCS needs to be refurbished
9	O Analyzers are not in service; hence excess air cannot be assessed for proper fuel combustion.	New O Analyzers are to be installed.
10	Pyrometer Hoses	Most of the hoses are leaking compromising the cooling
11	Excitation System	The system is old and unreliable
12	Soot Blowers	Partially available and balance to be made available
13	ID Fans	ID Fans impellers are eroded
14	Condenser	Fouling of condenser tubes resulting in drop in vacuum

Table 6: Problems at ThermPower plant: UNIT – 3

1	Turbine	Turbine end thrust & shaft position is running high
2	Milling Plant	Poor performance of mills, mills have completed long running hours & are overdue for overhauling.
3	Spray-water by-pass valves	Spray water by-pass valves are passing badly disturbing the control of boiler parameters
4	Feed regulation station	Heavy passing through the feed regulating valves of A & B lines.
5	BFP	Standby BFP is not available
6	Burner management System	Burner availability is very poor
7	UPS	UPS Backup supply is not available due to following problems: 24V Battery Chargers require servicing/repair of cards 110V A.C needs replacement 220V AC UPS for DCS needs to be refurbished
8	O measurement system	O Analyzers are not in service; hence excess air cannot be assessed for proper fuel combustion.
9	Pyrometer Hoses	Most of the hoses are leaking compromising the cooling
10	380V Switchgear	Switchgear Boards for 380V is giving frequent problems
11	Generator Transformer	Winding Temperature is running high
12	Oil Purifier	Not working satisfactorily
13	Group Drains Actuators	No Spares
14	Condenser	Fouling of condenser tubes resulting in drop in vacuum

Table 7: Problems at ThermPower plant: UNIT – 4

1	Turbine	Turbine end thrust & shaft position is running high
2	Milling Plant	Poor performance of mills, mills have completed long running hours & are overdue for overhauling.
3	Feed regulation station	Heavy passing through the feed regulating valves of A & B lines.
4	UPS	UPS Backup supply is not available due to following problems: 24V Battery Chargers require servicing/repair of cards 110V A.C needs replacement 220V AC UPS for DCS needs to be refurbished
5	O measurement system	O Analyzers are not in service; hence excess air cannot be assessed for proper fuel combustion.
6	Excitation system	The system is old and unreliable.
7	380V Switchgear	Switchgear Boards for 380V is giving frequent problems
8	Soot Blowers	Partially available and balance to be made available
9	Oil Purifier	Not working satisfactorily
10	ID Fans	ID Fans impellers are eroded
11	Burner management System	Burner availability is very poor
12	Condenser	Fouling of condenser tubes resulting in drop in vacuum

Table 8: Problems at ThermPower plant: UNIT – 5

1	Air heater Baskets	Air-heater Baskets are badly worn
2	Soot Blowers	Partially available. Not fully in operation thus decreasing the boiler efficiency.
3	ID Fans	ID Fans impellers are eroded
4	ID Fan Motor	No spare ID Fan motor is available and one motor is giving frequent problems
5	HP/LP Heaters	HP/LP heaters are not charged due to non-availability of: Actuators & Group Protection Sempell valves
6	Electro Hydraulic Controller	The existing system is old & unreliable
7	BFP 5B	Couplings are required to be procured
8	Burner management System	Burner availability is very poor
9	Economizer tubes	Unit has frequent economizer tube leaks
10	Electrostatic Precipitators	Not working properly
11	Gland steam vapor exhauster	No standby Gland steam vapor exhauster
12	UPS	UPS Backup supply is not available due to following problems: 24V Battery Chargers require servicing/repair of cards 110V A.C needs replacement 220V AC UPS for DCS needs to be refurbished

