FMEA AND FTA ANALYSIS FOR APPLICATION OF THE RELIABILITY-CENTERED MAINTENANCE METHODOLOGY: CASE STUDY ON HYDRAULIC TURBINES

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Abstract. *The general objective of this work is to evaluate the application impact of the RCM (Reliability-Centered Maintenance) methodology on a power generating system. The RCM warrants significant improvements in the maintenance-functions performance, and also an increase in reliability and availability of equipments. It permits the definition of a maintenance planning in a structured form.*
It was developed a case study on the oil circulation system of combined (guide and prop) bearing of a hydraulic Kaplan turbine used in the hydroelectric plant of Balbina – Amazonas ─ Brazil. This study was done making use of the magnitudes monitored by the plant supervision and control system. Were used the tools FMEA (Failure Modes and Effects Analysis) and FTA (Fault Tree Analysis) to support the study of failures. This work presents a comparative analysis of these two tools, showing the contribution of each one for the implementation of a structured predictive maintenance planning.

Keywords: *FMEA, FTA, reliability, failures.*

1. INTRODUCTION

The development of the so-called new technologies has promoted fundamental changes in the working structure and processes. The most intense adoption of automatized systems and modern equipment has taken the maintenance areas to a strategic position in face of the importance of operational availability for the global result of companies.

Among the contemporaneous maintenance technologies, the RCM (Reliability-Centered Maintenance) has expanded its application to practically all the human activity branches, wherever it has necessity to keep the functioning of physical assets or processes. Originated on aeronautical American industry, and adopted for the nuclear and electric world-wide industries, today the RCM is applied in many other modern sectors of the economy, including the tertiary and the service ones. The application of the RCM has been motivated either by the improvement requirements imposed by the society, related to the people and patrimony security and to the environment preservation, or by the improvement of the efficiency, productivity and competitiveness in industry.

In the electric sector, the companies face the challenge of survival with the new imposed rules of relationship and market, as well as the challenge of technological and managerial obsolescence. However, due to sophistication of the electric and electronic equipments used by the consumers, the requirements on reliability of the electric energy supply have increased extensively.

In order to reduce the probability, frequency and duration of failure events and reduce its effects, it is necessary to perform financial investments in direction to increase the system reliability. In this context, the maintenance of electrical systems endure more challenges than any another management area. The techniques of conditional maintenance - where the equipment is monitored during its functioning and the stops are executed only if identified the presence of any defect to be corrected - had become absolutely necessary.

With the implantation of the RCM in Balbina's plant, it is expected: To subsidize the decision-taking and the functional strategies prioritization in order to reduce the corrective stops of equipments, and to dispose a consolidated maintenance systematics, optimizing availability and reliability of the equipments.

Ahead of such objectives, this work is structured in seven chapters: In the **second chapter** are presented the basic concepts of reliability-centered maintenance, its general formulation and methodology. The **third chapter** describes the combined bearing of the turbine-generator group of Balbina, detailing the bearing lubrication-and-oil-cooling system. The **fourth** and **fifth** chapters illustrate the application of the tools FMEA and FTA, respectively, on the system in study. In the **sixth** chapter is developed a comparative analysis of these two tools applications. And the **seventh** chapter contains the conclusions, where a more global evaluation of the potentiality of FMEA and FTA in the RCM context is elaborated based on of the results gotten in Balbina. Finally are presented some recommendations, as well as improvements and some limitations of the studied methods.

2. RELIABILITY-CENTERED MAINTENANCE

Literature points the RCM as a maintenance tool that aims to rationalize and systemize the determination of adequate tasks, which may be adopted in the maintenance plan. It also aims to guarantee the reliability and the operational security of equipments and installations to the lesser cost (Siqueira, 2005).

Using different forms of maintenance, the RCM intend to protect the function of equipments by determining the maintenance requirements of each equipment. In these terms, for Moss (1985), the RCM is structuralized with the basic principle that all task of maintenance must be justified before being executed. The justification criterions correspond to security, availability and economy in delaying or preventing a specific failure mode. These criterions capture the main characteristic of the RCM application, that is, to establish the most adjusted maintenance tasks, which guarantee the plant operational performance, from an accurate evaluation of the functions developed by each component of a productive system or equipment.

2.1. Methodology

When it uses the RCM to establish a maintenance method, is necessary to keep in mind that these maintenance methods must answer correctly and accurately to the following questions: Which are the functions to preserve? Which are the functional failures? Which are the failure modes? Which are the failure effects? Which are the failure consequences? Which are the applicable and effective tasks? Which are the remaining alternatives?

To answer each question, the RCM uses many methods and tools from an open set of solutions, some traditional ones, and other recent and modern ones, according to a structuralized and property documented sequence. In this article, the tools used to develop a maintenance method in accordance with the RCM specifications were FMEA (Failure Modes and Effects Analysis) and FTA (Fault Tree Analysis). The FTA and FMEA are tools of product and processes analysis that allow to a systematic and standardized evaluation of possible failures, establishing its consequences and guiding the adoption of corrective or preventive actions.

