Condition-based Maintenance by in-service Oil Analysis

Case Study at *The Navigator Company*

João Maria Brissos e Silva
joao.maria.brissos.e.silva@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

January 2021

ABSTRACT

In the current global economy, where the smallest detail influences a company's competitiveness, maintenance plays an essential role. Growing competition and higher complexity of the equipment, demands for more efficient maintenance in order to increase the availability of their production equipment, safely and with reduced costs.

Out of the several maintenance strategies, this master's thesis focuses on preventive maintenance of the condition-based maintenance type, particularly the one performed by in-service Oil Analysis.

For factual support of this thesis, it was considered the application of the method to a steam turbine, an integral part of a turbo-generator in operation at *The Navigator Company* - Complexo Industrial da Figueira da Foz, with emphasis on the condition monitoring of the turbine main bearings, and respective control data obtained from due in-service lubricating oil analysis.

Aiming at establishing two proposals for due sampling process method improvement, the following information was considered: the pertinent functionality of the equipment under study, its existing maintenance plan, data from the current in-service oil analysis and respective corrective actions applied.

At the end of the work, two possible solutions involving the uniformity of sampling frequencies and amplification of the present lubrication system's set of sampling points, were believed to bring advantages in improving the information extracted from the in-service oil analysis, allowing for a more efficient monitoring of the turbine main bearings.

Keywords

Maintenance, Oil Analysis, Lubrication System, Steam Turbine, Turbine Main Bearings;

1. INTRODUCTION

Nowadays, an industry not meeting with the high standards of demand has no place in the competitive framework of the global economy. *The Navigator Company* has, in this respect, a great importance in the international pulp and paper market, particularly in regard to its Figueira da Foz Industrial Complex. Here, *The Navigator Company* has opted for a process of cogeneration of energy from forest biomass, ensuring the production of electrical energy and guaranteeing its independence from the regular electrical energy suppliers.

It is in this context that the turbine emerges as a vital element of the economy of the industrial process in question. In case of its inoperability, the industrial unit is unable to dispose of the electrical energy necessary for its production.

In this sense, it should be noted that, in the search for better results and greater efficiencies, the turbines have been subjected to increasingly severe conditions, operating at higher temperatures and pressures, with smaller reservoirs of lubricating oil also resulting in increasingly extreme service conditions for this lubricant [1]. Thus, the monitoring of the in service oil condition proves to be fundamental for preservation of both oil's useful life and turbine's operational performance [2].

All this being said, this dissertation focuses mainly on Condition-based Maintenance, a concept based in monitoring the actual status of the equipment in service, aiming to maximize its availability by means of a in-service Oil Analysis technique applied to the condition control of a steam turbine in an industrial environment, whose failures in lubricated parts are, in most cases, related with oil, or its additives, degradation, or associated with oil contamination (either by wear particles or by external agents) [3]. Worthy of note, the success of an oil analysis program involves the early identification and location of the potential cause of failure, aiming at its neutralization.

2. LITERATURE REVIEW

2.1. Turbine Oil Lubrication Systems

The basic object of this work is a steam turbine, centered on its rotor shaft, supported on plain bearings, with a forced lubrication system, at high pressure, by a hydraulic oil pump.

In the high power segment, at high speeds, the forced circulation lubrication systems are the most used, namely in the steam turbine. They consist of a main reservoir, from which the oil is pumped to the components to be lubricated. They are also properly equipped with filters, coolers and other devices to guarantee the system's durability, and maintain the physical and chemical properties of the lubricating oil.

Although the bearings normally work under hydrodynamic lubrication, it happens that many of the forced stops of industrial turbines are due to lubrication problems, especially in their plain bearings [4]. As such, it is essential to ensure, for a continuous production of energy, an effective monitoring of the lubrication of the turbine, and its bearings.

2.2. Common Problems in Steam Turbine Oils

With regard to the prevention of the most common problems in steam turbine oils that can lead to their inoperability, it is then considered the following signs of the most occurring problems, and their causes:

- Oxidation of the oil - since it is put into service, the lubricating oil is subject to a continuous and inevitable degradation by oxidation. In steam turbines, the oil is continuously in contact with oxygen, reacting with it, generating acidic compounds. The effect is aggravated by the increase in temperature and with the presence of water in the oil, leading to a faster consumption of antioxidant additives and so, to the destructive oxidation of the oil, with drastic effects on the quality of its lubrication.

The excessive oxidation of the oil can also result in products such as "sludge" and "varnishes" in the lubricated components which, in the case of bearings, can lead to an excessive increase in its temperature, putting at risk its surface integrity.

