Use of Reliability Concepts to Support Pas 55 Standard Application to Improve Hydro Power Generator Availability

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Abstract: The electric power generation industry seeks for high equipment availability to fulfill the requirements of regulatory agencies contracts and demands. The availability of electric power generation equipment is affected not only by equipment design characteristics but also by maintenance policies. The recently developed British Standard PAS 55 presents requirements to improve asset integrity aiming at increasing availability and reducing safety risk. The present paper presents a discussion regarding the advantages of application of PAS 55 requirements to increase operational availability of hydro power generator and its relation with traditional reliability techniques used to develop equipment maintenance policy. An assessment is presented to link operational information, standards requirements and the associated reliability analysis techniques are linked to requirements of PAS 55. An example of application is presented for a 30 MW hydro power generator showing the advantages of applying reliability requirements to improve equipment availability.

Keywords: Degradation Analysis, Monitoring System, Reliability and Probabilistic Models.

1. INTRODUCTION

The rapid increase in world energy prices from 2003 to 2008, combined with concerns about the environmental consequences of greenhouse gas emissions, has led to renewed interest in alternatives to fossil fuels—particularly, nuclear power and renewable resources.

According to [8] from 2007 to 2035, world renewable energy use for electricity generation will grow by an average of 3.0 percent per year, as shown in Figure 1, and the renewable share of world electricity generation will increase from 18 percent in 2007 to 23 percent in 2035.

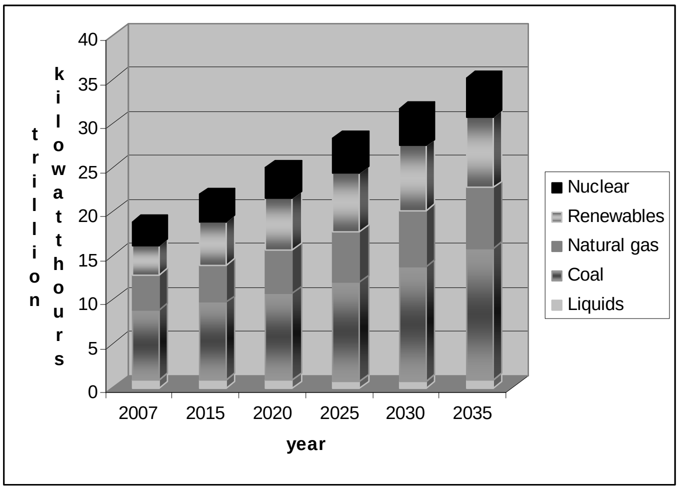

Figure 1. Forecast of World Net Electricity Generation by Fuel, 2007-2030, [8]

The category liquids include petroleum based fuels, such as Diesel oil or crude oil, and the category renewable includes hydroelectric, wind and other renewable electric power generation Those

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projections are based on a business-as-usual trend estimate, given known technology and technological and demographic trends, [8].

Most of the world's electricity is produced at thermal power plants (TPP), which use traditional fuels, coal, gas and fuel oil, and up to 20% of the world's electricity is produced by hydroelectric power plants (HPP). In countries with well-to hydropower, the figure is much higher: Norway (99%), Brazil (85%), Austria, Canada, Peru, New Zealand - over 50%, [8].

Process companies are adopting a consolidated approach to performance improvement based upon the use of a key performance indicator known as Overall Equipment Effectiveness (OEE), [9]. OEE can be calculated as:

$$OEE = (Availability)\times(Performance)\times(Quality) \qquad (1)$$

Availability refers to the process equipment being available for production when scheduled. Performance is determined by how much waste is created through running at less than optimal speed. Quality focuses on identifying time that was wasted by producing a product that does not meet quality standards.

PAS 55 is the British Standards Institution's (BSI) Publicly Available Specification for the optimized management of physical assets, [6]. The specification states that organizations must establish, document, implement, maintain, and continually improve their asset management system. In this context, asset management system refers collectively to the overall policy, strategies, governance, plans and actions of an organization regarding its asset infrastructure. Reliability and maintenance analysis play an important role in asset management according to that standard.

Traditionally, reliability analysis of equipment, or its components, is performed by the selection of a probability distribution that best models the times between failures recorded for the devices in question. The record of the time between failures is usually performed by maintenance staff, feeding the data into a computerized maintenance management system. This probability distribution models the reliability of the equipment/component.

This paper presents a methodology for reliability analysis used to describe the reliability of hydro generator, including the basic concepts of reliability and maintenance, which served as the basis for the development of the research. Furthermore an application of this methodology for reliability analysis is presented for a generating unit of a specific hydroelectric plant located at São Paulo State, Brazil. The analysis is used to support the future application of PAS 55 concepts to hydro generator management.