The objective of this work is to develop a comparative analysis of these two tools in a case study on the oil circulation system (lubrication and cooling) of the combined bearing of the hydraulic generating unit 04 from Balbina hydroelectric plant.

3. LUBRICATION AND COOLING SYSTEM OF COMBINED BEARING (GUIDE AND PROP)

All the rotating mass of the turbine-generator group is supported axially in the prop bearing and radially in the guide bearing, both contained into the same oil container. All this set is called combined bearing.

The combined bearing is sliding type, composed by two main and distinct surfaces, being the mobile part connected to the axle, and the fixed part constituent by the skids or sabots. The mobile part is composed by a polishing steel disc, commonly called mirror.

There isn't contact between the two surfaces because always it will have an oil film between them, whose function is to prevent the direct contact metal with metal and also to make cool, wasting the heat generated by attrition between the surfaces. The Figure (1) shows a diagram of the turbine-generator group to ease the localization of the combined bearing.

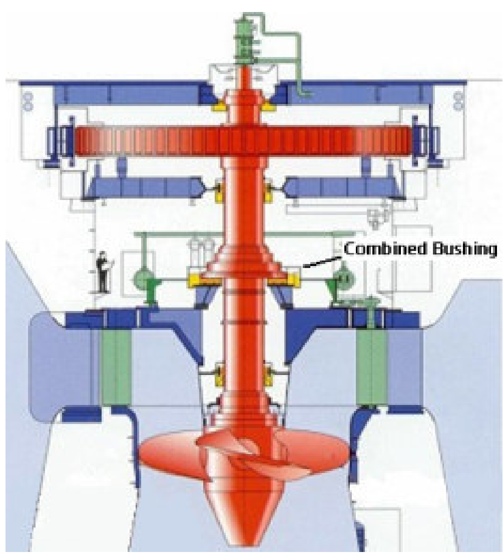

Figure 1. Group Kaplan turbine-generator, detaching the combined bearing

The oil is removed from the container by a set of bombs; it is cooled through heat exchangers and led back to the container where the bearing active parts are immersed. The heat exchangers have as cooling fluid the water. There are two exchangers, one being normally in operation and the other as reserve.

In the suppressing tubing, after the cooling system, is installed a set of filters, with the purpose to complete the oil cleanness before returning to container.

Due to the weight of the rotating mass and the hydraulic counter-attraction that come across the prop bearing, it is necessary that, during the machine start and stop, be injected oil between sabot and the prop bearing ring, to lubricate it. The prop bearing oil injection system forms a film of oil between the fixed and rotating parts, in the band of 0% to 50% of the nominal rotation. In its nominal rotation or even above 50% of it, the prop bearing is auto-lubricated.

The oil injection in prop bearing is realized by two high-pressure bombs, identified as "AG" and "AH", and the oil cooling is also realized by two bombs, identified bombs as "AI" and "AJ".

4. FAILURE MODES AND EFFECTS ANALYSIS (FMEA)

The failure modes and effects analysis (FMEA) is one of the most efficient low-risk tools for prevention of problems and for identification of more efficacious solutions, in cost terms, in order to prevent such problems.

FMEA is a deductive technique that consists on failure identification in each component, its causes and consequences on the equipment and on the whole system.

The FMEA can offer, with bigger facility and objectivity, answers to those questions cited in the sub-section (2.1) referring to the equipment failures. The phases of RCM implementation depend on the answers to such questions.

4.1. Case study using FMEA

To develop the FMEA, initially was done a survey on the functions of each component, as well as on its failure modes and effects. Were been used, as support for the analysis, the system textual description, contained in the technical operation instructions, the fault registers in the abnormality cards (service orders for maintenance) of the plant, the maintenance plans currently used and the instrumentation descriptions of the equipment and components. It was also performed a brainstorming in a join into the plant operators, so that it was possible to get with more details about the description of the possible failures of each component. The documentation of analysis FMEA was developed according to shown standardized form in the Tab. (1).

Table 1. Standardized form for FMEA analysis.

SYSTEM IDENTIFICATION					
FUNCTION	Description of system function				
COMPONENT	**COMPONENT FUNCTION**	**FUNCTIONAL FAILURE**	**FAILURE MODE**	**FAILURE CAUSE**	**FAILURE EFFECT**

Forward there is an explanation of each column of the presented form.

- Function: Action which the user desires that the item or system executes in a specified performance standard.
- Component (Comp.): Identification of each component belonged to the system.
- Component function: Succinct and accurate description of the task that the component must execute.
- Functional failure: Description of all the possible failures pertinent to each component.
- Failure Mode: Description of the form as the failure is observed by the operation team. For example, performance of one determined type of alarm, or performance of a relay signaling failure.
- Failure cause: Simple and concise description of the occurrences (causes) that they can origin to the considered type of failure.
- Failure effect: Consequence of the occurrence of the failure, perceived or not for the final user. It can be local (it does not affect the other components) or global (it can affect other functions or components).