- Water contamination - the presence of water, inevitable in the humid environment of a steam turbine, will always act as a catalyst for the oxidation of the oil, as well as depleting it, over time, of some of its additives. Furthermore, water promotes the metallic corrosion of the components, promoting the acceleration of the abrasive wear of their surfaces, by formation of ferrous oxides [4], a fact aggravated by the removal of corrosion inhibitor additives, which are water soluble.

- Foam formation and Air presence - Another inevitability in lubrication systems is the formation of foam by air-oil mixture [1]. Its effect is pointed out as one of the main problems in the industry, related with the difficulty of air release from the oil, namely in the case of steam turbines: reduction of oil film thickness at the lubrication points; aggravation of the oil oxidation rate by the air-oil contact surface increase; risk of cavitation, with its perverse effects of wear out on the pump and bearings.

- Particle contamination - the presence of insoluble particles in suspension in the oil may promote its oxidation, lower water demulsibility, and depletion of additives, also contributing to the abrasive wear of lubricated surfaces. In case of metal particles they may indicate a primary lubricant anomaly alarm, so being extremely important to know the level of oil contamination for planning condition-based maintenance, or for proactive analysis of failure root identification.

2.3. Condition-based Analyses in Steam Turbines

Condition-based Control by in service Oil Analysis of steam turbines allows to predict its functional failure, with an enormous positive impact on the profitability of an energy producing industry. It is carried out by means of standardized laboratory procedures that allow information to be collected on the real state of the oil condition, and thus evaluate the trend of various parameters over time and, if necessary, take corrective actions.

This type of analysis evaluates not only the physical and chemical properties of lubricating fluids, but also their additives. Considering the most common failure modes of steam turbines, the corresponding oil analysis package for this equipment's condition-based maintenance is as presented below:

- Viscosity – To measure, in general, the kinematic viscosity of oil at 40ºC, and at 100ºC. A change in lubricating oil viscosity may be due to oil oxidation or particle contamination, which may impair the hydrodynamic lubricating film;

- Total Acid Number (TAN) - The oil's acidity level is measured to control its oxidation state. Normally, an increase in acidity indicates an increase in the oxidation level of the oil;

- Fourier Transform Infrared (FTIR) - Involving the absorption of infrared energy at specific frequencies, the presence of several oil contaminants (namely, degradation by oxidation, or presence of water) is simultaneously monitored;

- Rotating Pressure Vessel Oxidation Test (RPVOT) - To evaluate the stability of the oil to oxidation in the presence of water. It complements other methods of simple verification of the oxidation status, as an indicator of the remaining useful life of the oil;

- Remaining Useful Life Evaluation Routine (RULER) - Test to monitor the reserve concentration of hidden phenols and aromatic amines antioxidant agents still present in the oil, to control its remaining useful life, especially in the case of the oils Class II and III;

- Water by the Karl Fischer Method – To determine the concentration of total water (free, emulsified or dissolved) present in the oil;

- Membrane Patch Colorimetry (MPC) – Test to control the accumulation of insoluble products in the oil (namely, varnishes) by visualizing the appearance of the membrane after filtration;

- Corrosion Inhibition (Rust) - Test to assess the oil´s capability to prevent the occurrence of corrosion in the equipment it lubricates (usually in steel or copper alloy components);

- Demulsibility – Test to check for the ability of the oil to free itself from the water that has been incorporated into it;

- Foaming - To determine the tendency to foam development in the oil is determined, as well as its stability;

- Air Release - To check for the oil's ability to free itself from air bubbles that have been incorporated into it;

- Insoluble Particle Count / Analysis - To quantify the number of insoluble contaminant particles per volume of oil, being the concentration and distribution of particle quantities expressed by an appropriate "ISO cleanliness code" (ISO 4406 Standard).

- Wear Metals Analysis - The detection and characterization of wear particles allows the identification and localization of the lubricated components from which they originate. Among the various types of wear metals analysis, the following techniques of ferrography and elementary spectrometry techniques stand out:

- Analytical Ferrography - In each test the size, shape, texture and metallurgy of the ferrous and non-ferrous aggregated particles are checked in order to predict and locate a probable affected component and its failure mode.

- Elemental Spectrometry - By adequate atomic spectrometry, the respective spectrum is analyzed, per atomic element present in the oil, to reveal the presence of dissolved or suspended inorganic materials in it. This will identify the chemical nature of wear particles of constituent elements of additives and other types of contaminants, and also quantify their concentrations.

