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Predictions of Vacuum Pump Degradation By Condition Monitoring and Improving Performance

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Abstract: *Condition Monitoring is an area that has seen substantial growth in the last few decades. The purpose for implementing condition monitoring in thermal power plant is to decrease maintenance costs and increase safety of the equipment. Condition Monitoring identifies the issue of vacuum pump degradation in thermal power plant. The ability to identify the number of factors depend on the effect of vacuum pump degradation and predicts the Remaining-Useful-Life (RUL) of a vacuum pump and reduces the instances of unexpected pump failures, which can incur significant costs. Some typical causes of low vacuum levels, including: open valve in the vacuum line or header; plugged screens at the vacuum pump inlet; low seal water flow, number of leakages in system includes valve gland, manholes, pump gland, LP turbine gland seal ring, LPT rapture disk, cooling water flow, temperature and pressure at the vacuum system are discussed this paper.Condition Monitoring is applied to the rotor blades of pump degradation using pump operating parameters as inputs and techniques prediction method is employed to estimate the Remaining-Useful-Life (RUL) of the pump. This paper investigates the causes of cavitation. Potential solutions for installations with cavitation issues are discussed but some of these can be very expensive and disruptive. Condition monitoring carried out so that cavitation and the downstream impact on maintenance and repair costs can be avoided. This paper will increase awareness of the cavitation issue and offer some solutions for vacuum pump.*
Keyword: *Cavitation, condition monitoring, performance, degradation, vacuum, leakages.*

I. Introduction

Vacuum systems have been used in the power thermal power plant for over 100 years.[1] The typical configuration of the sub-critical 300MW unit vacuum system is often equipped with one low pressure turbine cylinders, one condenser and two 100% capacity water-ring vacuum pumps. Today, vacuum equipment, such as water ring vacuum pumps systems, is used in all types of power plants.[2] The running method of the water ring vacuum pumps is one pump runs with one standby mode.[3] The water-ring vacuum pump is usually designed to meet the demands of start-up and shut-off conditions, which will bring about a large margin of the vacuum pump output, and unnecessary power consumption. Now a days more renewable power is available in India, power plants that previously ran at full load now turn down their generation capability to provide only enough power to "fill in the cracks" on the power grid. At reduced load, the turbine main condenser will operate at a lower pressure than it did at full load. Since turbine condensers operate at the saturation temperature, the lower operating pressure means the vapor pressure of the water ring will be closer to the saturation temperature at the operating pressure. As the ambient temperature increases, the risk of the vacuum pumps rotor damages will also increase, which will lower the reliability of the unit. This is a recipe for vacuum systems in 'unhealthy' condition. But also results in significant reduce heat rate of plant, which can be a major expense. Furthermore, a vacuum pump failure results in unplanned maintenance of a pump which is significantly more expensive than planned maintenance in terms of resources, planning and manpower.The condition monitoring is considered in based diagnostic scheme to detect mechanical inefficiency and several issues of vacuum pump in a system. In this paper, the condition monitoring is used to reform, diagnosis, recommendations and improve the vacuum system.

II. Performance problem formulation

The performance of a power plant is expressed by some common performance factors as: heat rate, thermal efficiency, economic efficiency and operational efficiency. These performance indices are affected by several plant components, whereby failure of a component will result in the performance indices deviating from the desired results. The performance problems encountered at the low vacuum: poor performance of condenser or vacuum pump in thermal power plant were,