The spread sheet of analysis of the functions, modes and effects of failure of the components of the lubrication and cooling system of combined bearing is shown following (Tab. 2).

Table 2a. FMEA of the filters of lubrication and cooling system of combined bearing of GHU-04 of Balbina.

LUBRICATION AND COOLING SYSTEM OF COMBINED BEARING					
FUNCTION	To dissipate the heat generated in the combined bearing and lubricate its components.				
COMP.	**COMPONENT FUNCTION**	**FUNCTIONAL FAILURE**	**FAILURE MODE**	**FAILURE CAUSE**	**FAILURE EFFECT**
1. Filter	Filter the oil	Do not filter the oil	1.1 Deterioration	Disruption of the filter mesh	- Risk of contaminating the oil load with residues
				Disruption of the O-rings	
		Obstruct the oil flow	1.2 Clogging. High differential pressure	Excess of impurities in the filter element	- Consignment in the system lubrication and cooling

Table 2b. FMEA of the motorpumps and valves.

LUBRICATION AND COOLING SYSTEM OF COMBINED BEARING					
COMP.	**COMPONENT FUNCTION**	**FUNCTIONAL FAILURE**	**FAILURE MODE**	**FAILURE CAUSE**	**FAILURE EFFECT**
2. Circulation motorpumps AI e AJ	Pump the oil	Operate below of the 1,2 bar pressure	2.1 Low oil pressure on the motorpumps exit	Oil leakage on the mechanical stamp	- Turns off the priority bomb and turns on the reserve bomb in the low pressure. In case that it also fails, it provokes TRIP in the generating unit. - Disturbance in the normal functioning system (failure in the lubrication and cooling)
				Coupling damage	
				Corrosion due to contaminated oil or a bad quality one	
				Cavitations of the gears due to presence of air in the oil	
				Electric defect (damaged poles)	
		Abnormal noise	2.2 Noise	Wasted rolls	- Risk that the motorpump breaks
				Rolls badly lubricated	
		Overheating	2.3 Thermal relay performing	Loss of internal parts, provoking attrite with the motorpump axel	- Turns off the priority bomb and turns on the reserve bomb in the low pressure. In case that it also fails, it provokes TRIP in the generating unit. - Disturbance in the normal functioning system (failure in the lubrication and cooling)
				Excessive lubrication	
				Bad lubrication	
3. Injection motorpumps AG e AH	Pump the oil	Operate below of the pressure of 35 bar	3.1 Low oil pressure on the exit of the motorpumps	Oil leakage on the mechanical stamp	- Turns off the priority bomb and turns on the reserve bomb in the low pressure. In case that it also fails, it provokes TRIP in the generating unit. - Disturbance in the normal functioning system (failure in the lubrication and cooling)
				Coupling damage	
				Corrosion due to contaminated oil or a bad quality one	
				Cavitations of the gears due to presence of air in the oil	
				Electric defect (damaged poles)	
		Abnormal noise	3.2 Noise	Wasted rolls	- Risk that the motorpump breaks
				Rolls badly lubricated	
		Overheating	3.3 Thermal relay performing	Loss of internal parts, provoking attrite with the motorpump axel	- Turns off the priority bomb and turns on the reserve bomb in the low pressure. In case that it also fails, it provokes TRIP in the generating unit. - Disturbance in the normal functioning system (failure in the lubrication and cooling)
				Excessive lubrication	
				Bad lubrication	
4. Valves	Isolate system components and supervision and control accessories	Do not isolate supervision and control accessories	4.1 Leakage	Head valve or opposed head valve deterioration	- Impossibility to execute maintenance in the supervision and control accessories - Risk of accident
		Improperly isolate the supervision and control accessories		Valve piston stiff	
				Lack of squeeze in the closing of the valve	
	Limit the pressure in case of circuit blockage	Do not relief the pressure	4.2 Overpressure. High pressure in the exit of motorpumps	Incorrect adjustment	- Actuation of TRIP in the generating unit - Risk of disrupting the tubing and gaskets - Risk of break in the motorpump - Risk of environment contamination - Risk of accident
		Operate above the maximum pressure		Stiffing	
				Flow obstruction due to internal mechanism break	

Table 2c. FMEA of the heat exchangers, circuit of motorpumps command and control, and tubing.