2.4. Sampling Strategies in Lubrication Oils

The sampling process is of fundamental importance in controlling the condition of the oil in service. Appropriate sampling procedures, namely free from any contamination during collection, allows that important information obtained from the oil, regarding the intended diagnosis, be statistically representative [1].

Two crucial factors to be considered when planning the sampling task are the sampling location and frequency, detailed below.

Sampling Location

The potential failure detection and its origin are achieved by installing oil access points in critical locations of the lubrication system - the "sampling points" - usually consisting of simple sampling valves, whose location should follow the following basic rules [3]:

- Turbulence - Turbulent oil flow areas are the best for sampling points;

- Sources of Contamination - Sampling points are also preferably located downstream of wear prone components, or close to contaminant entries, for enrichment of the sample as to the state of the equipment;

- Filtration - Filters, separators, or other purification components, remove contaminants from the oil and, therefore, removing vital information regarding the state of the equipment. So, samples should be taken upstream from those devices, unless the performance of any of them is in question, in which case it is necessary to have sampling points upstream and downstream of the same;

- Drain lines and return lines - in circulation systems it is in the drain lines, or in return lines, before filtering to the reservoir, where the best samples can be taken regarding solid contaminants, or wear of lubricated components.

Sampling Frequency

The success of an oil analysis program depends heavily on the sampling frequency. This is based on the operating time of the equipment, being made a schedule of sampling intervals for each machine or, even, for each component, and adjusting it to the type of equipment, its oil, and the environment in which it operates, taking into account [3]:

- The risks and consequences of a failure - considering not only the costs of repair and production downtime, but also, the safety of the operation;

- The equipment's useful life curve - in terms of the known "bathtub curve", with a very low overall failure rate in the "useful life" phase, and where most of its failures occur in the "infant mortality" phase, or when the equipment begins to approach its "wearout" phase at the end of its "useful life". Naturally, the sampling frequency should be higher when the "useful life" period is shorter;

- The service time of the oil - either new, or at the end of life, the oil will require a more frequent sampling. In case of "new" it may incidentally present some degree of contamination, or being misused in the particular application. At the end of life, the oil generally shows a visible degradation by continued oxidation, contamination, or additive depletion;

- Operating conditions - where factors such as load, speed, temperature or humidity adversely affect the reliability of the equipment-lubricant assembly, with notable consequences for the planning of lubricant sampling intervals.

3. CASE STUDY

3.1. Siemens Steam Turbine SST-800

The turbine considered in this work is a Siemens steam turbine model SST-800, manufactured by the German multinational, Siemens Power Generation, of very common application not only in power plants of paper industries, but also in the petrochemical, cement, or heavy manufacturing facilities. The turbine in question is a component of one of the turbo-generator groups of the *The Navigator Company* industrial complex, along with the electric generator, the condensation system and other instrumentation and control equipment.

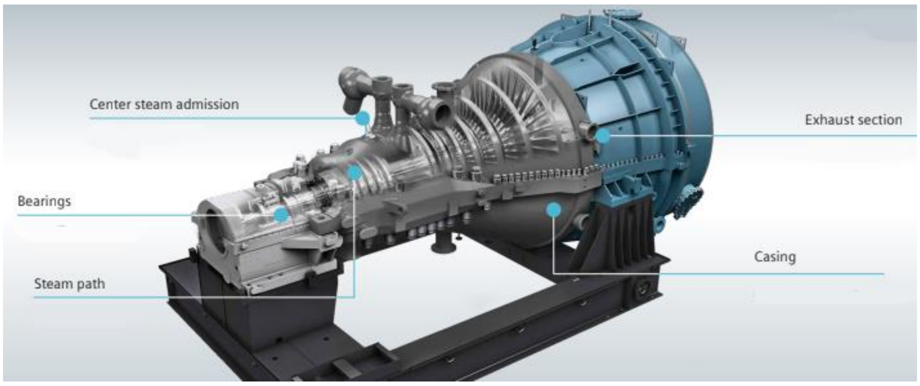

Figure 1: Siemens Steam Turbine SST-800 [5]

<u>Turbine's technical topics</u>

Year of Manufacture: 2010

Total weight: 143 336 kg

Maximum Power: 71 377 kW

Maximum speed in continuous service: 3000 rpm

Rotor weight: 25 190 kg

Oil Viscosity Grade required: ISO VG 46

The turbine rotor (shaft and its set of disks and blades) is a very important group of components of the steam turbine, whose risk of failure dramatically affects the turbine's main function: the conversion of thermal energy from steam into mechanical energy, and from this its conversion into electrical energy, in the driven electric generator. The rotor profiles itself as the "backbone" of the turbine, being imperative to guarantee its maximum availability, where, on this subject, is of utmost concern the condition control of the lubrication of its respective supports: one of simple radial constraint and another of both radial and axial constraints, both consisting of properly lubricated plain bearings.