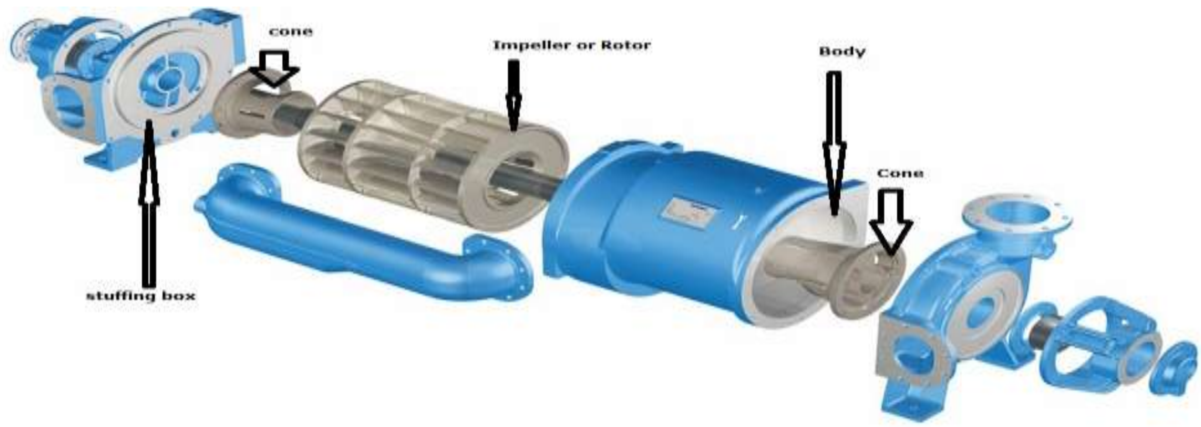

Fig.1 Vacuum pump cross section view

2.1 Due to leakage in gland packing.
2.2 Rotor blades with high erosion, cavitation, external corrosion etc.
2.3 Poor water chemistry has affected the condition of heat exchangers performance.
2.4 Low flow of sealing water of recirculation pump and cooling water system resulting maintaining in higher temperature of sealing water.
2.5 Low vacuum in condenser due to dirty / plugged tubes, air ingress and tube leakages.
2.6 High vibrations in vacuum pumps resulting in cavitation.During its lifetime, a vacuum pump is exposed to large quantities of often non condensable gases. In some cases, the higher temperature gases used may reduce the expected lifetime of the pump. This non condensable gas is highly corrosive, higher temperature in hotwell and in large quantities, can lead to an increased rate of degradation of pump components, resulting in the gradual loss of vacuum performance. Eventually, this loss of performance results in the sealing water exceeding temperature limits and the possibility of irreparable damage to rotor blades. This paper focuses on a means to identify of vacuum pump degradation from analysis of pump operating parameters and having identified the vacuum pump performance, provide a means to estimate the Remaining-Useful-Life (RUL) of the pump As analyzed above, it can be seen that the vacuum pumps of the condenser is affected by the ambient temperature, determined by the steam saturation temperature and pressure corresponding to the sealed cooling water flow and temperature. It is known that the ambient temperature is higher in summer than in winter, which will bring about cavitation phenomenon, resulting in decreasing the unit economy, increasing pump vibrations, and decreasing the reliability.

III. Condition Monitoring

Condition monitoring is an area that has seen substantial growth in the last few decades. As a simple definition, condition monitoring is an approach which can be used to gain information on the “health” of components or systems. Condition monitoring includes not only fault detection and fault diagnosis, but also fault analysis. The purpose for implementing condition monitoring in thermal power plant is to decrease maintenance costs, enhanced safety of equipment, reliability and the knowledge gained through continuous assessment of critical plant components. Therefore, condition monitoring can be used not only for planning maintenance, but also for allowing the selection of the most efficient equipment to minimize operating costs. The final goal of a successful condition monitoring scheme is to detect the presence of faults before a catastrophic event or unscheduled shutdown occurs. Condition monitoring provides information about the likely future performance, which is most suitable when the failure mode is gradual and progressive. The condition monitoring techniques as applied to vacuum pump is a significant technical challenge. In the degradation of a vacuum pump rotor to excessive loss of vacuum performance is addressed. To develop a means to identify, track and predict the rate of pump degradation. 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 condition monitoring system can be acquired through. The ability to identify and predict the loss of vacuum performance will allow for pump maintenance at convenient times, resulting in less downtime and loss of heat rate. Checking of pump performance by slowly shut off the inlet side of pneumatic and gate valve of the vacuum pump. Some vacuum pumps are able to sustain complete shut off condition but then a system may leak or vacuum pump is not producing enough capacity to sustain your system at a sufficient vacuum level. Check system for leaks and adopt methods to inspect and/or test the capacity of vacuum pump. If the pump is not able to achieve high vacuum check the following points and rectify:-