2. RELIABILITY, AVAILABILITY, MAINTAINABILITY AND SAFETY (RAMS) ANALYSIS OF HYDRO GENERATOR

Reliability is the probability of the equipment or process functioning without failure, when operated as prescribed for a given interval of time, under stated conditions. Reliability in power plants is affected by operating periods, i.e. between scheduled outages; budget periods; and peak-production periods. Measuring the reliabilities of plant and equipment by quantifying the annual cost of unreliability incurred by the facility puts reliability into a business context. Higher-plant reliability reduces equipment failure costs. Failure decreases production and limits gross profits. Failure is a loss of function when that function is needed – particularly for meeting finance goals. Failure requires a clear definition for organizations striving to make reliability improvements, [3].

General calculations of reliability are based on considerations of the initial failure-mode, which may be termed ‘‘infant’’ mortality (decreasing failure rates then with time) or wear-out mode (i.e. increasing failure rates then with time). Key parameters describing reliability are mean time to failure, mean time between/before repairs, mean life of components, failure rate and the maximum number of failures in a specific time-interval, [4].

High reliability (i.e. corresponding to relatively few failures) and ease of maintainability of the system influence availability, which is related to both frequency and duration of outages as follows:

$$A = \frac{MTBF}{MTBF + MTTR} \quad (2)$$

where MTBF means ‘mean time between failure’ and MTTR means ‘mean time to repair’.

Thus, the availability goal can be converted into reliability and maintainability requirements in terms of acceptable failure rates and outage hours for each component as explicit design objectives.

PAS 55 is the British Standards Institution's (BSI) Publicly Available Specification (PAS) for the optimized management of physical assets. It provides clear definitions and a 28-point requirements specification for establishing and verifying an integrated, optimized and whole-life management system for all types of physical assets. One of the key aspects of PAS 55 is to connect the company's strategic objectives, including short-term and long-term objectives, with day-to-day asset management activities.

All PAS 55 requirements stress the importance of having a good data collection system, because the core of a good and successful asset management program is based on the analysis of data aiming at supporting reliability and maintainability analysis. The standard sets that the reliability and maintainability analysis of critical equipment support the Life Cycle Cost Analysis of the asset.

Based on reliability analysis, the standard requires the development of root cause analysis aiming at defining the basic cause (usually defined by the failure of a component) of an undesirable behavior of equipment of a processing plant. This analysis should support the application of maintenance plans developed to maximize plant availability, [5].

The analysis of reliability and maintainability of hydro generator proposed in the present paper is based on application of reliability concepts to define critical items of a hydropower electric generation system from the point of view of failure consequences and maintenance planning, having as objective to achieve the availability planned for the system, minimizing downtime for corrective maintenance or even reducing the downtime associated with preventive maintenance, supporting PAS 55 application to manage hydro generator life cycle cost and performance.

To achieve this goal, the method is based on steps. As first step the functional tree of the hydropower generator must be developed, which aims to define the key equipment that compose the system as well as the functional relationship between them. This study analyzes in depth the hydro generator.

From the functional tree a FMEA analysis of all systems that comprise the generating unit can be developed, seeking to define the system main components, their failure modes associated with specific operating conditions and what are the consequences of these failures on the operation of the equipment. Additionally, the analysis seeks to define whether the occurrence of a failure mode presents symptoms, allowing the maintenance action before the occurrence of the machine failure.

This analysis allows the evaluation of the equipment considered critical for the interruption of power generation, either from the point of view of the excessive time to repair the failure or due to the high frequency of occurrence of a fault. This equipment considered critical should have their maintenance prioritized. With the aid of the functional tree and estimated reliability for the most critical equipment the hydro generator reliability may be characterized by building a block diagram.

Finally, to select the most appropriate maintenance policy for specific equipment, a decision process that allows defining the most appropriate maintenance practices for the same should be formulated, keeping in mind the characteristics of its fault modes and maintenance practices employed in mechanical or electrical equipment, which are: corrective, preventive and predictive. This decision is based on RCM technique.