3.2. Lubrication Oil System

The pressurized oil supply to the bearings is ensured by the main oil pump of the lubrication system, driven by the rotor shaft itself.

Although the operation of the bearings is maintained by constant lubricating oil circulation via the main pump, the overall availability of the system is guaranteed by means of a standby, redundant, auxiliary pump, which, in case of the main pump's failure, or when the oil pressure in the system drops by 25%, comes into service, then remaining in active parallel with the faulty main pump. Moreover, if both the previous pumps fail, a second redundancy takes place by means of a DC electric motor driven emergency oil pump. It is also worth mentioning the existence of another oil pump to lift the rotor, to provide an adequate hydrostatic lubrication during the start-stops phases of the turbine operation - Figure 8.

Within the list of oils approved by Siemens AG for turbine lubrication, it is applied to the SST-800 turbine on subject, the API Class II mineral oil Castrol Perfecto X46, viscosity class ISO VG 46, and supplied by BP Portugal.

3.3. Data Treatment

The data treatment of the various behavioral parameters of the oil in service serves to highlight the importance that oil monitoring has in extending the service life of the equipment, allowing the timely detection of potential causes of failure – condition-based maintenance – and, on the other hand, in unveil an opportunity for some improvement action in the oil or in the lubricated components - proactive maintenance - aiming at increasing the reliability of the equipment.

The here considered data were provided by *The Navigator Company*, the tests having been carried out by the oil supplier, BP Portugal, between 2015 and 2020, at its own laboratory operated in Gent, Belgium, and in another commercial laboratory located in Spain.

3.3.1. Sampling Frequencies

From the typical analyses for in-service oil condition-based control in steam turbines, there are ten of them carried out by the above mentioned laboratories, that it makes sense to divide them into three groups:

- Low Periodicity Analyses, for evaluation of the basic parameters indicating the condition state of the oil and its eventual contamination;

- Medium Periodicity Analyses, performed where there are some test parameters which may indicate either a possible oil deterioration, or a potential mechanical failure of any lubricated component;

- Special Analyses, performed as needed, only when the result of some evaluated parameter may seem to be a premonitory sign of some operational problem for the equipment;

Low Periodicity Analyses	Medium Periodicity Analyses	Special Analyses, performed as needed
• Viscosity @ 40 °C • Water by Karl Fischer Method • Total Acid Number (TAN) • Elemental Spectrometry (ICP), **only wear metals** • ISO Cleanliness Code (Particle Count Analysis) • Fourier Transform Infrared Spectrometric (FTIR – Oxidação)	• Membrane Patch Colorimetry (MPC) • Remaining Useful Life Evaluation Routine (RULER) • Analytical Ferrography • Elemental Spectrometry (ICP), **complete**	• Foam Tendency and Stability (Seq. I)

Table 1: Steam Turbine Oil Analyses Package Division

Tables 1 and 2 summarize the group division and the general advisable frequencies of the various types of in-service oil analyses, usually applicable to steam turbines.

Analysis	Standard	Recommended Frequency
Viscosity @ 40 °C	ASTM D445 ASTM 7279	Monthly or Quarterly maximum
ISO Cleanliness Code (Particle Count Analysis)	ISO 4406	Monthly or Quarterly maximum
Total Acid Number (TAN)	ASTM D974 ASTM D664	Monthly or Quarterly maximum
Water by Karl Fischer Method	ASTM D6304 ASTM D1744	Monthly or Quarterly maximum
Membrane Patch Colorimetry (MPC)	ASTM D7843	Quarterly or Annually maximum
Fourier Transform Infrared Spectrometric (FTIR – Oxidation)	ASTM E2412 ASTM D7414	Monthly, Quarterly or Annually depending on the criticality of the application
Foam Tendency and Stability (Seq. I)	ASTM D892	Annually or only if necessary
Remaining Useful Life Evaluation Routine (RULER)	ASTM D6971	Quarterly or Annually maximum
Elemental Spectrometry (ICP)	ASTM D5185	Monthly or Quarterly maximum
Analytical Ferrography	ASTM D7690	Annually

Table 2: Advisable Frequencies for Steam Turbine Oil Analyses

In general, in practically all the analyses performed on the turbine oil here in consideration, the samples were collected in a regular way and within the advisable frequency. In a few cases the recommended frequency was exceeded, but they were neither significantly expressive nor recurrent.

