APPLICATION OF RELIABILITY TECHNIQUES FOR SELECTION OF MAINTENANCE POLICIES IN SPEED GOVERNING SYSTEM OF TURBINE FRANCIS

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Abstract. *The consumer is increasing its demanding in the quality of the electrical energy which must be defined with a voltage and a current with a given nominal value and a specific frequency. To keep the frequency constant it is necessary that the machinery involved in the production of electrical energy, keeps a constant speed and must be able to correct any derivation in the pre–defined speed. This study aims at developing a method to select maintenance policies for components of the speed governing system of the Francis turbine, through the application of reliability based techniques like FMEA (Failure mode and effects analysis) and FTA (Fault tree analysis).The use of those system reliability analysis methods aims at defining the possible failure modes presented by the governing system components and their consequencesfor the system operation. For the critical components it is possible to select preventive actions to avoid failures based on RCM concepts, ensuring a reduction in maintenance costs and increasing availability due to reduction of corrective interventions. At the end of the paper the proposed methodology is applied in the analysis of a 30MW hydro generator speed governing system.*

Keywords*: Speed governing system, reliability techniques and RCM.*

1. INTRODUCTION

Brazil is a world power in generating electrical energy with the use of hydroelectric power plants, because it has the largest hydrographic basin in the world. According to the national energy balance carried out by the Ministry of Mines and Energy in 2008, approximately 73.1% of national production of electric energy is obtained from hydropower plants.

The consumer is demanding more quality of the electrical energy which must be defined by nominal voltage and nominal current and a specific frequency. To keep the frequency constant, it is necessary that the machinery involved in the production of electric energy run with constant speed and must be able to correct any deviation in the speed caused by variable power output demand. These deviations will be corrected by the speed governing system.

The speed governor of a hydrogenerator has the function of controlling the hydro power that is converted into mechanical power to match the electrical energy demand and to prevent loss of synchronism. Additionally, it is indirectly responsible for the quality of electrical energy generated (De Negri, 2001) and (Yesid, 2006).

This study aims at presenting a method for selecting maintenance policies in the speed governing system of the Francis turbine. The method is developed through the application of reliability analysis techniques. From the results of this analysis the critical system components are identified, in other words, those whose failures cause loss of performance. For those components a maintenance proposal based on the concepts of Reliability Centered Maintenance (RCM) is presented in order to reduce their frequency of failure.

2. RELIABILITY CENTERED MAINTENANCE

This process finds its origins in the international commercial aviation industry. Driven by the need to improve reliability of the aircrafts, this industry has developed a broad process to decide which maintenance works are needed to keep an airplane flying in safety conditions. This process has evolved permanently since its beginnings in 1960 (Moubray, 2000) and (Smith and Hinchcliffe, 2004).

According to Moubray (2000), a broader definition of the RCM could be "a process that is used to determine what should be done to ensure that a physical element continue to perform the required functions in its present operating context".

The main aim of RCM is to reduce maintenance costs, focusing on the most important functions of the system and avoiding maintenance actions that are not strictly necessary. If a maintenance program already exists, the result of a RCM analysis will often be eliminating ineffective preventive maintenance tasks.

The deployment of a RCM program involves a series of steps and activities in a sequential way, which are:

a) Definition of system
b) Data and information collection
c) Functional Description – elaboration of the Functional tree
d) Failure Modes and Effects Analysis (FMEA) - determination of the consequence of system's functional failure associated with each component failure modes.
e) Identification of critical components.
f) Selection of maintenance policies for critical components.
g) Evaluating the results of implementing these policies.

3. METHOD

The proposed method is based on the Reliability Centered Maintenance philosophy, and intends to determine and to identify the critical components of the hydraulic system in speed governing system of Francis turbine, and to propose maintenance policies based on the Reliability Centered Maintenance concepts. Figure 1 shows the method schematically, showing the sequence of activities associated with its application.

The first step involves the study of the hydraulic system of the speed governing system, detailing the functional architecture of each subsystem.