LUBRICATION AND COOLING SYSTEM OF COMBINED BEARING					
COMP.	**COMPONENT FUNCTION**	**FUNCTIONAL FAILURE**	**FAILURE MODE**	**FAILURE CAUSE**	**FAILURE EFFECT**
5. Heat exchangers	Cool the oil	Insufficient cooling oil	5.1 Low difference of temperature between the oil entrance and exit terminals of the heat exchangers. Low water flow. High temperature on the exit of water	Incrustation on the inox plaques	- Loss of the physical-chemistry oil characteristics - Bad formation of the oil film
		Oil leakage	5.2 Low oil flow	Wastage on the gasket rubbers	- Actuation of TRIP in the generating unit - Risk of contaminating the oil load - Loss of the physical-chemistry oil characteristics - Disturbance in the normal functioning system (failure in the lubrication and cooling)
				Loss of the inox plaque connections	
		Water leakage	5.3 Low water flow	Loss of the water tubing connections	- Actuation of TRIP in the generating unit - Disturbance in the normal functioning system (failure in the lubrication and cooling)
6. Circuit of motorpumps command and control	Indicate the status, automatically start, stop and commute the motorpumps. Execute emergency stops.	Loss of status indication	6.1 Loss of indication	Bad contact in the wiring	- Supervision failure
				Burning of LED's	
		Troubles on motorpumps automatism	6.2 Problems of automatic actuation	Bad connection of the contactor bournes	- Risk for occurrence of TRIP in the generating unit - Disturbance in the normal functioning system
				Burning of components in the electronic console	
				Contactor bobbins with dry resistance	
				Damaged contacts	
		Do not obey manual commands	6.3 Problems of manual actuation	Bad connection of the contactor bournes	- Risk for occurrence of TRIP in the generating unit - Disturbance in the normal functioning system
				Burning of components in the electronic console	
				Damaged command button	
				Damaged contacts	
7. Tubing	Lead the oil	Do not lead oil properly	7.1 Leakage. Low oil outflow	Loss on the connections	- Consignment in the oil restitution to the system
				Damage in the tubing	
				Wastage on the gasket rubbers	

It was chosen, specifically, the hydraulic generating unit (HGU) 04 of Balbina's plant because it is the unit whose failures distribution by components, on the lubrication and oil cooling system, is considered median, in relation to the other units. That is, the behavior of its lubrication and cooling system is the one that better represents the average of failures in this system in comparison to all generating units of the plant. The critically analysis of each failure mode is developed in the follow section.

4.2. FMEA punctuation

Each failure mode is sequentially numbered, restarting the counting for each new component. This number will be used as a failure mode pointer, being referenced at the FMEA punctuation form.

From the failure mode pointers, had been established indices for evaluation of the importance that each mode represents for the hydraulic generation process. The factors for components evaluation consist on a series of criteria used to evaluate the criticality or risk priority of a component. In this evaluation the influence of three parameters is considered: severity, occurrence and failure detection.

- Severity: It is an index that reflects the gravity of the failure consequences. Occurrence: It is an index defined in function of the number of failure occurrences registered in the anomaly cards and administrative orders of Balbina in the last 3 years (in this case, during the period of 2004 the 2006). The occurrence index is dynamic and must be reevaluated annually considering the number of imperfections of the 3 last immediately posterior years to the year in question. Therefore, the FMEA analysis is dynamic and has its values annually modified.
- Detection: It is an index constructed based on the probability estimative that a failure can be detected, assuming that it has occurred.

Such parameters normally are measured in a scale of 1 to 10, the number 1 indicate a lesser importance of the failure, in the point of view of determined parameter, and number 10 indicates that the biggest importance that must be attributed to the failure. The classification criteria of each one of these parameters are presented in the Tab. (3).

Table 3. Criteria for failure modes evaluation.

Severity		Occurrence	
1	Very insignificant effect, corrected immediately by the operation team.	1	Without failure registry in the last 3 years.
2	Insignificant effect, corrected immediately by the maintenance.	2	1 failure in the last 3 years.
3	Minor effect, the component suffers to a gradual degradation case is not repaired.	3	2 failures in the last 3 years.
4	Moderate effect, the component does not execute its function, but the failure does not provoke TRIP in the generating unit and its maintenance does not demand stop of machine.	4	3 failures in the last 3 years.
5	Moderate effect, which does not provoke TRIP actuation in the generating unit, but whose maintenance demands stop of machine.	5	4 or 5 failures in the last 3 years.
6	Moderate effect, which provokes TRIP actuation in the generating unit and whose maintenance demands stop of machine during one day or less.	6	6 failures in the last 3 years.
7	Critical effect that provokes TRIP actuation in the generating unit and whose maintenance demands stop of machine for more than one day.	7	7 failures in the last 3 years.
8	Very critical effect that provokes TRIP actuation in the generating unit and brusquely interrupts the system functions.	8	8 failures in the last 3 years.
9	Very critical effect that provokes BLACKOUT actuation in the generating units and collapse of the process.	9	9 failures in the last 3 years.
10	Catastrophic effect that can cause damages to properties or people.	10	10 or more failures in the last 3 years.
Detection			
1	Failure indicated directly by the instrumentation.		
3	Failure identified by the team operation daily inspections (Ex. emptyings, fluid condensed in the air balloons).		
5	Failure identified for abnormal noises, or indirectly by the instrumentation.		
7	Occult failure, impossible to be identified by the operator.		