3. EXAMPLE OF ANALYSIS

Aiming to run an example demonstrating the applicability of the methodology proposed in this paper, it is necessary to define a hydroelectric plant that will be taken as the basis of analysis in order to complete characterize their systems, allowing the application of failure modes and effects analysis, which forms the basis for a future implementation of RCM based maintenance policies and asset management techniques according to PAS 55 requirements. The hydro power plant in analysis is located in São Paulo State, Brazil, and has four hydro power generators each one equipped with Francis turbine and presenting 27 MW nominal output

3.1. Functional tree analysis

Initially, in Figure 2, the functional diagram has been proposed for the plant. It is proposed that the plant be subdivided into systems: dam, water intake, auxiliary services of alternating current and direct current, synchronization system, other auxiliary equipment and generating units.

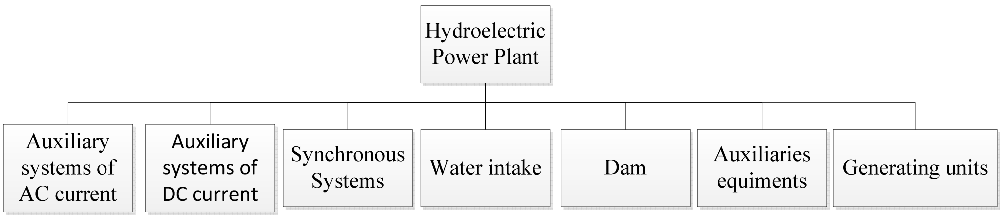

Figure 2. Hydroelectric Power Plant Functional Tree

Figure 3 shows the functional diagram of a generating unit. This piece of equipment is divided into eight subsystems, which are: turbine, generator, thrust and guide bearings, draft tube and suction, power substation, and control/monitoring system.

Throughout the study functional trees of each of subsystems were developed. In Figure 4 is shown as an example the turbine functional tree. According to the diagram in Figure 4, the turbine system is composed of several components having primary function of transforming the kinetic energy of fluid flow into mechanical energy. Therefore the turbine must have a control system, which maintains the frequency of its rotation, regardless of the magnitude of energy transformed, and must have components that act directly on the transformation and transmission of energy to the generator, such as the rotor, axis, the guide bearing and shaft coupling. Additionally, this system has components that support its operation, but do not act directly in the main function, such as the shaft seal, the aeration system, monitoring and protection equipment.