The second step involves the elaboration of the functional description (identifying the functions of each of the components of the system) and elaboration of the functional tree (graphical representation of the functional relations of equipment components). This tree should be observed as a system, which will be divided into subsystems. The third step of method aims at identifying the critical components through the application of two system reliability analysis techniques: failure modes and effects analysis and fault tree analysis.

Once defined the critical components the most appropriate maintenance policies are selected, through the application of decision diagrams for selection of maintenance practices proposed by the RCM philosophy.

4. APPLICATION OF METHOD

4.1. Speed Governing System.

The use of speed governing system started in the seventeenth century by James Watt, who developed a centrifugal controller of speed in a steam engine. The Watt speed governing system is one of the most important mechanical devices because of its role in the early development of control theory.

The speed governing system has the primary function of increasing or decreasing the power generated by the turbine when speed or frequency deviate from a reference value. According to the system demand, the speed governing system acts on the position of the blades of the distributor controlling the distributor opening and therefore the flow that reaches the rotor, generating only the required power for consumption (Yesid, 2006).

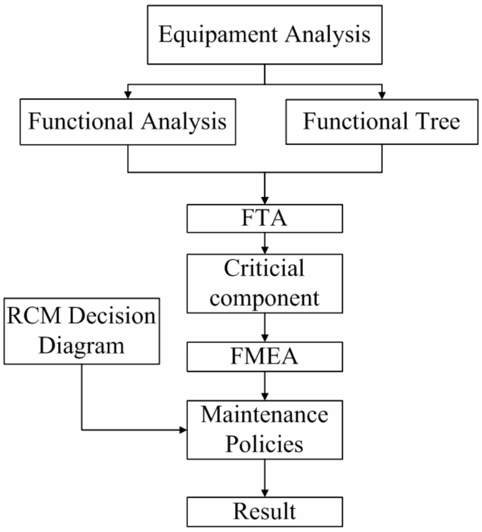

Figure 1. Flowchart of proposed method

The speed governor is an electro-mechanical device that detects any variation of speed in the turbine shaft and the correct it according to a reference value. In the case of Francis turbines an hydraulic actuator is used to move the ring distributor and consequently, to adjust the water flow. The distributor is a ring of adjustable blades involving the turbine rotor. To change the rotation speed of the turbine it is necessary to modify the volume of water flowing through the rotor. Figure 2 shows the hydraulic diagram for the speed governing system.

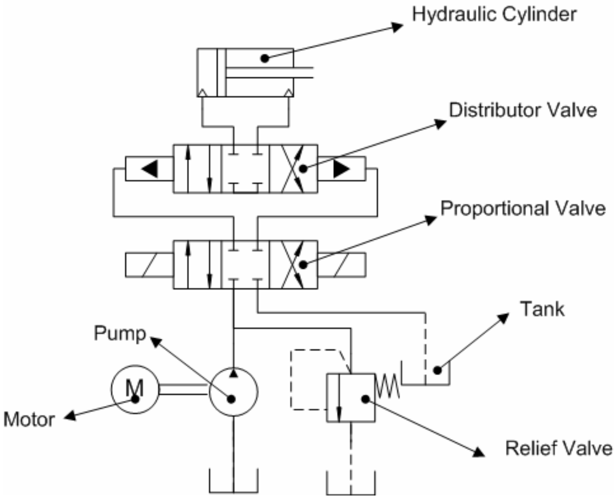

Figure 2. Hydraulic Diagram of Speed Governing System

4.2. Functional Tree

To elaborate a functional tree it is necessary to know the logic of system operation. For this study it is necessary to understand the operating scheme of the hydraulic system of speed governing system, defining the functional relation between subsystems and components (Souza, 2008).

To elaborate the functional tree it is necessary to answer the following questions: 1) How is executed (fulfilled) a pre-defined function? or 2) Why a function must be performed?.