The only exception were the analyses of medium periodicity, namely the ICP Elementary Spectrometry, RULER test and MPC colorimetric analysis. In the first one, and taking into account that it is advisable, at most, a quarterly frequency for spectrometric analyses, it is observed through Figure 2 that this requirement could only be regularized from October 2019 onwards. This was only due to the need of doing some adjustments in the maintenance program for the use of industrial stoppages for sampling, and also to the fact that a previous spectrometric analysis (ICP) "only wear metals", had already been conducted.

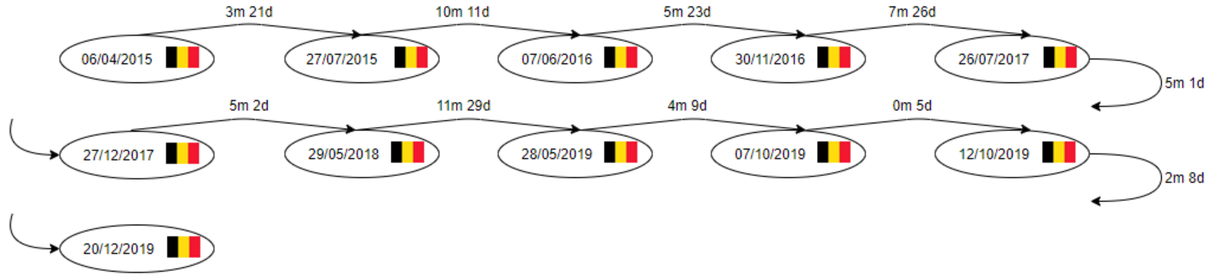

Figure 2 – Elemental Spectrometry (ICP) analysis frequency

Regarding MPC and RULER analyses - Figures 3 and 4 - they were conducted within the advisable limits - Table 2 - being, however, performed according to an uneven sampling frequency.

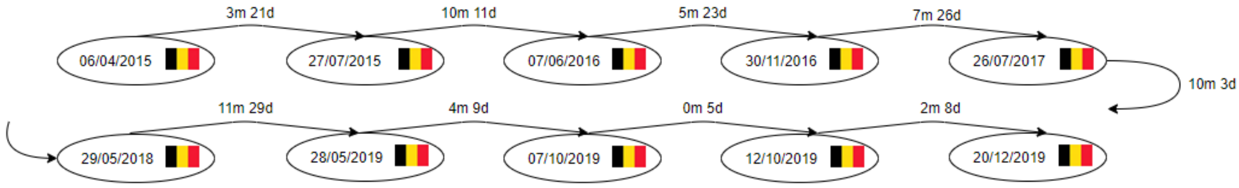

Figure 3 – MPC analysis frequency

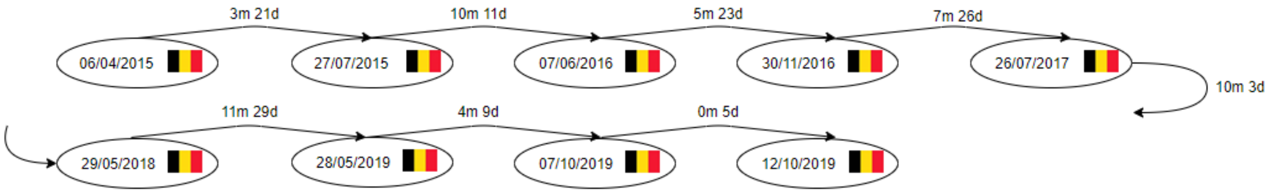

Figure 4 – RULER test frequency

3.3.2. Monitoring of Oil Parameters

After analyzing the sampling frequencies for the set of analyses specifically performed on the oil in service in the SST-800 turbine, the various parameters of the oil were monitored, based on admissible values in accordance with the manufacturer's specific requirements and the literature on the subject - Table 3.