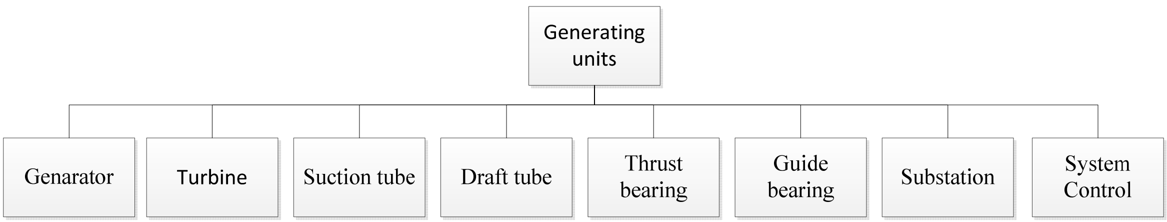

Figure 3. Generating Unit Functional Tree

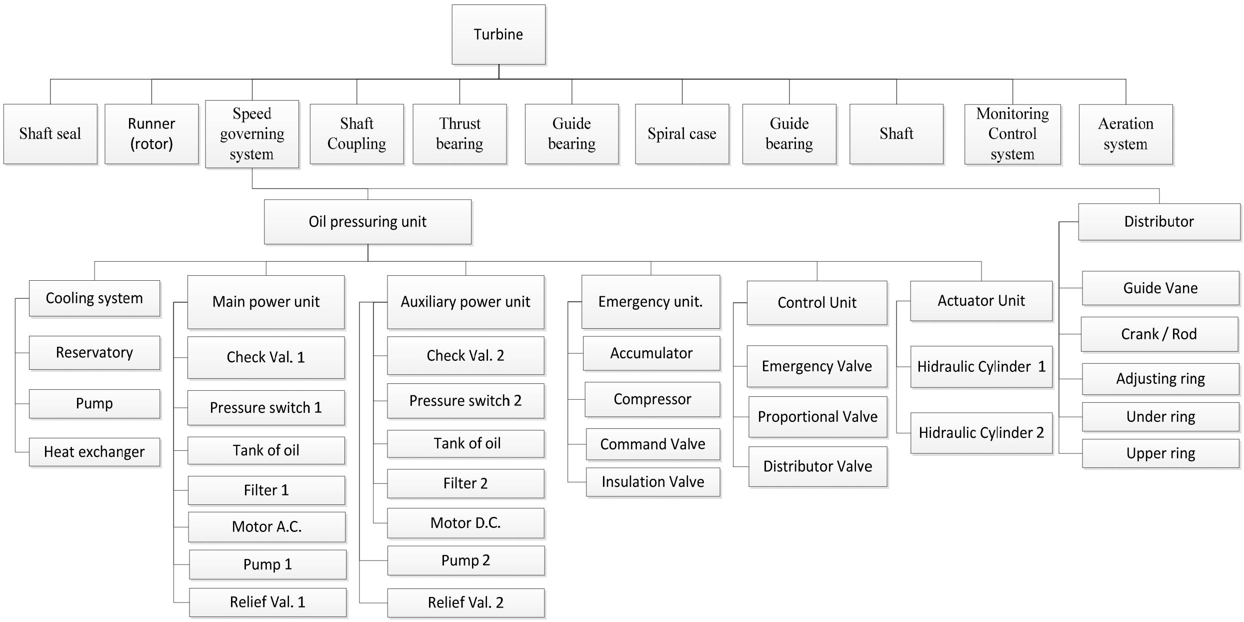

Figure 4. Hydraulic Turbine Functional Tree

The generating unit depends on some systems for monitoring and controlling its operation that includes monitoring of both active and reactive power, voltage in the generator, and temperature in some parts of the machinery, such as winding insulation and heat exchangers fluid temperature. Finally, the output of the generating unit is coupled to a substation, which connects the unit with the transmission line, having transformers that fit with the generated voltage required by the transmission line, and has a protective system which aims to protect the generating unit against faults that could occur in the transmission line.

3.2. Failure Mode and Effects Analysis (FMEA)

The analysis was performed using as initial event a failure mode of a hydro generator component. The analysis allows the study of the propagation of the failure in other subsystems or hydro generator systems, aiming at defining the loss of performance caused by the initial failure. The failure propagation effects analysis are considered in subsystems with which the component has operational relationship in accordance with the functional tree. In other words considers the propagation in the subsystems located in the higher levels of the functional tree.

For carrying on a FMEA analysis the form recommended by reference [13] is used. FMEA analysis was performed considering only the severity of the failure, defined as the loss of performance of hydro generator due to a component failure. Although the spreadsheet allows the analysis of the frequency of occurrence of the fault and even the possibility of detecting the failure in the early stages of development, depending on the application of monitoring techniques, for the present study this part of the analysis was disregarded For the present analysis the severity index is classified into three main severity levels: marginal, critical and catastrophic. Each level is split into three other sub-levels to express some variety of failure effects. A criticality scale between 1 and 9 is proposed. Values between 1 and 3 express minor effects on the turbine operation while values between 4 and 6 express significant effects on the turbine operation. Finally, failures that cause turbine unavailability or environmental degradation are classified by criticality values between 7 and 9.

FMEA analysis supports the selection of the mechanical failures that cause immediate shutdown of the hydro generator, associated with severity 9, which are: i) Failure in the turbine or generator shaft, represented by the cross section rupture due to the presence of excessive permanent deformation (due to overloads), varying its straightness, or due to crack growth associated to variable loading; ii) Failure in the turbine rotor, involving the rupture of the rotor blade due to fatigue mechanism and iii) Failure in the bearings structures, involving the rupture or permanent deformation.

Besides the catastrophic failure modes that cause equipment shutdown, the hydro generator has many auxiliary systems that are very important to support equipment performance. The FMEA analysis indicates that guides and trust bearings lubrication systems failure can cause hydro generator shutdown due to loss of oil pressure or increase of oil temperature. Those problems are caused by lubrication oil systems components failures.

The same failures for the speed governor hydraulic system will also cause the hydro generator shutdown. The failure of the refrigeration system used by the hydraulic systems and also by the generator can cause machine shutdown. Another type of failure that implies in machine shutdown is the deterioration of rotor and stator winding insulation, which operational condition must be verified over time.

3.3. Availability and reliability analysis.

For a generating unit of the hydroelectric plant, an availability analysis employing the block diagram shown in Figure 5 is carried out. From the failure data collected for two years, it was possible to characterize the reliability of the subsystems shown in Figure 5.

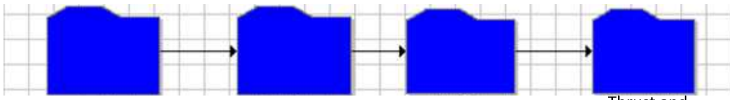

Figure 5 Simplified Block diagram of Hydroelectric

The operational data for the four generating units were registered during two consecutive years aiming at defining the failures that cause equipment unavailability (associated with corrective maintenance actions) and the expended time in programmed maintenance activities.