Starting from the primary level that defines the function of the hydraulic system in speed governing system, the response to the first question leads us to a level below and the functions that ensure compliance of the above level function and successively until the level of equipment/components. The answer to second question goes down-up or from the level of components until to the primary level and provides a form of check the tree. The functional tree for the system hydraulic of speed governing system of the Francis turbine is presented in Fig. 3.

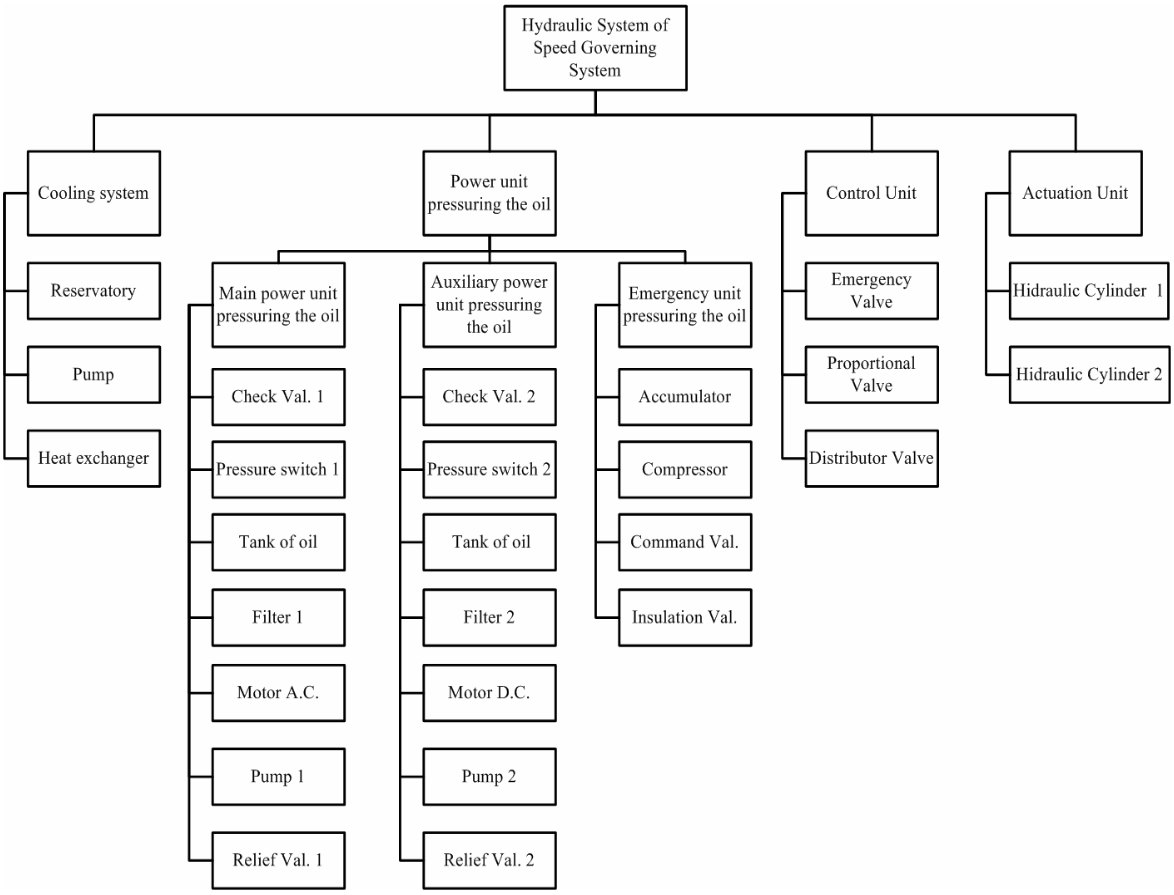

Figure 3. Functional Tree of Speed Governing System

4.3. Failure Modes and Effects Analysis

The method of Failure Modes and Effects Analysis (FMEA) originated in the military environment, being frequently cited the standard MIL-STD 1629A. According to Jingyi et al (2001) and Cassanelli (2006) the FMEA analysis is defined as a procedure by the which each potential failure mode in one component of system is analyzed to determine the results or effects of its occurrence in the operating performance of the system, enabling to classify each potential failure mode according to their severity.