3.1 Low seal water flow rate

The seal water pressure gauge and seal water flow meter provide the data of flow of Seal water into the vacuum pump. However, the flow rate of seal water required at vacuum pump inlet is 15 – 17 cubic meter per hour. High seal water flow reduces efficiency by taking up space that would otherwise be used by air and increases horse power. Less seal water flow can cause a large temperature to rise in the pump. The higher temperature rises if accompanied by vacuum and hot seal water supply can reduce the pump performance and may result in internal damage of the pump. Therefore, it is important to determine the water flow to the pump as it is the essential parameter as far as the performance of the pump is considered.

Fig. 2 Sealing water spray nozzle and replacement of gland sealing line valve.

The seal water flow can be varied by increasing or decreasing size of orifice installed in the seal water line. During inspection, Orifice Size in Spray Nozzle line was found 14 mm and Orifice Size in seal water line was found 16 mm. Install the flow meter so that the exact seal water parameters can be monitored.

3.2 Calibration of pressure gauges and temperature gauges

The correct readings by all the gauges help in recording the exact performance parameters of the vacuum pump system. Hence, calibrate all the gauges installed in the vacuum pump system. Check the details of instruments missing/damaged or not functioning correctly and to replace/rectify the same.

Fig. 3 Pressure gauges

3.3 Air ingress during shut- off head.

While taking the shut-Off trial of the vacuum pump air- ingress was observed while taking the reading through rotameter. Higher air- ingress results in deteriorated vacuum pump performance and in turn affects the vacuum pump holding capacity. The various reasons for air- ingress are as below: Air-ingress through Stuffing Box due to long operation of the vacuum pump. This results in damage of the gland packing and may cause scoring on the shaft if prevails for longer duration. Air–ingress through body drive end (DE) and non drive end (NDE) ends because of the damage in the O-rings / body gaskets. Air ingress may also be possible through the flanges because of the damage of the gaskets with due course of time. Importance of checking rotameter leakages during holding operation of vacuum pump with System: The capacity of the pump is 20 SCFM; i.e. the pump is designed to handle 20 SCFM of air at design point; beyond this, the pump performance will get affected.

Fig. 4 Air ingress in rotameter during shut off head

The vacuum pump efficiency can be improved by improving shut-off vacuum i.e. by avoiding the air ingress in the vacuum pump package, maintaining Seal water temperature and setting correct clearances between the vacuum pump internals. There are many factors which influence the vacuum being maintained by the pump and with the diagnostics during overhauling, Best practices are recommended which might also save costs related to power consumption, DM water consumption.

Table no 1-Suction pressure measured during inspection

UNIT	VACUUM PUMP	DESIGN OF SUCTION PRESSURE	DESIGN COOLING WATER TEMPERATURE	SEALING WATER FLOW IN m^3/hr	SUCTION PRESSURE MEASURED DURING INSPECTION
1	1A	690 mmHg	$33\ ^0$ c	15	650 mmHg
	1B				660 mmHg
2	2A				725 mmHg
	2B				655 mmHg

Fig.5 Suction pressure measured during shutoff head

3.4 Heat exchangers performance

Heat exchanger serves the purpose of maintaining the seal water temperature which is crucial for efficient and effective working of vacuum pump. Chocking in heat exchangers would lead to slower flow of cooling water thus the heat exchange rate would be affected, which would eventually lead to the higher seal water temperature. Generally, the standard seal water temperature to vacuum pump inlet should below 36 ^oC. High temperature of seal water can cause distortion of water, decrease the compression of the process inlet and increase the operating temperature. Hot seal water temperature 43°C to 49°C and higher - also causes reduced vacuum pump capacity. This in turn can cause cavitations and damage the pump rotor permanently.