The operational registered data are presented in Table 1. The generating units states present in that table are defined according to IEEE 762 standard [10]. The ‘in service hours’ represents the number of hours that a unit is in service state. The ‘reserve shutdown hours’ represent the number of hours that an available unit is in reserve shutdown. The ‘forced outage hours’ represent the number of hours that an unit is unavailable due to the occurrence of a component failure that causes immediate removal from service. The ‘basic planned outage’ represents the number of hours that the unit is unavailable due to the execution of programmed maintenance activities.

Table 2 shows the number of failures associated with the basic generating unit subsystems which will be used as for reliability analysis.

From data presented in Table 2 it is interesting to observe that during two years none of the generating units presented bearing failures. It is also interesting to observe the great number of failures associated with the generator subsystem. The hydro power plant administrator only registers failures that cause interruption of power generation. According to Brazilian Electric Energy Regulatory Agency the plant administrator must report the subsystem that causes the forced outage without any root cause analysis to define the failed component.

Based on the plant operator report most of the turbine subsystem failures are associated with control guide vanes failures, including breakage of mechanical actuators, and speed governor hydraulic system failures. Regarding generator subsystem failures, most of them are caused by exciter components failures including 125 DC system failures. The penstock and draft tube subsystem failures are associated with butterfly inlet valve failures caused by hydraulic system failures.

Based on the in service hours of each generating unit and the number of failures of each subsystem the failure rate for a given subsystem is defined, as presented in Table 3. All subsystems under analysis are composed by a great number of components that must be presenting a minimum performance to guarantee the expected performance of the generating unit. As for reliability analysis each subsystem can be modeled as a series system with components presenting different reliability distributions.

Table 1. Operational data of generating units

Distribution of Hours	Generating Unit	Operational Data	
		Year 1	Year 2
In Service Hours (h)	UG1	6245.05	7699.59
	UG2	7622.36	6541.75
	UG3	5275.59	4181.21
	UG4	4442.91	3653.00
Forced Outage Hours (h)	UG1	22.55	5.41
	UG2	43.66	7.29
	UG3	0.88	10.67
	UG4	36.80	4.46
Basic Planned Outage (h)	UG1	2420.17	397.08
	UG2	1025.26	1459.02
	UG3	157.47	1383.61
	UG4	1361.70	486.81
Reserve Shutdown Hours (h)	UG1	73.23	658.82
	UG2	69.72	753.94
	UG3	3327.06	3185.51
	UG4	2919.59	4616.73
Number of Failures that cause Forced Outage	UG1	6	3
	UG2	8	3
	UG3	1	3
	UG4	7	3

Table 2. Failures distribution of generating units

		Number of failures	
Generating Unit	Subsystem	Year 1	Year 2
UG1	Generator	6	1
	Turbine	1	
	Penstock and Draft tube	0	2
	Thrust and Guide Bearings	0	0
UG2	Generator	7	1
	Turbine	1	0
	Penstock and Draft tube		2
	Thrust and Guide Bearings	0	0
UG3	Generator	1	0
	Turbine	0	1
	Penstock and Draft tube	0	2
	Thrust and Guide Bearings	0	0
UG4	Generator	3	1
	Turbine	4	0
	Penstock and Draft tube	0	2
	Thrust and Guide Bearings	0	0

Usually, for series systems with too many components, the system reliability can be modeled by an exponential distribution given that there is no frequent failure of a specific component. Once the reliability of the components are unknown and due to the small number of registered failures and diversity of failures root-causes of the subsystems it is initially recommend to adopt an exponential distribution to model their reliability distributions, [7] and [11]. The exponential distribution is defined according to the following equation:

$$R(t) = e^{-\lambda t} \tag{3}$$

where R(t) is the subsystem reliability and λ is the subsystem failure rate.

According to Table 3 a great variability in the failure rate for the same subsystems of each generating unit is noticed. Those data indicate that although the generating units have the same design their failure rates can be influenced by possible differences in their operational conditions or even due to differences during the onsite assembly process.

The generating unit failure rate is defined as the sum of the subsystems failure rates and also presented in Table 3. Generating unit 4 presents the greater failure rate once it presented the same number of failures of units 1 and 2 with the smallest in service hours. According to the power plant generation data units 1 and 2 are preferentially used to attend the power generation demand while units 3 and 4 are used to complement generation in case of higher demand. Due to this fact generating units 1 and 2 were submitted during the two years under analysis to comprehensive scheduled maintenance (duodecennial activities) representing a mean of almost 1200 annually planned outage hours for those units. Unit 4 presented a mean of 900 annually planned outage hours. Considering that units 1 and 2 can be considered 'as good as new' after the execution of preventive maintenance tasks, their reliability were improved as shown in Table 4.