To develop the FMEA analysis is used a table consisting of six columns as indicated in Tab. 1: Component (identification of each component that belongs to the system), function (brief description of task that must be executed by the component), potential failure mode (Description of the form that the failure is observed by the operation team), failure cause (simple and concise description of the physical mechanism associated with the failure mode), failure effect (Consequence of the occurrence of failure, for the system operational performance), severity (this is an indicator that reflects the gravity of the consequences of the failures about the operational condition of system).

This study uses a classification of severity ranging from 1 to 9. Levels 1-3 are associated with faults that affect slightly the performance of hydro generator. The levels of severity 4-6 affect the operational performance, causing restrictions on the generated power output. The levels 7-9, which are described in Tab. 2, represent situations that causes the failure of hydrogenerator without power output, and even could cause damage to the environment. Failures classified between the levels 7-9 of severity are considered the most critical for the operation of hydro generator. The components which failure cause those consequences should be object of the RCM analysis.

Table 1. Failure Mode and Effect Analysis Sheet

Failure Mode and Effect Analysis					
Component	Fucntional	Failure Mode	Failure Causes	Failure Effects	Severity

Table 2. Severity Index Description for FMEA Analysis

Criticality Index	Effects on the Turbine Operation
7 (Severe)	This severity ranking is given when a component potential failure mode can cause unavailability of the equipment but does not cause damage to other equipment components, possibly affecting: i) the equipment operation, since it must be stopped; ii) the environmental in a severe manner; iii) the compliance with government requirements. The failure also causes the need for repair and/or replacement of the failed component. The plant is unavailable for a short period of time.
8 (Very Severe)	This severity ranking is given when a component potential failure mode can cause unavailability of the equipment but does not cause damage to other equipment components, possibly affecting: i) the equipment operation, since it must be stopped; ii) the environmental in a very severe manner; iii) compliance with government requirements. The failure also causes the need for repair and/or replacement of the failed component. The plant is unavailable for a long period of time.
9 (Hazardous Effects)	This severity ranking is given when a component potential failure mode can cause severe damage to other components and/or to the equipment, possibly affecting: i) the equipment operation, since it must be stopped; ii) the environmental safety, including leakage of hazardous materials; iii) the safe power plant operation; iv) the compliance with government requirements. The failure also causes the need for repair and/or replacement of a great number of components. The plant is unavailable for long period of time.

As an example the failure modes and effects analysis for the electric motor that drives the hydraulic pump is shown in Tab. 3.

Table 3. Failure mode and Effects Analysis: Example – Electric Motor

Failure Mode and Effect Analysis					
Component	**Fucntional**	**Failure Mode**	**Failure Causes**	**Failure Effects**	**Severity**
Electric Motor	Transform electrical energy in mechanical energy to drive the pump	Motor won't start	Failure in motor terminal or broken connections	Failure in the speed governing system	8
			Overloaded		
			failure in input power to star or Under-voltage		
			Loss of insulation of the coils		
			Bearings damage causing excessive friction		

4.4. Failure Tree Analysis

The Fault Tree Analysis was introduced in 1962 and became one of main techniques to evaluate systems reliability, being widely applied in various industrial sectors, where the system reliability has fundamental importance to assure the safety of operations and efficient of themselves. It was originally proposed Bell Telephone Laboratories for the evaluation of the reliability of the launching control system of Minuteman missile (RAUSAND and ARNLJOT, 2004).

The FTA is basically a deductive method that aims at identifying the causes or causes combination that could lead to the defined top event. The analysis is basically qualitative, however, depending on conditions, can also be quantitative.

The methodology of the FTA can be divided into four phases:

- Define the system, the top event (accident potential);
- Construction of the failure tree;
- Qualitative analysis of the failure tree;
- Quantitative analysis of the failure tree.

A fault tree analysis of speed governing system of hydraulic turbines is show in the Fig. 4, considering the top event "Total stop of the speed governing system", which represents the group of failure that cause lack of mobility of the hydraulic actuators.