Table 4. FMEA punctuation form.

LUBRICATION AND COOLING SYSTEM OF COMBINED BEARING														
ID OF THE FAILURE MODE	FACTORS FOR FAILURE MODE EVALUATION				ID OF THE FAILURE MODE	FACTORS FOR FAILURE MODE EVALUATION				ID OF THE FAILURE MODE	FACTORS FOR FAILURE MODE EVALUATION			
	SEVERITY	OCURRÊNCE	DETECTION	GENERAL EVALUATION (RPN)		SEVERITY	OCURRÊNCE	DETECTION	GENERAL EVALUATION (RPN)		SEVERITY	OCURRÊNCE	DETECTION	GENERAL EVALUATION (RPN)
1.1	4	1	1	4	**3.1**	2	10*	1	20	**6.1**	3	1	3	9
1.2	3	1	5	15	**3.2**	7	1	1	7	**6.2**	6	1	1	6
1.3	4	1	1	4	**3.3**	3	2	1	6	**7.1**	1	1	1	1
2.1	6	1	1	6	**4.1**	4	2	7	56	**7.2**	6	4	3	72
2.2	3	1	5	15	**4.2**	4	1	1	4	**7.3**	6	2	3	36
2.3	4	1	1	4	**5.1**	7	1	3	21					

* Amount of cleannesses in the heat exchangers (HGU-04): 19.

From theses parameters it is defined the called Risk Priority Number (RPN). The RPN is the value calculated by the product of the three previous indices (*Severity x Occurrence x Detection*). It is used to action taking prioritization. It is a practical way to prioritize certain failures and to evaluate which steps they must be taken first. The form of FMEA punctuation for the lubrication and cooling system of combined bearing of the hydraulic generating unit 04 of Balbina power station is shown in the Tab. (4).

Made FMEA analysis, it follows an analysis through fault tree (FTA) so that can be developed a comparative study of these two tools.

5. FAULT TREE ANALYSIS (FTA)

The FTA consists on a construction of a logical diagram (fault tree), through a deductive process that, from a predefined undesired event, searches the possible causes of such event. The process follows investigating the successive combinations of failures of the components until reaching the called basic failures (or FT basic events), which constitute the limit of analysis resolution. The undesired event is commonly called the tree "top event".

The fundamental concept of the FTA consists on the translation of a physical system in a structuralized logical diagram, in which certain specific causes lead to an interest top event.

The great popularity of the FTA results, basically, from two aspects:

- first, due to the bigger flexibility of the graphical representation of complex systems proportionate by the specific symbology e,
- second, due to the bigger computational easiness in function of the lesser number of significant numbers needed for the failure probabilities calculation when compared with the necessary one for the case of typical values of success probabilities.

5.1. Case study using FTA

It is a common practice among the specialists in reliability and risk, when analyzing a system of fault tree (FT), dividing it in stages: **Stage 1** - Definition of the system, its frontiers and interfaces, **Stage 2** - Definition of the FT top event top of the FT, **Stage 3** - Construction of the FT, **Stage 4** - Survey the events failure data, **Stage 5** - Determination of the minimum cuts, **Stage 6** - Qualitative evaluation of the FT, **Stage 7** - Quantitative evaluation of the FT, **Stage 8** - Evaluation of the importance of the minimum cuts, **Stage 9** - Analysis of the gotten results, and **Stage 10** - Conclusions.

The system that will be analyzed consists on the same of the FMEA analysis, that is, the lubrication and cooling system of the combined bearing, whose components and frontiers are already well defined. The top event of the FT was defined as being "failure in the lubrication and cooling system of the combined bearing". The tree whose logical combination of basic events leads to the failures in the related system is shown in the Fig. (2). This fault tree was developed using the computational tool Relex® software belonged to the Relex Software Corporation.