Table 2 comparison of vacuum pump sealing water temperature measured with shell and tube type cooler & plate type heat exchanger.

Vacuum pump sealing water temperature					
Vacuum pump	**ACW inlet temperature in** °C	**shell and tube type cooler**		**Plate type heat exchanger**	
		Before cooler °C	**After cooler** °C	**Before cooler** °C	**After cooler** °C
2A	33.64	53	47.6	53	47.1
	30.91	49	44	53	47.1
2B	30.97	48	43.2	41.3	31.3
	29.3	46	41.6	43	31

Fig. 6 Replacements of existing shell and tube cooler by plate type heat exchanger

3.5 Gland packing leakages

The leakage from gland packing is for sealing and maintaining the healthiness of the gland packing by maintaining proper moisture to it. If the healthiness of the gland packing is maintained, it ensures no air ingress and also increases the life of the rotor shaft. In case of no water leakage from the gland, the packing will heat up and get and will also lead to rubbing marks on the shaft. If operated for longer in this condition, it can damage the rotor shaft and also affect the performance of pump due to air ingress.

Fig.7 Wear Gland packing replaced by one gland packing

In case of more flow, there will be loss of seal water and the gland packing will also get damaged, resulting in damage to the rotor shaft; eventually damaging the pump. So inspection must be carried out from time to time to inspect and correct the flow of seal water from the gland packing i.e. 60-80 drops per minute.

3.6 Overflow and pump vent line

The main purpose of the non return valve (NRV) in the overflow line is to prevent back flow of water or air inside the separator. Hence, install the same in the over-flow line in order to maintain the level in the separator.

Fig.8 Non return valve (NRV) installation required Overflow line

3.7 Separator tank level

The level in the separator tank of the vacuum pump is higher than the recommended. The recommended level for normal level should be 15 cm and low-level switch be at 9 cm. Also inspect make-up solenoid valve and by-pass manual valve for all vacuum pump system for any passing to check it and valve replaced. High water level in separator tank can cause:

3.7.1 High Motor Power Consumption due to overload due to flooded pump
3.7.2 Affects the Vacuum level due to back pressure inside the separator tank.
3.7.3 Loss of demineralized water.

3.7.4 High vibration level-excessive loading - motor is overloaded by excessive load from rubbing pump components due to flooded pump.

Fig. 9 Normal water levels in separator tank

It is observed that vacuum pump in separator tank continuously overflow during pump running condition. 3.5 m^3/day demineralized water overflow in tank due to pump take non condensable gas with saturated steam from condenser. It reduces the performance of pump.

3.8 Abnormal sound or high vibration during operation

Bearing failure – abnormal sound is coming from the motor and pump during operation probably indicates a bearing failure. Rotate the system or motor by hand and listen carefully to determine if abnormal sound is coming from bearings. Replace bearings and/or motor as necessary.

3.8.1 Pump Cavitations – If the noise is coming from the pump during operation and the vacuum level is relatively lower. The pump will vibrate and sound as if it has marbles inside. Check the pump performance curve and make sure the pump is not running above the maximum or minimum rated vacuum level. You may also bleed air into the system to reduce the vacuum level. If the noise is eliminated at lower vacuum levels it is most likely due to cavitation. Run the pump at a vacuum level that does not create cavitation, try reducing the seal water temperature maintain 33 ^oC.

3.8.2 Drive System vibration/noise – vibration are created due to drive system is improperly aligned (direct drive). Adjust alignment as necessary to eliminate the problem.

Rotating components improperly balanced or damaged – the rotating components of the pump (rotor, shaft, gear coupling etc.) or the system are not properly balanced or damaged.

3.8.3 Recirculation pump

In water ring vacuum pumps, significantly reduced seal water flow can result in lower pump capacity. Vacuum pumps require 1.3 - 1.5 bar seal water pressure at a point measured upstream of an orifice. However, a plugged orifice may not let the proper seal water flow pass, even when the correct pressure is indicated. Remember that pressure does not indicate flow. The recirculation pump of the standby vacuum pump is always operating. It should operate only when the stand-by pump is in operation.