Table 9: Problems at ThermPower plant: UNIT – 6

1	Air heater Baskets	Air-heater Baskets are badly worn
2	Soot Blowers	Partially available. Not fully in operation thus decreasing the boiler efficiency.
3	ID Fans	ID Fans impellers are eroded
4	Economizer tubes	Unit has frequent economizer tube leaks
5	Burner management System	Burner availability is very poor
6	Electro Hydraulic Controller	The existing system is old & unreliable
7	CW Pump-7	Erosion on bell mouth
8	HP/LP Heaters	HP/LP heaters are not charged due to non-availability of: Actuators & Group Protection Sempell valves
9	Electrostatic Precipitators	Not working properly
10	Condenser	Fouling of condenser tubes resulting in drop in vacuum
11	BFP 6A	Coupling between Motor & Booster pump is damaged
12	UPS	UPS Backup supply is not available due to following problems: 24V Battery Chargers require servicing/repair of cards 110V A.C needs replacement 220V AC UPS for DCS needs to be refurbished

Table 10: Problems at ThermPower plant: UNIT – 7

1	Battery chargers	Old & Unreliable
2	Air compressor system	Out of three instrument air compressors, one is out of service and both the station air compressors are not working properly
3	Hydrogen plant	The station Hydrogen plant is not working
4	Coal Plant control system	The plant is running without any interlocks and safety systems posing great risk to the supply of coal to running units
5	Coal conveyor belt	Conveyors 2,8,10 & 13 are badly worn out & need to be replaced
6	ADS system in the coal Plant	Not working causing dusty atmosphere in the coal plant which is very harmful to the operators and the equipment
7	Ash slurry pumps in the Ash plants	Out of 9 ash slurry pumps, only 4 are working
8	Clinker Grinders in the Ash pump house	Out of 4 clinker Grinders, only 3 are working and the performance is not reliable
9	Ash handling sluiceway liners	Worn out
10	Ash handling sluiceway nozzles	Worn out
11	Ash Dam	The existing construction equipment is old & frequently breaks down
12	Water reservoir	Leakage in reservoirs
13	Water treatment	The plant is operating poorly and there is no monitoring system
14	Deka Pumping station	Pumps are unreliable & not giving full output. Settling tanks need repair. Cathodic protection not working. NRVs, Scour valves, Air releases valves, isolating valves need repair. Switch gear and instrumentation not working properly.
15	Chlorine plant	The plant is not in working condition due to which proper dozing is not carried out

8.2 ThermPower plant data analysis

8.2.1 Performance summary for 2008

Table 11: Operational summary year 2008

Measure	Target	Actual
Plant load factor %	36.89	23.42
Plant availability %	71.41	36.47
Thermal efficiency %	28.73	23.37
Planned outage rate %	20.72	33.94
Unplanned outage rate %	7.87	29.59
Coal consumption(tons)	N/A	1 005 729
Units Generated (GWH)	2972.97	1892.939

Definitions of the measures used:

Plant load factor: The value of the current average plant generating capacity (KWH)/ the theoretical value of the plant generating capacity.
Plant availability: The measure of the time at which the plant is able to generate electricity for a certain period of time.
Thermal efficiency: The ratio between the generated electricity (KWH)/ the energy inputted into the system (KJ).
Planned Outages rate: The number of outages under management control (for repairs or other reasons) per period of time.

Unplanned Outages: The number of outages which are not under management control due to component failure per period of time.

Table 12 below shows the major generation losses that occurred at ThermPower plant in the year 2008.

Table 12: Major Losses 2008

Fault	Generation Loss (GWH)	Revenue Lost (USD) Mill
Unit 6 ID fan high vibrations	235.43	30.61
Unit 6 Primary fan high vibrations	204.25	26.55
Unit 5 furnace tubes blocked	136.28	17.72
Unit 2 generator transformer temperatures running high	36.61	4.76
Boiler tube leaks	241.51	31.40
Unit 1 awaiting major overhaul	401.28	52.17
Unit 5 unavailability of gearbox oil pump	385.86	50.16
Total	**1641.22**	**213.37**

Note: 1KWH costs $0.13, assuming a domestic rate
Revenue lost: Generation loss (GWH) x cost per KWH

- ✓ It is evident that poor water treatment plant monitoring in the years prior as stated in the general performance problems document above, led to Boiler tubes fouling and corrosion with a final result of rapture and the same can be said for the following years.
- ✓ High ID Fan vibrations we mainly due to bearing failure due to wearing and in addition to that it were due to dirt building up on the impellers due to poor quality feed water which was fed into the boilers.
- ✓ The milling plant oil pump was unavailable due to motor failure and blocked oil filter.