4.4.1 Qualitative analysis of the fault Tree

Once is elaborated the fault tree for the top events, the qualitative evaluation of combinations of the basic events that cause the occurrence of the top event can be executed. This analysis aims at identifying the minimal cut sets that would cause the top event. To identify the minimal cut sets it is necessary to apply the main laws of Boolean algebra.

For the top event "Total stop of the speed governing system", shown in Fig. 4, and applying the Boolean algebra concepts, the expression presented is Eq. 1 is obtained, representing the result of qualitative analysis with combinations of basic events that would led to the occurrence of the event top.

$$\text{Top event} = X1 + X2 + (X3)(X6) + (X3)(X7) + (X3)(X8) + (X3)(X9) + (X4)(X6) + (X4)(X7) + (X4)(X8) + (X4)(X9) + (X5)(X6) + (X5)(X7) + (X5)(X8) + (X5)(X9) + X10 + X11 + X12 + X13 + X14. \tag{1}$$

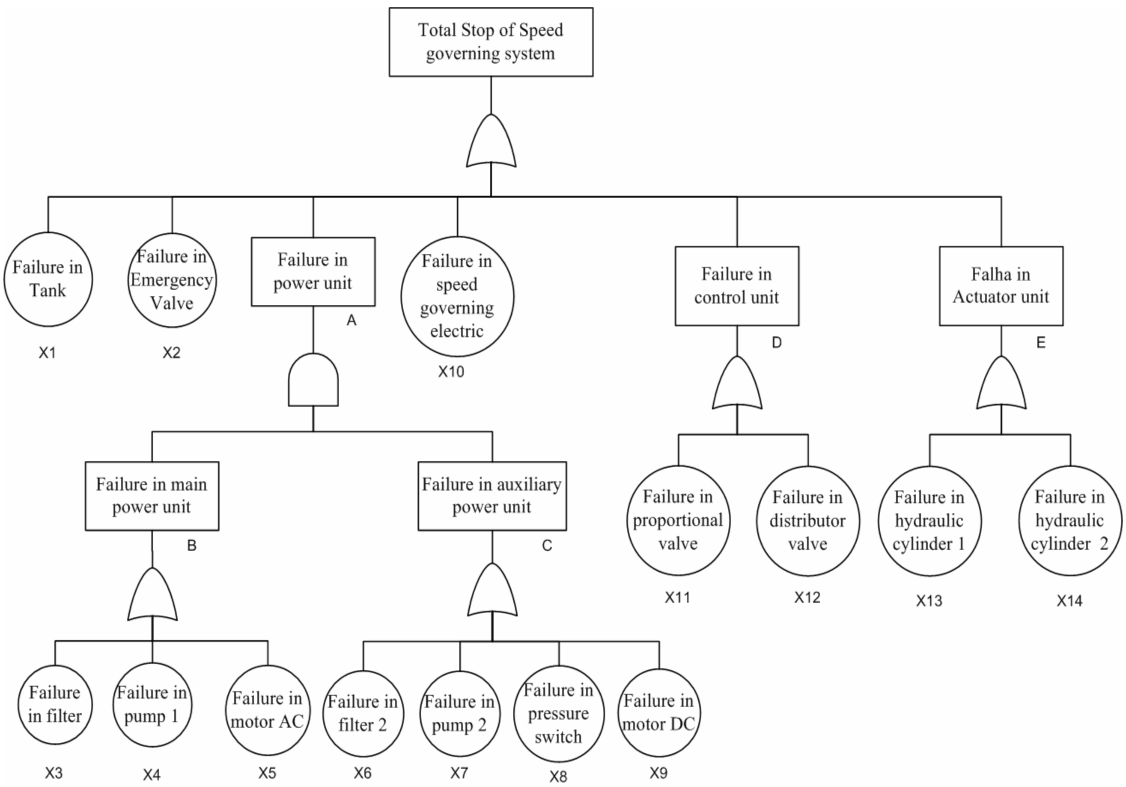

Figure 4. Fault Tree Analysis of Speed Governing System

4.4.1 Quantitative analysis of the fault Tree

The quantitative analysis was developed to estimate the probability of occurrence of the event and the cut set importance. The cut set calculated on qualitative analysis will be evaluated quantitative. Once the failure probability of basic events are determined, the effect of the basic events on the top event probability can be evaluated quantitatively.