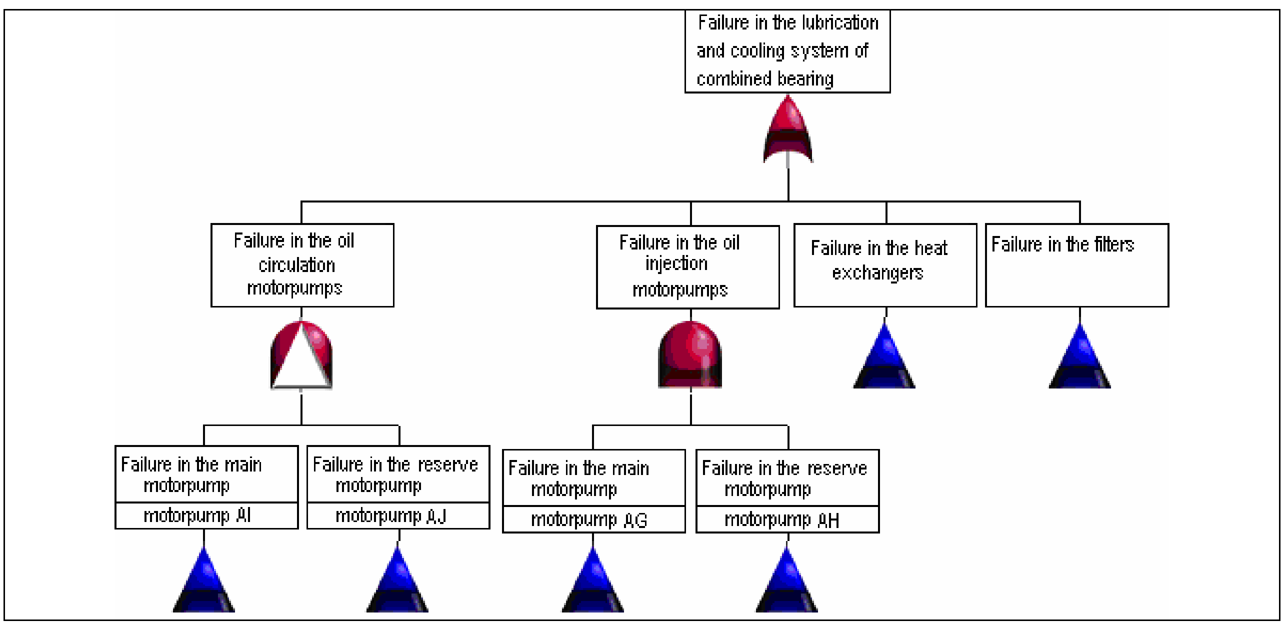

Figure 2a. Fault Tree illustrating the general failures in the lubrication and oil cooling system of the combined bearing.