Analysis	Standard	Admissible Values
Viscosity @ 40 °C	ASTM D445 ASTM 7279	+/- 10% of the value of the new oil; For the oil in use - of class ISO VG 46 - corresponds to a range between 41.4 and 50.6 mm2/s, at 40 ºC;
ISO Cleanliness Code (Particle Count Analysis)	ISO 4406	Max. */17/14
Total Acid Number (TAN)	ASTM D974 ASTM D664	w/ EP/AW additives – max. 0,3 mg KOH/g w/o EP/AW additives – max. 0,2 mg KOH/g
Water by Karl Fischer Method	ASTM D6304 ASTM D1744	Max. 100 ppm
Membrane Patch Colorimetry (MPC)	ASTM D7843	MPC *ΔE* scale
Fourier Transform Infrared Spectrometric (FTIR – Oxidation)	ASTM E2412 ASTM D7414	Between 1660 cm^{-1} and 1800 cm^{-1}, absorbances greater than 4 abs/cm should serve as an alarm;
Foam Tendency and Stability (Seq. I)	ASTM D892	Max. 400/10 (Seq. I)
Remaining Useful Life Evaluation Routine (RULER)	ASTM D6971	At least 25% of total initial antioxidant concentration (amines + phenolics);
Elemental Spectrometry (ICP)	ASTM D5185	• Maximum 10 ppm (or 4 ppm increases) in metallic elements; • A maximum of 25 ppm in elements coming from external agents (Silicon, for example); • Maximum 1000 ppm in sulfur;
Analytical Ferrography	ASTM D7690	Qualitative analysis of the equipment condition;

Table 3: Admissible Values for Oil Parameters

In general, all monitored parameters complied with the admissible values throughout the analyzed period, showing a good performance of the oil to lubricate the main bearings of the turbine. Proof of this is, for example, the evolution of viscosity, water content and Total Acid Number, represented in Figures 5, 6 and 7, respectively, where can be observed that the admissible values were never reached. In addition, the ferrographies conducted in the period under analysis have always indicated a low level of wear in the equipment.

It is also important to particularize the particle content, monitored by the particle count analysis, which was almost always within the limits defined by the manufacturer, based on the ISO Cleanliness Code, indicating an adequate purity of the lubricating oil.

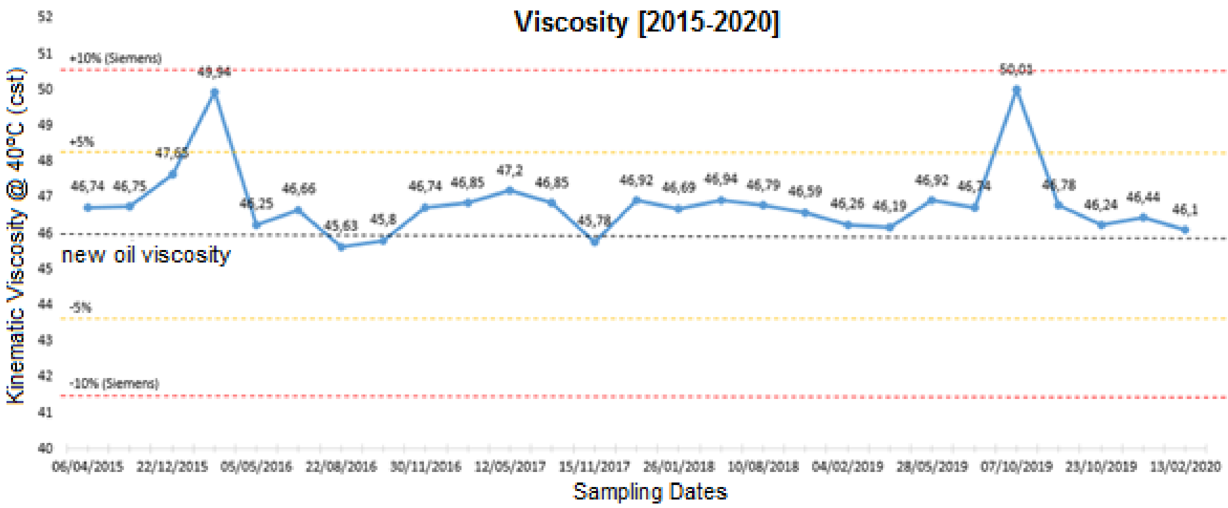

Figure 5: Oil Viscosity values (cst) [2015-2020]