Table 3. Failures rate estimate for generating units

Generating Unit	Subsystem	Total Number of Failures	In Service Hours (h)	Subsystem Failure rate (1/h)	Generating Unit Failure rate (1/h)
UG1	Generator	7	13944.64	0.00050198	0.00071698
	Turbine	1	13944.64	0.00007171	
	Penstock and Draft tube	2	13944.64	0.00014342	
UG2	Generator	7	14163.11	0.00049424	0.00070606
	Turbine	1	14163.11	0.00007061	
	Penstock and Draft tube	2	14163.11	0.00014121	
UG3	Generator	1	9456.80	0.00010574	0.00042297
	Turbine	1	9456.80	0.00010574	
	Penstock and Draft tube	2	9456.80	0.00021149	
UG4	Generator	4	8095.91	0.00049408	0.0012352
	Turbine	4	8095.91	0.00049408	
	Penstock and Draft tube	2	8095.91	0.00024704	

For repairable systems the asymptotic availability can be used as a measure of system capacity of providing a given amount of electric power per year. The analysis is presented for two generating units, 1 and 4, representing respectively a unit recently submitted to detailed maintenance plan and a unit still submitted to triennials maintenance plan. As for reliability analysis the power generation profile shown in Figure 6 is used for units 1 and 4.

Considering the 'time to repair' database the maintainability for each of those units is calculated and based on Monte Carlo Simulation, the availability for one operational year (8760 operational hours) is calculated. The results are summarized in Table 4. It is clear that even for a greater in service hours, UG1 availability is better than UG4. This fact is associated with the execution of planned maintenance of UG1.

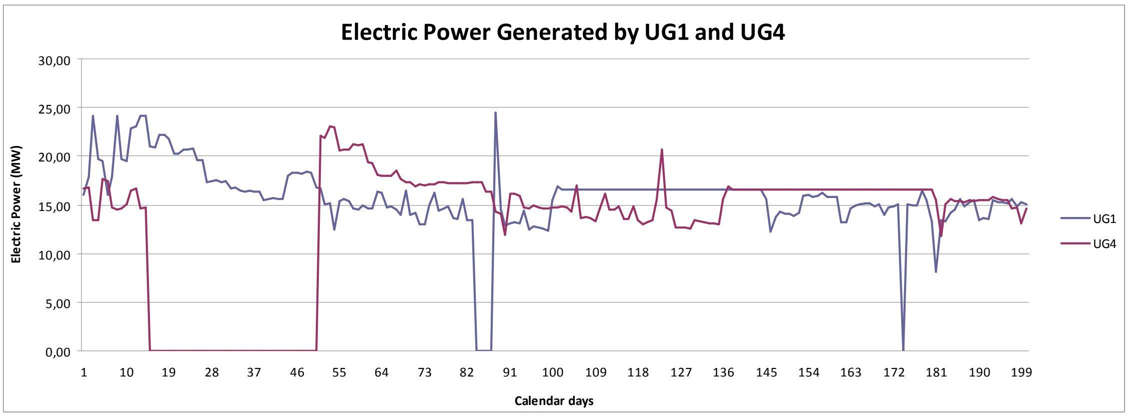

Figure 6. Power generation profile for Units 1 and 4

Table 4. Generating units availability estimate

	UG1	UG4
In service hours (h)	7450.7	4202.3
Forced outage hours	22.5	31.6
Availability	0.997	0.992

3.4. Proposals of Maintenance Policy

Taking as a basis the results of the FMEA analysis, suggestions are presented for the maintenance practices for critical equipment of the hydro power plant under study, which are defined according to the consequences of failure on the hydro generator operational condition, [12].

In accordance with RCM concepts, preventive or predictive maintenance practices must be evaluated to components whose failure modes generate consequences with severity greater than 6, in other words, those that degrade the performance or even cause shutdown of hydro generator.

Considering that most of the failures for subsystems turbine and penstock and draft tube are associated with hydraulic systems the faster the maintenance team locates a failed component the smaller will be the forced outage period. The failure diagnosis can be based on pre-defined faults that can cause interruption of hydraulic system operation. For each fault a tree must be developed to identify the possible components which failures cause the tree top event.