8.2.2 Performance summary for 2009

Table 13: Operational summary Year 2009

Measure	Target	Actual
Plant load factor %	46.51	22.98
Plant availability %	66.58	48.43
Thermal efficiency %	28.58	24.03
Planned outage rate %	25.54	36.36
Unplanned outage rate %	7.88	15.22
Coal consumption(tons)	N/A	1 009 033
Units Generated	3758.63	1851.609

Overall most performance measures were similar to the ones recorded in the year 2008 except for the increase in unplanned outages rate and higher plant availability. This information is further supported by nearly equal generation losses in the 2years.

Table 14: Major losses 2009

Faults	Generation Loss(GWH)	Revenue Lost (USD) Mill
Unit 6 Primary Air fan failure	832.65	108.25
Unit 5 ID fan high vibrations	384.63	50.00
Turbine failure	229.82	29.88
Excitation system problems	104.97	13.65
Boiler tube leaks	235.45	30.61
Boiler feed pump failure	50.80	6.61
Flame failure	44.32	5.76
Total	**1882.64**	**244.76**

- ✓ High ID fan vibrations continued due to the same reasons discussed earlier.
- ✓ Turbine failure was due to worn out bearings.
- ✓ Boiler feed pump failure due to motor failure.

8.2.3 Performance summary for 2010

Table 15: Operational summary year 2010

Measure	Target	Actual
Plant load factor %	49.17	35.81
Plant availability %	87.03	53.38
Thermal efficiency %	28.51	28.79
Planned outage rate %	9.97	12.43
Unplanned outage rate %	3.00	34.19
Coal consumption(tons)	N/A	1 376 986
Units Generated(GWH)	3973.378	2885.691

A noticeable improvement in most of the performance measures, but the unplanned outage rate still high.

Faults	*Generation loss (GWH)*	*Revenue Lost (USD) Mill*
LH ID fan vibrations	90.63	11.78
Turbine shaft misalignment	91.85	11.94
Excitation problems	115.77	15.05
Boiler feed pump problems	120.25	15.63
Boiler tube leaks	147.94	19.23
Turbine control valves fluctuating	474.23	61.65
Turbine thrust bearing worn out	583.75	75.89
System disturbances	153.13	19.91
Total	**1777.55**	**231.08**

- ✓ Tube leaks continue due to fouling and corrosion which ultimately led to rapture.
- ✓ Boiler feed pumps failures continue due to motor failure.
- ✓ Turbine thrust bearings issues continued
- ✓ Turbine control valves fluctuating due to corrosion, results of poor feed water quality

8.2.4 Performance summary for year 2011

Improvement of the plant availability and load factor but the thermal efficiency dipped. A decrease in the rate of unplanned outages is also noticeable.

Table 17: Operational summary 2011

Measure	Target	Actual
Plant load factor %	52.00	46.60
Plant availability %	80.00	68.83
Thermal efficiency %	26.00	24.80
Planned outage rate %	9.72	8.14
Unplanned outage rate %	10.33	23.03
Coal consumption(tons)	N/A	1 586 951
Units generated (GWH)	4005	3755.215

Table 18: Major Losses 2011

Faults	Generation Loss(GWH)	Revenue Lost (USD)Mill
Excessive furnace pressure	20.34	2.65
Milling plant oil pump failure	54.21	7.05
ID fans vibrating and motor failure	218.11	28.36
Boiler tube leaks	287.00	37.31
Turbine shaft misalignment	123.65	16.08
Excitation problems	79.69	10.36
Turbine control valves fluctuating	405.00	52.65
System disturbance	161.57	21.00
Boiler front on fire	51.26	6.66
Total	**1400.83**	**182.12**

- ✓ Turbine worn out bearings led to turbine shaft misalignment, further proof of the cascading effect of failures.
- ✓ Continuation of ID fan high vibrations due to worn out bearings and dirt building up on the impellers.
- ✓ Turbine control valves issues due to them being corroded and fatigued springs.