Fig. 10 Recirculation pump in vacuum system

IV. Diagonosis And Recommendations

According to the baroscopic inspection, operational parameters recorded, and other operational checks carried out at site, the diagnostics along with recommendations are mentioned as below:

4.1 Boroscope inspection

From the inspection point of view, the first stage rotor's inner blades and buckets show heavy damage due to cavitations. The baroscopic inspection clearly indicates severe damage to the rotor and thus the pump requires replacement of the same in order to avoid any sudden breakdown. Also, the overhauling of the pump required and during overhauling as any reused / repaired part may result in faulty operations. Regular and Planned overhauling will help with cost management and improve efficiency of vacuum pump. Timely and correct overhauling practice can help reducing downtime and reduce consumption of vacuum pump. Overhaul pump to avoid any sudden breakdown and rotor needs replacement.

4.2 Cavitation failure analysis

Cavitation in a water ring vacuum pump is caused when the operating pressure of the water ring reaches the vapor pressure of that water. This causes some of the water to become vapor, forming bubbles that travel around with the water ring. As these bubbles travel inside the pump they collapse, or implode, and can break off pieces of the pump rotor blades. These pieces travel with the water ring and cause further damage through erosion. Cavitation is a function of both temperature and pressure.The lower the operating temperature of the water ring, the lower the potential for cavitations. However, if the operating pressure of the pump is close to the vapor pressure of the ring water at the operating temperature, cavitations can still occur.

Fig.11 Boroscope inspections of second stage and first stage of Vacuum pump rotor.

In cavitations prone operations, like condenser vacuum pump duty, it is a good idea to periodically record the temperature of the seal water supply and discharge. Increase in temperature can indicate the need for a checkup, and trending them over time will allow to schedule preventative maintenance before reliability is affected.

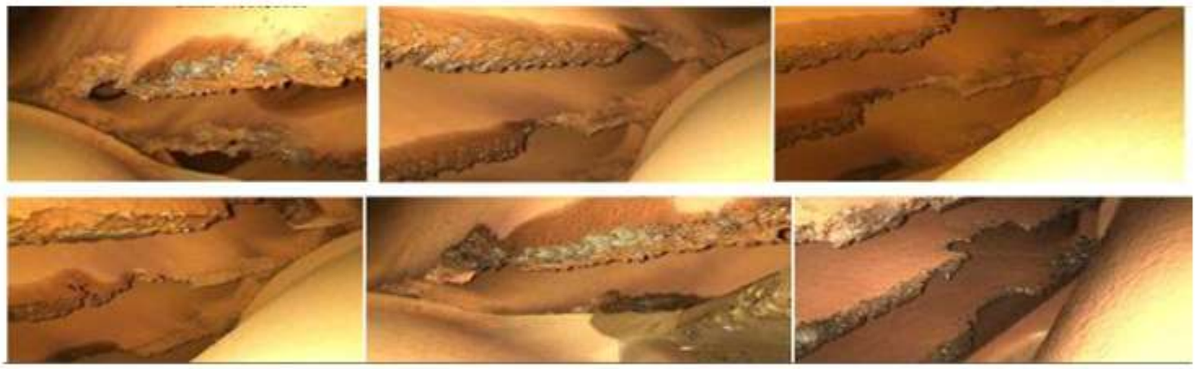

Fig. 12 Damages in Inner blades of vacuum pump rotor due to cavitations.