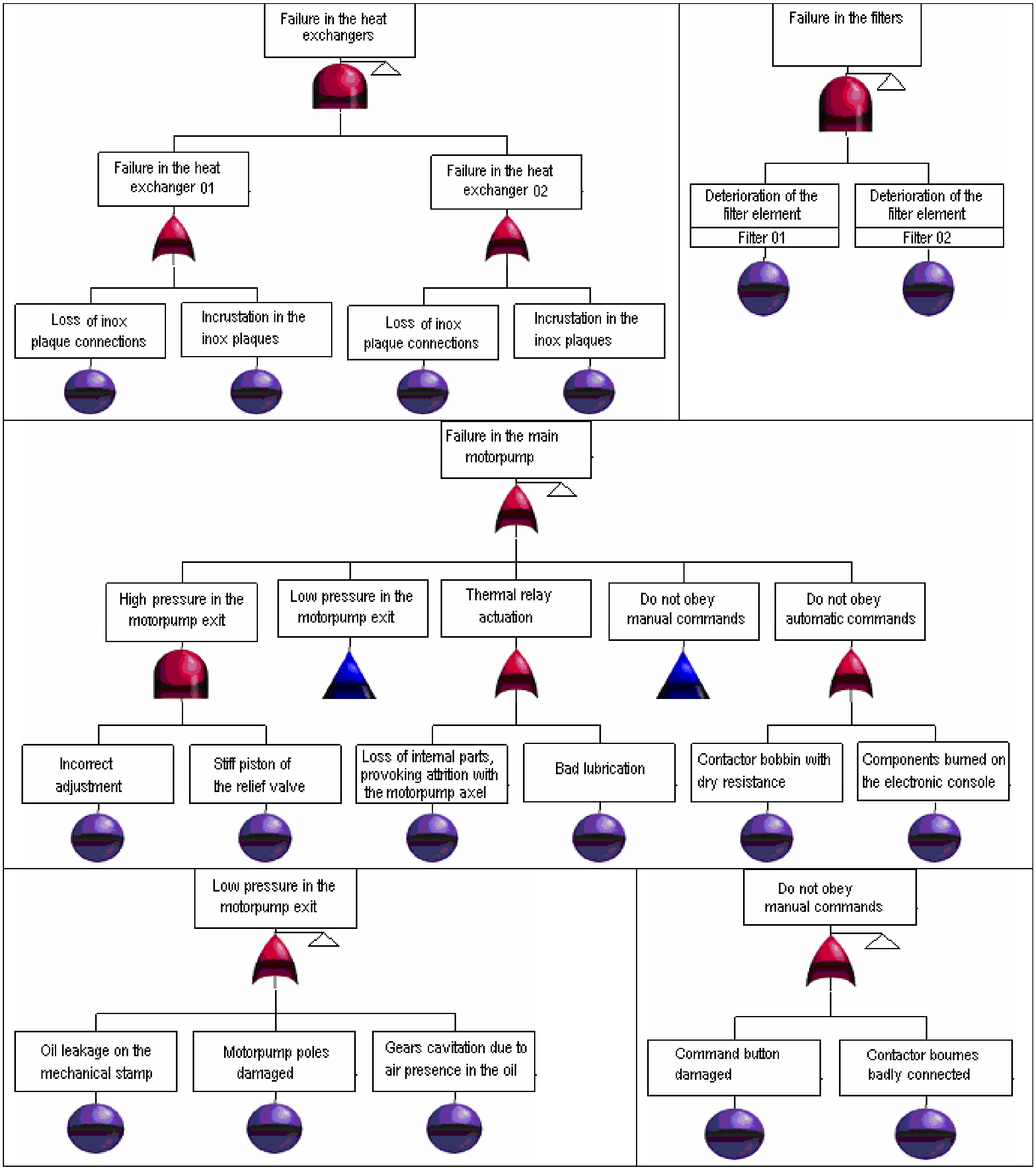

Figure 2b. Fault tree of the specific failures in the heat exchangers, filters and motorpumps.

It is important to emphasize that the basic failures referring to all motorpumps (AI, AJ, GAC and AH) are essentially the same ones and generically had been shown in the fault tree with the description *motorpump*. Therefore, the tree must be read knowing that the logic gate OR which has the description *motorpump* represents each one of motorpumps, AI, AJ, GAC or AH, as the case.

6. FMEA AND FTA, A COMPARATIVE STUDY

Once the field *failure occurrence*, in FMEA analysis, is a function of the amount of failures registered in the maintenance management system of the plant, it can be observed, through the field *occurrence* in Tab. (2), that, throughout the last 3 years, failures had occurred only in three components: 20 failures in the heat exchangers, 1 in filters and 4 in the motorpumps command circuit.

The priority risk number (PRN) is an important product generated by the FMEA, because it allows identifying critical failure modes in the system, that is, failure modes whose taken decision in relation to maintenance actions must be prioritized. Assuming that a PRN bigger than thirty indicates a critical failure mode and that components considered critical are components that present critical failure modes, the FMEA analysis indicates the existence of two critical components in the lubrication and cooling system of the combined bearing: the filter 01 and the motorpumps command and control circuits. It is noticed that the heat exchangers, although present 20 failures, do not constitute critical components, because the presented failures have practically insignificant effects, easily repairable.

It can be said that the RPN, with its simple and efficient form to calculate, is an advantage of the FMEA in compared with the FTA, since it allows prioritizing the failures not only for the number of occurrences, but also for severity that represents and the form with which they reveal and they are identified.

As well as in FMEA analysis, the survey of the failure data of the FT basic events was developed based on the number of failure occurrences registered in the anomaly cards and administrative orders of Balbina during the period of 2004 to 2006. The failure probability of each basic event of the FT was calculated in accordance with the failure rate, as described in the Eq. (1), from the detailed information about each failure and about the time of duration of the failures.

$$failure\ \ rate = \frac{number\ \ of\ \ component\ \ failures\ at\ the\ considered\ \ period}{total\ \ time\ \ that\ \ the\ \ component\ \ remain\ \ operating} \tag{1}$$

The failure rate of each basic event of the FT in study is shown in the Tab. (5).

Table 5. Probability of basic events failure.

Basic Event	Failure rate (failure/hour)	Basic Event	Failure rate (failure/hour)
Incrustation in the inox plaques of heat exchanger 01	$3{,}975 \cdot 10^{-4}$	Bobbin of the contactor of motorpump AI with dry resistance	$3{,}960 \cdot 10^{-5}$
Looseness in the inox plaque connections of heat exchanger 02	$3{,}961 \cdot 10^{-5}$	Bobbin of the contactor of motorpump AJ with dry resistance	$3{,}960 \cdot 10^{-5}$
Incrustation in the inox plaques heat exchanger 02	$3{,}576 \cdot 10^{-4}$	Bobbin of the contactor of motorpump AG with dry resistance	$3{,}960 \cdot 10^{-5}$
Deterioration of the filter element 01	$3{,}960 \cdot 10^{-5}$	Bad connection of the contactor bourns of motorpump AJ	$3{,}960 \cdot 10^{-5}$

The non-cited events in the Table (5) are not registered in the anomaly cards, that is, they represent failures that had not occurred in the last 3 years. For these events, it has been assumed a failure rate a corresponding to 1 failure in 15 years ($7{,}615 \cdot 10^{-6}$ failures/hour).

The FTA, due to be a graphical model, allows showing, in a clear manner, the chaining of different events that can result on the top event. The top event consists on a failure or particular problem of the system considered serious enough to demand a posterior analysis. There is an approaching difference of FTA in relation to FMEA, while the first one work with specific failure modes, carefully selected (top events), the second concentrates in the identification of all failure modes of each component separately.