8.2.5 Weighted Average Annual Operational Summary for the Years (2008-2011)

Table 19: Average Annual Operational Summary (2008-11)

Measure	Target	Actual
Weighted average Plant load factor %(**PLF**)	48.27	38.62
Weighted average Plant availability %(**PAF**)	77.90	55.86
Weighted average Thermal efficiency %	27.67	25.66
Weighted average Planned outage rate%(**PO**)	14.85	19.06
Weighted average Unplanned outage rate %(**UO**)	7.27	25.08
Average coal consumption(tons)	N/A	1 244 674.75
Weighted average Generated Units (GWH)	3830.72	3021.52

The table above gives consolidated information of how the power plant has performed over the years, in actual essence it's an average of the performance measure recorded since 2008-11.

8.2.6 Calculations

Table 22: Weighting factors

Year	Weighting factor
2008	0.10
2009	0.25
2010	0.30
2011	0.35

Weighted Average Plant load factor %: ∑ Weighted Annual plant load factors

Weighted Average Plant availability %: ∑ Weighted Annual Plant availability

Weighted Average thermal efficiency %: ∑ Weighted Annual thermal efficiency

Weighted Average Planned outage rate %: ∑ Weighted Annual planned outage rate

Weighted Average Unplanned outage rate %: ∑Weighted Annual unplanned outage rate

8.3 Trend analysis

8.3.1 Plant load factor

Performance measures for 2008 to 2011-12 shows that the plant load factor has significantly improved since 2008 but it is not comparable to what other thermal power stations across the world are achieving; at least 80% whilst over the 4 years the plant has only registered a highest plant load factor of 46.6%. Thermal efficiency has improved over the years but not by a sizeable change and this can also be improved from an average of 25.66% to world comparable figures of at least 75% [5]. It can be noted that the rate of unplanned outages is on the high as compared to planned outages.

8.3.2 Generation losses

Generation losses are attributable to Turbine and ID Fan related issues. The main cause of turbine failure was due to worn out bearings which eventually lead to shaft misalignment and high vibrations. A similar scenario can be said for ID fans whereby worn out bearings and dirt building up on the impellers resulted in high vibrations. Boiler tube leaks have also been a major performance problem over the years. The tubes failing due to fouling and corrosion, this mainly caused by poor water treatment. Poor quality feed water has also resulted in dirt building on the turbine rotors hence the excessive vibrations that were experienced, noticeable from the worn out turbine bearings. This gives a clear picture of the cascading effect of failures, whereby poor condition monitoring practiced in 2008 trigged a chain of poor performance issues in the years that followed.

8.4 Failure modes

When equipment failure occurs, it is important that the cause of the problem be correctly identified so that proper corrective steps can be taken to prevent a recurrence. An incorrect diagnosis of a failure can lead to improper corrective measures. If failure cause is not clear, considerable investigation is required to uncover the cause. Below are the main failures and failure modes that have been experienced at ThermPower plant.

8.4.1 Milling plant oil pump failure

The pump fails mainly due to extraterrestrial objects in the oil resulting in the oil filter blocked leading to pump failure. The foreign objects can be due to dirty oil being fed into the oil system, particles breaking from the meshing gears of the millers and other deposits from corrosion. Pump failure is associated with the driving motor overheating.