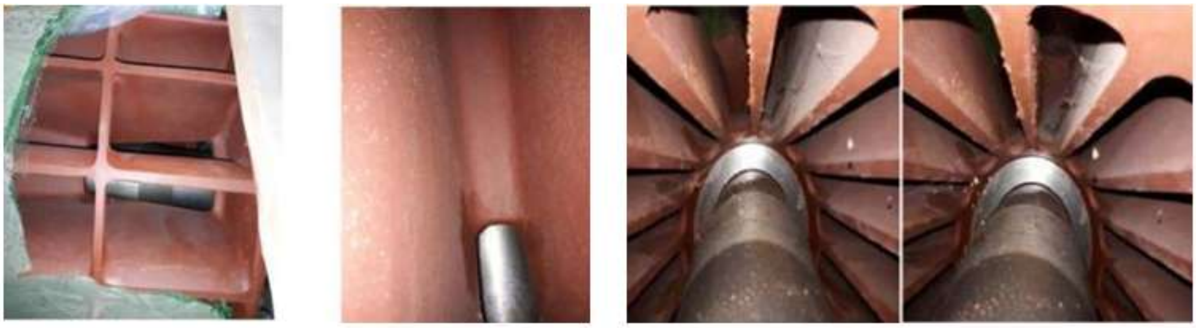

Fig.13 New rotor blades of vacuum pump

Probable Causes of Cavitations are:

4.2.1 Incorrect seal water flow rate.
4.2.2 Operation of seal water is above its vapor pressure
4.2.3 Seal Water saturated with minute gas bubbles under pressure.
4.2.4 Unsuitable PH value of seal water.
4.2.5 Clearance wide on pumps operating at high vacuum levels.

Since the clearances between the vacuum pump internals play an important role in the performance of the vacuum pump, it is critical to follow and observe correct practices recommended by OEM to set the tolerances. Therefore, to avoid major breakdown costs at a later stage and to enhance the life and performance of vacuum pump.

4.3 System checks point to improve the performance of Vacuum

Table.3 Instrument air connected to the control panel having following pressure.

Unit #1	**Pressure (kg/cm^2)**	**Unit #2**	**Pressure (kg/cm^2)**
Pump A	3.0	Pump A	3.0
Pump B	3.5	Pump B	4.5

As per the observation, the instrument pressure as per the pressure gauge is less than 4 kg/cm^2 only; Whereas the required air pressure to ascertain the proper operation of the air operated solenoid valve is 4 to 8 kg/cm^2 . Low instrument air pressure can delay the operation of opening the inlet butterfly valve. Checking the air filter regulator and clean it, adjust pressure.

Fig.14 suction pressure of pneumatic valves air for vacuum pumps

The recommended instrument air pressure to operate Pneumatic Butterfly Valve should be 4 to 8 Kg/cm2 required.
4.3.1 Check the direction of Rotation and free rotation of all Vacuum pumps and Seal Water Pump Motor.
4.3.2 Check in all the instruments installed are healthy in operational.
4.3.3. Carryout the flushing/draining of the vacuum pumps.
4.3.4. No Gland leakage should be observed from the gland packing stuffing box in any of the pumps.
4.3.5. The installation points of high and low-level switches at the separator tank are checked. The high and low-level switches are installed at a position 18 cm and 8cm respectively in level indicator.

Fig. 15 Position of level switches on level indicator

4.3.6. Check the pump bearings (DE/NDE) for lubrication and it was found that there was excess amount of grease filling in the bearings to remove.

Fig. 16 Vacuum pumps bearing excess lubrication

4.3.7. Check the working of Butterfly valve installed at the top of separator tank and it was found OK.

Fig. 17 Manual butterfly valve on separator tank

4.3.8. Check the operation of the Pneumatic Butterfly Valves for all 04No's of vacuum pumps and found OK.

Fig. 18 Suction butterfly valve

4.3.9. Check and clean seal water line strainers of all pumps.

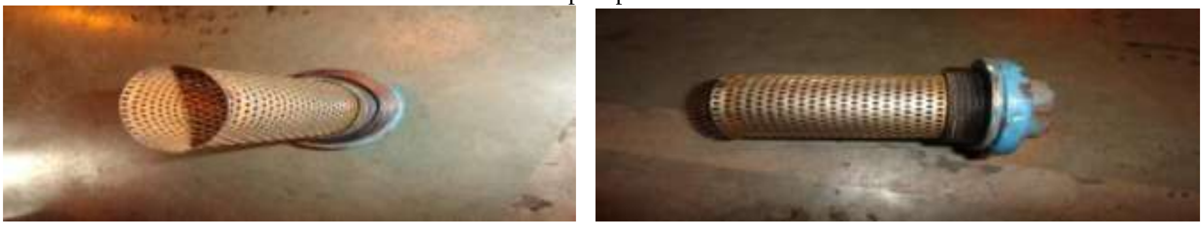

Fig.19 Recirculation pump of suction strainer.