Table 4 lists the basic events or failure causes with their respective failure probabilities. Those data were obtained from Smith (1997) and Chandler (1995). The failure probability of the hydraulic system was calculated for an operational time of 2000 hours. After that operational time the hydraulic fluid should be changed, according to Drapinski (1975). The type of distributions used to calculate the probabilities of failure are Exponential and Weibull.

Table 4. Basic events or causes of fault and their failure probability

			Distribution		
			Weibull		Exponencial
Cause identification	Cause description	Failure probabitity (2000 hours)	β	η (hours)	λ (Failure/ hours)
X1	Failure in Tank	0.0001			5.64E-08
X2	Failure in Emergency valve	0.0187			9.44E-06
A	Failure in the power unit pressuring the oil				
B	Failure in the main power unit pressuring the oil				
X3	Failure in filter 1	0.0603	1.1	25000	
X4	Failure in Pump 1	0.0286	1.1	50000	
X5	Failure in electric motor AC	0.0091	1.2	100000	
C	Failure in the auxiliary power unit pressuring the oil				
X6	Failure in filter 2	0.0663	1.1	25000	
X7	Failure in Pump 2	0.0286	1.1	50000	
X8	Failure in the pressure switch 1	0.0094			4.71E-06
X9	Failure in electric motor DC	0.0208	1.2	50000	
X10	Failure of speed governing electric	0.0005			5.71E-08
D	Failure in the control unit				
X11	Failure in the Proportional valve	0.0187			9.44 E-06
X12	Failure in the Distributor valve	0.0198	1	100000	
E	Failure in the actuation unit				
X13	Failure in Cylinder Hydrauic 1	0.0044	2	900000	
X14	Failure in Cylinder Hydrauic 2	0.0044	2	900000	

The Table 4 shows that the proportional and distribution valve have the reliability represented by Exponential and Weibull distribution, respectively. However, the shape parameter´s value (β) is equal to 1. In this situation, the Weibull distribution represents the exponential distribution, whose failure rate is equal to 1 / η (scale parameter). Therefore, the reliability of these mentioned valves are represented by an Exponential distribution.

The failure probabilities of basic events are substituted into Eq. 1 and the result for probability of occurrence of the top event is 8.1%, or the hydraulic system reliability is 91.9%. It is important for the proper performance of the hydraulic system to maintain the features of the hydraulic fluid, and depending on the work pattern it must be changed after 2000 hours of operation, aims at ensuring a reliability of approximately 90% for the system..

Cut set importance is defined as the ratio of probability of each minimal cut set to the sum of probability of all minimal cut set, equal to the probability from the simulation of the top event, meaning the importance of each minimal cut set.

The results of cut sets importance analysis are listed in Tab. 5. Information from the classification analysis of cut sets importance is useful since it allows us to identify critical components and to compare the results obtained with the classification of severity from FMEA analysis.

4.5. Selection of critical components

The selection of critical components was made based on the results of FMEA and FTA analysis. From the FMEA analysis the critical components are those that have a severity higher than 6.

Comparing the most important cut sets and the most important components identified through FMEA analysis, the pressure switch and tank were identified as critical components in the FMEA analysis, but according to cut sets importance in the FTA analysis, shown in Tab.5, they have a very small failure probability which allows us to deduce that they should not be considered as critical components of the system. In the case of the oil reservoir the maintenance team would need to perform simple tasks such as inspections and cleaning, and for the pressure switch it would be necessary to carry out inspections and supervise if it is calibrated. In case of Failure, it must be replaced.