8.4.2 Boiler feed pump failure

Boiler feed pumps fail due to eroded impellers, electric motor failure, worn out bearings, check valve failure etc. At ThermPower plant after looking at the general performance information it is evident that poor water treatment and monitoring has contributed to some of the pump failure. The impellers and check valves are eroded due to corrosive minerals in the water. Failure of check valves has led to back flow of the super-hot condensate from the boiler thereby causing cavitation. Bearings have been worn out due to contaminated oil or lubrication. The worn out bearings have led to the motor over heating resulting in motor failure.

8.4.3 Boiler tube leaks

Boiler tubes fail due to overheating, failure due to corrosion and several other reasons.

When tube failures occur due to overheating, a careful examination of the failed tube section reveals whether the failure is due to rapid escalation in tube wall temperature or a long-term, gradual buildup of deposit. When conditions cause a rapid elevation in metal temperature to 1600°F or above, plastic flow conditions are reached and a violent rupture occurs. Ruptures characterized by thin, sharp edges are identified as "thin-lipped" bursts. Violent bursts of the thin-lipped variety occur when water circulation in the tube is interrupted by blockage or by circulation failure caused by low water levels. Thin-lipped bursts occur in superheater tubes when steam flow is insufficient, when deposits restrict flow, or when tubes are blocked by water due to a rapid firing rate during boiler start-up.

8.4.4 Turbine related failures

Turbine thrust bearing worn out: This is caused by contaminated oil or lubrication, when stepping up or down the turbine it has to be done gradually in stages and if it is done instantaneous it results in wear of the meshing teeth thereby contaminating the oil. It will also result in the bearing being exposed to thermal loadings leading to failure. The same can be said when the turbine is being cooled, if it is done instantaneously the bearing will experience thermal loadings due to rapid cooling.

8.4.5 ID Fan vibrations

High fan vibrations is attributable to accumulation of dirt on blades, corrosion of blades, lubrication failure, excessively high temperature working environment and bearing looseness. The dirt building up can be due to poor dust and ash removal by the precipitator. The composition of the flue gases; fly ash concentration, ash particle and its chemical composition also cause corrosion of the blades. Excessively high flue gases temperature can also cause lubrication failure which will result in bearing failure. Lubrication or oil contamination also leads to bearing failure leading to high vibrations being experienced by the Fan. The high temperatures also have effects on the ID fan operational performance.

9. Potential improved plant performance

Financial benefits of condition monitoring system results due to the increase in generated units and lower maintenance costs since maintenance work will be planned in advance thereby allocation of resources is done in a manner which minimizes cost. The value of the “reduced maintenance cost” is the annual value of the average cost of maintenance that was experienced at ThermPower plant due to the unplanned generation losses.

Table 23: Financial benefits accrued

Benefit(Annual)	**US Dollars(Mill)**
Increase in Revenue	182.7
Reduction in maintenance cost	0.147
Total	**182.847**

Table 24 is a summary of the improved key performance indicators as a result of implementing online remote condition monitoring system.

Table 24: Improved performance for ThermPower plant

Measure	**Plant Target**	**Project Target**	**Current**	**Improved**
Plant capacity factor(CF) %	48.27	68.27	38.62	70.37
Reduction in failures %	N/A	70	N/A	76.67
Unplanned outages rate (UPOR)%	7.27	7.27	25.08	5.85
Reduction in plant down time(PDT)	N/A	65	N/A	76.67
Plant availability (PA)%	77.90	85	55.86	98.67
Reduction in Generation Losses	N/A	75	N/A	83.87
Thermal efficiency %	27.67	30	25.66	30.59

In summary ThermPower plants tends to benefit from both plant operational efficiencies and financial viability as it will realize an increase in annual revenue of USD$182.8 Million, a payback period of less than a year and an internal rate of return of 34.89% on implementation of this system and related software.

10. Research recommendations

The current system can be enhanced through use of clustering technology which gives it the ability to recognize patterns or failure modes that lead to component failure as well as enabling to estimate the life expectancy of the component. In addition to its ability to give early anomaly detection, the equipment also helps engineers in both diagnostics and planning for maintenance work; when it is most opportune to perform maintenance work and what might be causing that particular failure. Furthermore it will also increase personnel safety since some failures if not detected result in fatal accidents. Operator based maintenance to be initiated throughout the plant to avoid deterioration of simple failure causes. Table 25 gives a summary of the major component failures causing generation losses at ThermPower plant and the technology used to monitor such components and how it monitors it.