4.3.10. Seal water flow meter is not installed in any vacuum pump system.
4.3.11 Check inter stage non return valve (NRV) and it is found OK.

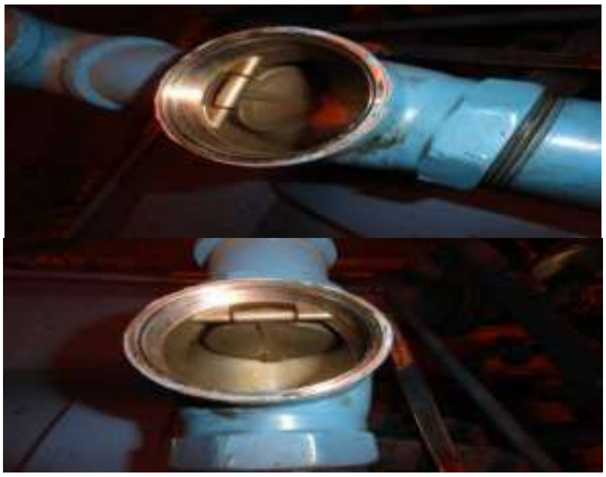

Fig. 20 Inter stage NRV condition

4.3.12. Check suction line non return valve (NRV) and the installation position is found Ok. However in two non return valve (NRV) O-ring found missing and same is replaced with the new one.

Fig. 21 Suction NRV without "o" ring and suction NRV with "o" ring.

4.3.13. Overflow non return valve (NRV) is not installed in any pump and this non return valve (NRV) is used for preventing back flow of air ingress in system.

Fig. 22 Recommendations for NRV installation overflow loop NRV missing

4.3.14. Check spray make up line and it is found wrong erected, frequently choking of strainer.

Fig. 23 Recommendations for makeup line modification.

Y-type strainers can be used to remove large particles. However, periodic inspection will be needed to insure that the strainer is not clogged. On systems without a recirculation pump installed, a y-type strainer should only be used on the make-up water line to filter out any particles. If it were to become clogged on the seal water line, then it would starve the pump of seal water and could cause damage. If the process is dirty, then a strainer ahead of the vacuum pump system should be installed.

V. Results and discussion

Plant operation and maintenance engineers should adhere to issues related vacuum system and understand the operation parameters as a low vacuum levels including: passing suction valve in the vacuum line or header; plugged screens at the vacuum pump inlet; low seal water flow, number of leakages in system includes valve gland, manholes, pump gland, LP turbine gland seal ring, LPT rapture disk, cooling water flow, temperature and pressure at the vacuum system. The observation was based on a poor operating parameters approaches in use at the power plant were cited as main causes. A step-by-step procedure, adopted in troubleshooting vacuum pump and condenser system helps in easily locating the problem and in finding appropriate solution. In general, the first step is to compare the original design conditions with the existing conditions. Any change in operational parameters including utilities may have a direct impact on the performance of the unit. Once it is ascertained that external and internal factors are responsible for performance of vacuum system, trouble shooting of equipment should be done. Keep mandatory as well as recommended spares in stock because of the fact that the vacuum pumps are very critical mechanical devices and the efficiency of the whole power plant depends on the efficiency of the condenser which in turn depends on the performance of the vacuum pumps. As aware of the fact that during condition monitoring the impeller rotor of both Vacuum pumps were found damaged and require overhauling, any sudden or immediate damage to the pump can stall the operation of the unit due to non-availability of spares at site. Since the clearances are critical in the Vacuum pump, fabricated, machined or worn out spares parts would not ensure proper clearances and as a result would affect the vacuum maintained by the pump. These can even cause popping/Cavitation. OEM has designed certain spares with MOC most suitable for specific application for e.g. spares like gaskets and gland packing ensures no air ingress/leakages and plays an important role in the vacuum pump maintaining desired vacuum and life of rotor shaft assembly. If suitable MOC and dimension are not used; it reduces life cycle and increases overall maintenance cost over a period of time. Since the Clearances between the Vacuum Pump internals play an important role in the performance of the Vacuum pump, it is critical to follow and observe correct practices recommended by OEM to set the tolerances. Therefore, to avoid major breakdown costs at a later stage, to enhance the life and performance of vacuum pump.