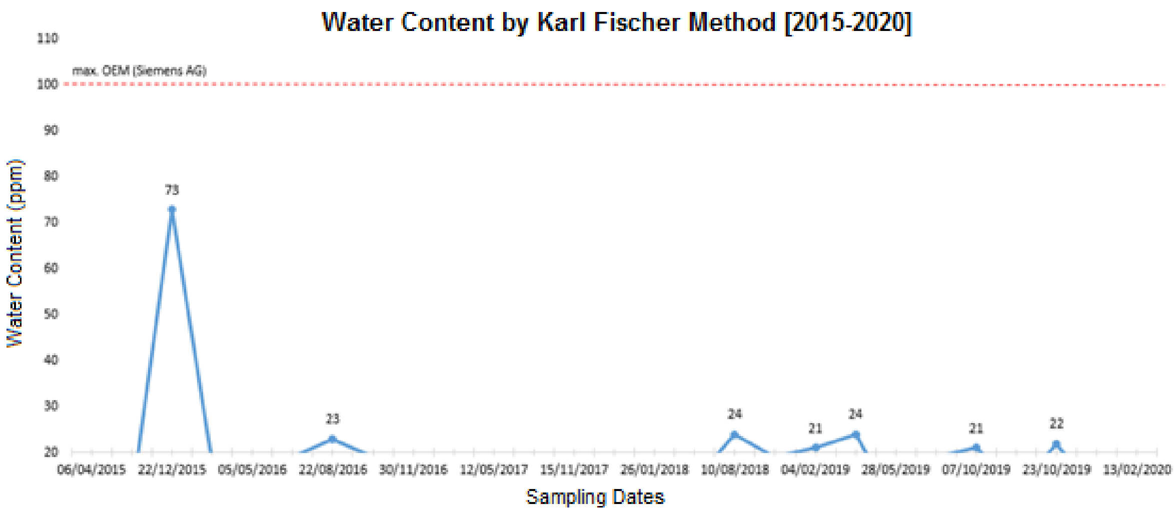

Figure 6: Oil Water Content values (ppm) [2015-2020]

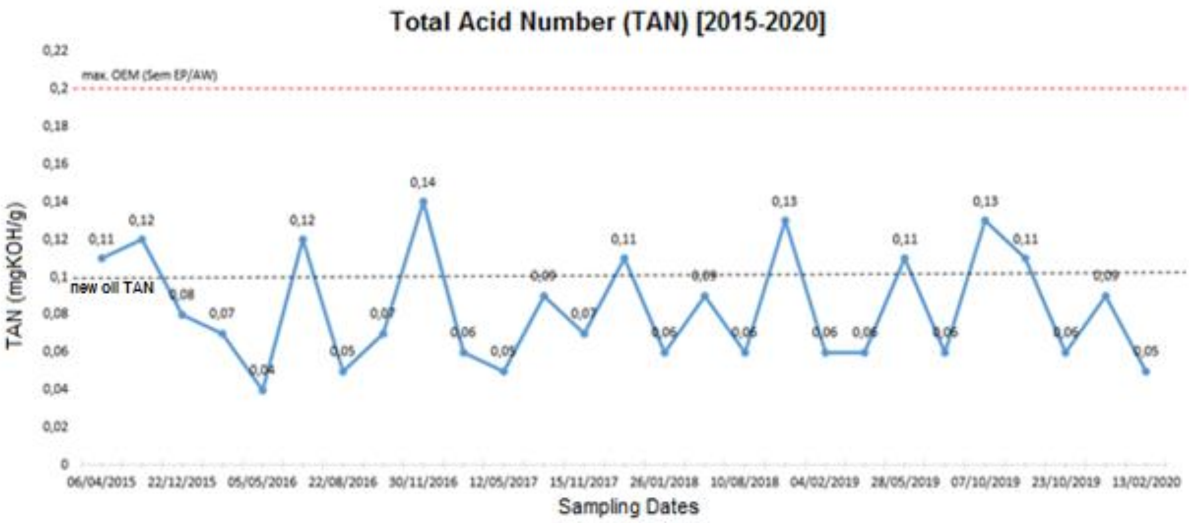

Figure 7: Oil TAN values (mgKOH/g) [2015-2020]

3.4. Improvement Proposals

Based on the technical description of the SST-800 turbine and its oil's condition data treatment, two proposals are presented that may be put in assessment as to possibly improve the representativity of the oil samples collected. Nevertheless, it is important to emphasize that, based on the history of the current ongoing analyses, the monitoring in practice has proved to be effective, as previously observed.

In this sense, the two measures suggested below are the following:

- **Uniformization of the sampling intervals of the medium periodicity analyses**, namely MPC analysis, RULER test and Elementary Spectrometry (ICP), performed by the oil supplier's own laboratory;

- **Expansion of the set of oil sampling points** in the equipment, namely for the turbine rotor plain bearings;

<u>Uniformization of the sampling intervals of the medium periodicity analyses</u>

Looking at Figures 2, 3 and 4, it can be seen that the analyses of medium periodicity (except the Analytical Ferrography) are performed with a poorly defined sampling frequency. Proof of this is the fact that the periods for two consecutive samples vary between two and eleven months. Thus, as a suggestion, these medium periodicity analyses could also have a specific accomplishment frequency (monthly, quarterly, semiannually, or even annually, depending on the recommendation for each type of analysis - Table 2), similarly to the analyses of low periodicity, in order to improve the representativity of the samples.