Table 25: Summary component failures

Failure		**Monitoring Technique**	**Monitored parameter**
Boiler tube leaks		Acoustic	Sound signal pattern and frequency of leak
		Thermography	Thermal distribution(Hot spots detection)
Turbine failure	**Bearings**	Thermography, Vibration monitoring	Thermal distribution (Hot spots detection) & turbine vibrations.
		Tribology (supporting information)	Oil quality
	Shaft misalignment	Vibration proximity probe	Shaft position
	Eroded rotors	Vibration monitoring	Rotor vibration rates
ID Fan		Thermography & Vibration monitoring	Bearing thermal distribution & fan vibrations
		Tribology (supporting information)	Oil quality
FD Fan	**Bearings**	Thermography & vibration monitoring Tribology	Bearing thermal distribution & fan vibrations. Oil quality
	Eroded impellers	Vibration analysis	Fan vibrations
Mill Oil Pump		Thermography, vibrational analysis & tribology	Motor temperature Motor & Pump vibrations, Oil quality
Boiler Feed Pump & check valves		Thermography, vibrational, acoustic analysis & tribology	Motor Temperature Motor & Pump vibrations, Oil quality

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Recommended condition monitoring sensors for thermography, vibration, and acoustics as shown by the Figure 5 below. It represents how data is relayed from the sensors to the system which processes it to information (detecting impending failures) reported to engineers who use the information for scheduling maintenance.

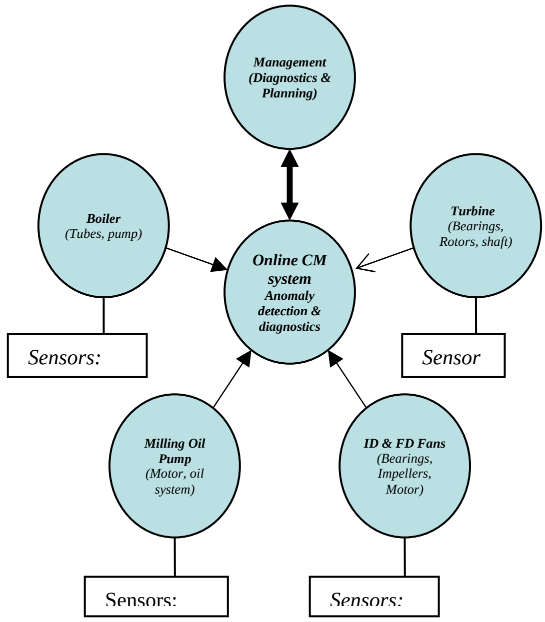

Figure 5: Recommended sensor system

11. Conclusion

Online remote condition monitoring system goes a long way into improving system efficiencies at ThermPower plant. From the research it can be concluded that the system has the ability to detect impending failures before they occur resulting in reduction of generation losses by 84%. The unique pattern recognition analysis that uses self-learning algorithm that creates a knowledge base of plant operational data which is critical to planning of work schedules.

Application of this system is a positive step towards attaining world class standards at PowerTherm plant since it enables the plant to have performance levels that are comparable to those of world class standards. Implementation of the system will result in increased plant capacity, reliability and availability for ThermPower.

12. Further research

Current practice is that maintenance is regularly scheduled for effectiveness. The demand on plant efficiencies, calls for predictive maintenance as well as on line condition monitoring maintenance. This is driven by Cleaner Production [5] which seeks to operate sustainably and save finite resources with minimum pollution to the environment. In this line, it is recommended to research further on lubrication analysis as a tool for condition monitoring tool as shown by this research that most failures cited are caused by deterioration of the lubricating fluids on mating component surfaces [6].

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