Table 4 vacuum pump compared parameter such as condenser vacuum, sealing water temperature, hotwell temperature, suction temperature of pump, motor current etc.

Date and Time	LOAD in MW	COND VACUUM in bar	U#2 Abs Vacuum Pressure trans in bar	Sealing water temperature in ^{O}C		HOTWELL TEMP ^{O}C	suction temperature in ^{O}C		Motor current in Ampere	
				VACUUM PUMP A	VACUUM PUMP B		VACUUM PUMP A	VACUUM PUMP B	VACUUM PUMP A	VACUUM PUMP B
	With vacuum pump 2B ON									
10-Feb-18 09:00:00	310.63	-0.8766	78.04	29.90	43.60	46.54	33.59	44.19	0.00	141.10
10-Feb-18 10:00:00	310.75	-0.8773	78.02	29.85	43.58	46.56	31.73	44.18	0.00	140.99
10-Feb-18 11:00:00	310.60	-0.8791	77.19	29.77	43.41	46.32	30.68	43.87	0.00	140.65
10-Feb-18 12:00:00	310.54	-0.8774	77.92	30.02	43.65	46.51	30.41	44.18	0.00	140.86
Avg 2B	310.63	-0.8776	77.79	29.89	43.56	46.49	31.60	44.11	0.00	140.90
	With vacuum pump 2A ON									
11-Feb-18 09:00:00	309.99	-0.8894	72.34	30.23	29.86	44.17	42.56	34.44	151.63	0.00
11-Feb-18 10:00:00	309.92	-0.8896	72.43	30.40	29.93	44.25	42.65	32.49	150.40	0.00
11-Feb-18 11:00:00	310.00	-0.8883	73.09	30.79	30.26	44.51	42.93	31.72	149.50	0.00
11-Feb-18 12:00:00	310.03	-0.8834	74.81	31.62	30.93	45.26	43.72	31.51	148.84	0.00
Avg 2A	309.99	-0.8877	73.17	30.76	30.24	44.54	42.96	32.54	150.09	0.00
Diff between 2A&2B(Avg 2B - Avg 2A)	0.64	0.0101	4.63	-0.87	13.32	1.94	-11.36	11.56	-9.19	

Table 5 shows condenser vacuum pump energy saving impact.

Condenser vacuum					
Parameters	**Unit**	**Design value**	**Deviation**	**Heat rate (Kcal/Kwh)**	**Monetary Impact (Rs/day)**
Condenser vacuum	Kg/cm^2	-0.8713	0.01 kg/cm^2	13	82000

VI. Conclusion

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 thermal power plant due to the unplanned generation losses. In this paper presented a method to both, identify the high ampere, poor vacuum and higher sealing water temperature in vacuum pump degradation, and to estimate the Remaining-Useful-Life (RUL) of a vacuum pump. The identify solution has the potential to reduce the instances of unexpected pump failures caused by pump degradation. This could help reduce pump maintenance costs, but also, the costs associated with heat rate of plant, following an unexpected pump failure. It is reasonable for the vacuum system reform mentioned in this paper. After the vacuum system reform, the vacuum of the condenser will be increased higher, with coal consumption reduced, and power consumption decreased, through which energy consumption of the power plant reduces and coal emission cuts. Meanwhile, it will avoid the vacuum pumps cavitation, which improves the reliability of equipment and unit operation.

Conflict of interest: The authors declare that there is no conflict of interests regarding the publication of this paper.

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