Those trees can be developed by engineering and maintenance crew of each power plant. In Figure 7 a tree is presented to indicate the root-cause analysis of increase in ´hydraulic oil temperature´ which causes hydraulic system operational interruption. Those trees can also be used to define monitoring systems that could be able to alert about failures development in hydraulic system basic components aiming at applying predictive maintenance to improve hydro generator reliability.

This methodology can be used to develop analysis of other critical components failure modes aiming at defining monitoring systems to evaluate mechanical components degradation and to support root cause analysis as recommended by PAS 55.

The availability analysis indicates that the hydro generator maintenance practices employed by the generation company have proved effective from the point of view of maximizing the availability with reduction of corrective maintenance interventions mainly for hydro generator bearings. The use of maintenance policies selected from the application of the RCM philosophy should increase the availability of machines, minimizing the preventive and corrective interventions.

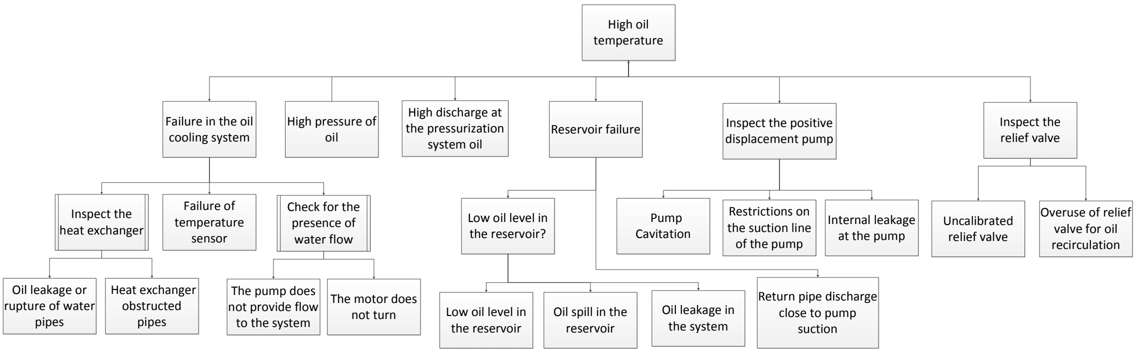

Figure 7. Example of root-cause analysis tree for failure diagnosis

The results of this analysis are:

i) It is vital the use of an on-line system for monitoring oil temperature used as a lubricating fluid in the bearings of the turbine and generator. Presently, the temperature is registered and displayed in a DCS screen but is not recorded in a database. The temperature history must be stored in a database that should be coupled to an asset management system allowing supporting bearing degradation analysis. The increase of the oil temperature may be an indicator of a failure in the cooling system or bearing failure due to oil film thickness reduction between the shaft and the pads of the bearing. Specifically in the case of monitoring system for the bearings oil temperature, if the oil temperature increases in all bearings simultaneously, there is a clear indication of oil cooling system failure. If the fault is associated with some component of the raw water feeding system an increase in temperature of the air inside the generator can also be detected, based on the indications of air temperature sensors installed near generator radiators. If the failure is associated with the oil treatment and conditioning system, it won´t be observed variation of the air temperature inside the generator;
ii) The increase of oil temperature in a single bearing is an evidence of failure in cooling system (or pipes). If the failure is associated with an absence of flow of raw water, there will be an indication of water level sensor. Thus, measurement of the oil temperature is an important parameter for determining the performance of hydro-generator and may indicate the occurrence of failures in the cooling system of the hydro-generator;
iii) The temperature rise of the bearing pad indicated by the temperature sensors may be caused by an increase in oil temperature (which would also be recorded by the oil temperature sensor) or due to an improper contact between the shaft and pads, as function of the shaft vibration. The shaft vibration can be detected by proximity sensors located in the bearings;
iv) The oil analysis may assist in predicting of the occurrence of wear in the bearing components, which may be associated with a possible contact between shaft and pads, caused by the vibration of the turbine and generator shaft, or by oil contamination due to filtering system failure. A degradation analysis may be executed based on oil analysis results time history. Presently, the oil analysis is annually executed but not used for trend analysis. It is used to check the instantaneous oil condition and to program immediate corrective maintenance actions;
iv) The installation of proximity sensors in the generator to measure air gap is suggested. Such proximity sensors enable the assessment of the orbit of the generator rotor shaft, allowing the assessment of abnormalities in this orbit which characterizes the vibration of the shaft. Moreover, this sensor can monitor the evolution of a failure mode whose effect is the shaft vibration, enabling a maintenance action before a higher degradation of the operational performance of hydro generator.