Expansion of the set of oil sampling points

In the SST-800 turbine lubrication system, there is only one sampling point, located on the oil return line to the reservoir. In this sampling point, routine samples are taken to provide, in theory, a good and representative overview of the condition of the oil, and of the equipment, relative to presence of impurities or changes in the physical-chemical properties of the lubricant, and wear of components. Nevertheless, although the samples taken at this sampling point provide important information about the general condition of the equipment, the adoption of a more extensive sampling policy, would not be only limited to a general evaluation of the system, but could provide a better condition control, achieved at the level of those components considered to be more critical.

Therefore, it is proposed to expand the set of sampling ports in the SST-800 turbine circulation system, namely with the installation of secondary sampling points immediately downstream of the plain bearings supporting the turbine rotor - Figure 8. This way, should the samples collected in the return line suggest any abnormal wear in the equipment, the secondary sampling points could be used to isolate and locate what would be the affected bearing.

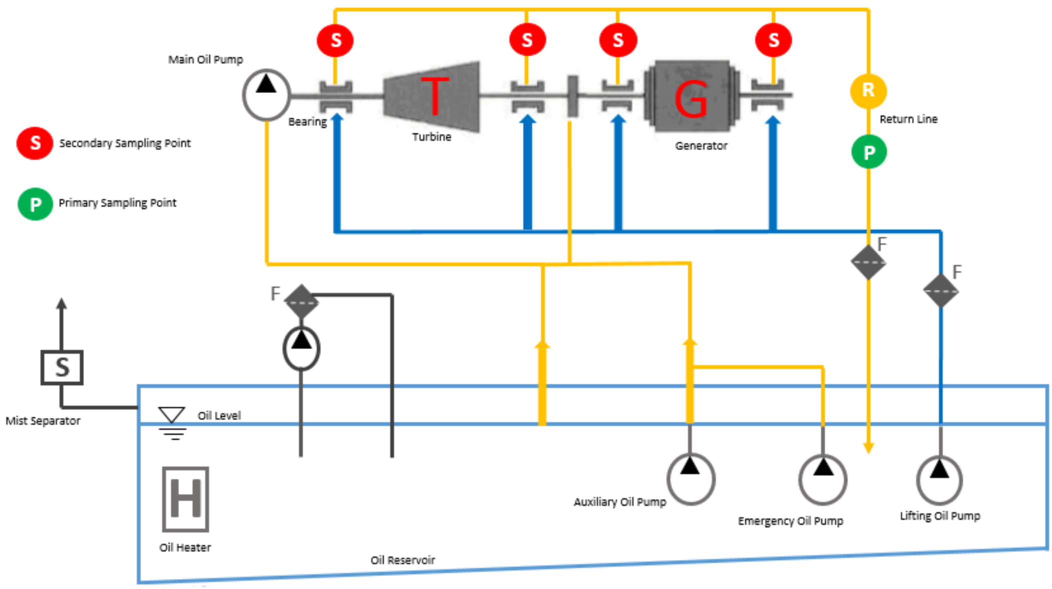

Figure 8: Lubrication Oil System with new set of sampling points

4. CONCLUSIONS AND CONTRIBUTIONS

Although they are not disruptive in any way, the proposals presented are thought to be very useful in the continuous improvement of the monitoring process of the condition-based maintenance of the equipment. These measures further exploit the benefits of an oil analysis program, allowing early and local diagnosis of the failure, elaboration and planning of corrective actions in the correct time, resulting in increased availability and operational performance of the turbine, and a possible reduction of costs and downtime due to failure.

References

[1]Kamal, G. (March 2013). In-Service Condition Monitoring of Turbine Oils. Second Middle East Turbomachinery Symposium. Doha, Qatar.

[2]Graça, B., Sousa, P., & Seabra, J. (1º Trimestre 2013). Análise de Lubrificantes em Turbinas a Vapor - Um caso de estudo. Revista Manutenção.

[3]Troyer, D., & Fitch, J. (1999). Oil Analysis Basics. Noria Corporation.

[4]Sander, J. (2012). Steam Turbine Oil Challenges. Lubrication Engineers White Paper. Obtido de https://www.lelubricants.com/newsroom/white-papers/.

[5]Siemens AG. (2019). Siemens Steam Turbine Portfolio - Steam Turbines from 10 kW to 1900 MW. Siemens AG, Gas and Power, Erlangen, Alemanha. Obtido em 12 de Junho de 2020, de siemens.com/steamturbines.