The FTA allows the joint analysis of many causes that will lead to the top event occurrence, providing to the analyst a bigger understanding about the system operational behavior. It allows yet identifying how the constituent components of the system are linked. It allows, for example, defining the behavior of equipments in redundancy, as it is the case of the filters and heat exchangers, or in stand-by, as it is the case of motorpumps.

Obtained the set of events that constitute the limit of resolution of the fault tree and identified the called basic causes and the occurrence probabilities of the basic causes, the next stage on the fault tree analysis is the determination of the minimum cuts. A cut of a FT is a set of basic events whose occurrence implies in the occurrence of the event top. And a minimum cut is a set of basic events that cannot be reduced without losing the cut condition or is the minimum combination of events that when they occur they lead to the system failure. The FT in study possesses 98 minimum cuts, such that 1 is a first-class one, 87 second-class, 9 third and 1 fourth.

The critical minimum cuts, that is, the ones with bigger probability of occur are the failure in the heat exchangers due to incrustation in the inox plaques, with occurrence probability $1{,}421 \cdot 10^{-7}$ failures/hour and the failure in the motorpumps command and control circuits, with occurrence probability $1{,}568 \cdot 10^{-9}$. The failures in the heat exchangers are considered critical minimum cuts in function of the great occurrence of this type of failure, as observed in the Table (2). In this in case, one notices that the equipment redundancy protection allowed that the most frequent imperfection of all hydraulic generating unit 04, dirt in the heat exchangers of the combined bearing, was not so intensely reflected in the top event, once although the 19 cases of dirt in the heat exchangers registered on the administrative orders of the plant, the probability of this minimum cut provoking a failure in the system in study is of magnitude order of one in ten million $\left(10^{-7}\right)$. It is important to emphasize that the probability of failure occurrence in equipments that operate at redundancy is equal to the product of the failure probabilities of each equipment operating separately.

7. CONCLUSION

Comparing the answers of each one of two reliability analysis tools, different results can be observed. The FMEA analysis indicates that the critical components of the system are the motorpumps command and control circuits and the filters. This result comes from the relatively high severity that the failures in these components present. The failures in the command circuits of the motorpumps can make their automatic commutation impracticable, which can cause stop in the turbine-generator group for insufficient oil outflow, low oil level in the container or high temperature. And the deterioration of the filter meshes makes the correct oil filtering impracticable, modifying the physical properties of the oil lubrication and, therefore, causing extreme attrition and high system temperature. These two cited failures are considered severe and must be prioritized in an eventual decision -taking about maintenance.

However, these two above-mentioned equipment, motorpumps and filters, are in redundancy, as it can be observed in the fault tree. So, the probability that failures in these equipments affect the rest of the system is much reduced. The FTA analysis considers as critical components of the lubrication and cooling system on the combined bearing, the heat exchangers and the command circuits of motorpumps. Although the exchangers does not present failures considered severe, they present failures much frequent. It is observed that FTA analysis does not consider the severity of the failures, but only the occurrence. Therefore, when a FTA analysis is developed, the top event must be selected carefully, in way that all the basic events can be considered, in a certain form, severe. The second component most critical, found by the FTA corresponds to the component most critical found by the FMEA, which it indicates that the failure in the motorpumps command circuit is as severe as frequent.

At last, it is verified that the two techniques, FMEA and FTA, have great importance for evaluation of potential failures in a system. They propitiate an objective analysis to system project for justify changes, analyze common failure modes and demonstrate attendance to the security requirements. They are techniques that complement themselves. It is recommended that both be used for a more complete reliability study. The techniques FMEA and FTA can provide to the company: a systematic mean of cataloguing information about the products/processes failures; better knowledge about the problems in the products/processes; actions of improvement in the product/process project based on properly monitored data; reduction of costs trough the failure-occurrence prevention; the benefit of incorporating inside the organization the attitude of failure prevention, the attitude of cooperation and work in team and the concern with the customers satisfaction.

Both analyzes possess great advantages: FMEA for meticulously listing each failure mode and making possible the classification of failures not only for the frequency with that they occur, but also for severity that they present and for the degree of difficulty to be detected. And FTA for making possible to the analyst a general vision of the plant components and the manner which they relate. It allows to easily identify the process defects and to propose improvements as protections for redundancies or efficient monitoring systems.

The analysis done using FTA and FMEA must lead to the elaboration of a plan of action to execute the recommended corrective or preventive maintenance actions. It was observed by the application of these techniques, that the system in study has a very high reliability, with failure rates very reduced due to the equipment redundancy. An adequate improvement suggested in this in case may be a planning in direction to reduce the dirt accumulation in the heat exchangers, so that this failure mode will not be accused as critical by the FTA. A manner to do this may be improving the filtering of the water that circulates up to exchangers or modifying the point of water taking in the spiral box of the turbine, in a way that enters a lesser amount of dirt.

8. REFERENCES

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9. RESPONSIBILITY NOTICE