It should be noted that the monitoring techniques, which support decisions associated with the implementation of predictive maintenance, are basically applied to mechanical components, for failure modes whose time dependency development is clearly defined. However, the behavior of the parameter analyzed, selected as an indicator of the development of a specific failure mode, when the machine operates in a normal condition without any performance loss, should be clearly defined, based on observations executed with a specific machine. This means that for each hydro generator should defined the "normal" behavior (associated with the optimal performance of the machine) of parameters selected for monitoring operational performance. Additionally, it should be evaluated the time evolution of these parameters considering the development of several failure modes, in order to characterize their behavior due to the occurrence of specific failure modes. Only after this survey the results of the monitoring will be used as input for decision making regarding the implementation of an intervention to execute the maintenance of a critical component of the hydro-generator. For each parameter an alarm level must defined, indicating the need to stop the machine immediately in order to avoid further damage to its components.

4. CONCLUSIONS

The methodology for implementing reliability analysis proved to be very suitable for hydro generator analysis and can support the development of asset management based on PAS 55 requirements.

The importance of carrying out a detailed functional analysis of hydro generator as an initial step in the development of reliability analysis is emphasized. This analysis should seek to define all the systems that compose a hydro-generator and the interrelationship between them, describing their functions. This analysis yields the understanding of the function of each hydro generator system and the interrelationship between components to ensure that its function is performed in accordance with a specific requirement.

Functional analysis serves as subsidy for the implementation of the Failure Modes and Effects Analysis of hydro generator, which aims to analyze the effects of the hydro generator components failures on its operational performance. The results allow the identification of critical hydro generator components, in other words those whose failure causes machine shutdown or even a severe reduction in operational performance. During the execution of this analysis it is clear that regardless of the type of hydro generator analyzed, there are some critical subsystems for ensuring the operational required performance such as the speed governing system, oil cooling system in order to control the bearing lubricating oil temperature (and hence its viscosity) and the stator winding insulation. These subsystems should be the subject to constant attention from maintenance crews which, through application of preventive or predictive tasks, should reduce the probability of unexpected failures of those components.

From the results of the FMEA analysis, the critical components or subsystems that can be submitted to predictive maintenance programs are defined, which is the main focus of the RCM philosophy. Some simple measures can be used as techniques for monitoring the operating condition of the critical components of a hydro generator, such as monitoring the oil temperature inside the bearing and in the speed governing system, monitoring the temperature of the copper conductors in the stator bars, monitoring the air temperature in the core of the generator, monitoring the temperature of bearings pads, or even checking for the presence of contaminants in the bearing lubricating oil and in the hydraulic unit of the speed governing system. The monitoring of those data already enables verification of the occurrence of anomalies in the operating condition of hydro generator, and with the aid of the FMEA tables may be used to identify possible causes of these anomalies and to predict the need for maintenance tasks before generating unit performance is reduced below a minimum value, requiring the implementation of corrective maintenance. Those variables time history can be used as part of degradation studies developed by the hydro generator operator.

To calculate the reliability and availability of the generating unit it is necessary to model the reliability and maintainability of its various components. For both analysis a database is needed where the time between failure, repair time and the causes of failure associated to each corrective intervention executed on the component are recorded in a systematic manner. Operating condition of hydro generator should be continuously recorded to correlate the occurrence of a component failure mode with its operating condition.

To demonstrate the application of the proposed methodology the reliability and availability analysis of hydro generators of a hydroelectric plant located in São Paulo, Brazil was carried out. This analysis was performed according to the steps shown in item 2 and allows the following conclusions:

i) The system for monitoring the operating temperature of some components of this hydro generator is very well designed, allowing the evaluation of abnormalities which are indicative of the development of some component failure, supporting the application of predictive maintenance techniques;
ii) The association of this temperature monitoring system database with the effects of component failures on the hydro generator operational performance, presented in the FMEA analysis, may help in the process of defining the origin of any abnormal hydro generator operational condition;
iii) The generator unit has its availability greatly affected by the number of hours employed in preventive tasks and by the required number of operational hours;
iv) The calculated availability for hydro-generators based on fault records for two years are close to the values reported by the Brazilian Association of Electric Power Generation Enterprises (ABRAGE), [1] and [2], for availability of generating units (hydro and thermal) with power range between 10MW and 30MW, which were 89.86% in 2001 and 90.95% in 2003;
v) With the increase in efficiency of maintenance tasks, focusing on predictive and preventive activities associated with items that are critical to guarantee the operating performance of generating units in accordance with the philosophy of RCM, the availability of generating units is expected to increase, affecting the operational performance of the hydroelectric plant.

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