Table 6 has a list of critical components with their respective failure modes consequence the comparison between the results of FTA and FMEA analysis. The failure of those components severely affects the hydrogenerator performance due to the inoperance of the speed governing system.

Table 5. Cut set importance of speed governing system

	Minimal cut set	Cut set importance
1	X12	0,2544
2	X2	0,2319
3	X11	0,2319
4	X13	0,0643
5	X14	0,0643
6	(X3)(X6)	0,0441
7	(X3)(X7)	0,0213
8	(X4)(X6)	0,0213
9	(X3)(X9)	0,0154
10	(X4)(X7)	0,0101
11	X10	0,0074
12	(X4)(X9)	0,0072
13	(X5)(X6)	0,0067
14	X1	0,0061
15	(X3)(X8)	0,0051
16	(X5)(X7)	0,0031
17	(X4)(X8)	0,0024
18	(X5)(X9)	0,0022
19	(X5)(X8)	0,0008

4.5. Selection and Maintenance Policies recommendation

To select an appropriate maintenance policy for the critical components the maintenance team has to apply a decision process, which allows to select the most recommended maintenance practices for each critical component, in accordance with the characteristics of their failure modes.

To apply the decision diagram proposed by RCM philosophy (Moubray, 2000) it is necessary to carry out the classification of failures of components, as a function of the consequences of their failure on the operational performance. On the point of view of decision making in maintenance, failures can be functional or potential. Functional failures are non-fulfillment of desired component functions. The potential failure is represented by the presence of physical evidences that a process of deterioration of a component is going on, which will culminate in a functional failure.

The application of maintenance decision diagram for hydraulic systems components is shown in Tab.7 taking as an example of application the analysis of the hydraulic pump.

Table 6. The most critical components of the speed governing system

System	**Sub-system**	**Component**	**Failure mode**
Speed governing system	Oil cooler	Heat exchanger	Does not cool the hydraulic fluid
	Power unit pressurizing the oil	Hydraulic Fluid	High Viscosity
			Low Viscosity
		Filter	Rupture of the filter element
			Obstructed
		Electric Motor AC	Won't start
		Electric Motor DC	Won't start
		Pump	Pump delivers abnormal or unstable flow
			External leakage
		Relief valve	Does not regulate the pressure
		Accumulator	Total loss of the accumulator
	Control unit	Emergency valve	Does not move
		Proportional valve	Does not move
			Does not adequately respond to the command
		Distributor valve	Does not move
			Does not adequately respond to the command
			External leakage
	Actuation unit	Hydraulic cylinder	Does not move
			Incorrect speed
			External leakage
			Insufficient force

Table 7. Maintenance policies for the Electric Motor AC.

	System				Speed Governing System						
	Component				Electric Motor AC						
Failure Modes	Consequence evaluation				H1	H2	H3	Default action			Proposed Task
					S1	S2	S3				
					O1	O1	O3				
	H	S	E	O	N1	N1	N3	H4	H5	S4	
Motor won't start	N	S	S	S	X	X					Preventive maintenance task 1. Check all electrical connections 2. Bearing Lubrication 3. Motor cleaning
											Predictive maintenance task 1. Vibration analysis 2. Thermography analysis 3. Electrical test (insultion Resistance)

According to Jingyi (2006) about 50% of the problems encountered in hydraulic systems are related to the hydraulic fluid. In FMEA analysis it could be noted that the hydraulic fluid is a major contributor in the propagation of failure modes through the hydraulic system of the speed governing system. In this way, maintaining, controlling or eliminating the failure modes of the hydraulic fluid, can prevent a greater number of undesirable effects on the system.

It recommends carrying out periodical oil analysis. The tests can be performed to determine the viscosity, particle contamination and the presence of water in the fluid. The results of those tests will allow the maintenance team to identify the quality and state of the hydraulic fluid.

Others very important elements in the hydraulic system are the filters. The state of the filters is shown by the pressure difference observed between the input and output, which indicates possible obstruction of the component. The filters must be changed before they are blocked or occurs rupture of the filter element. The temporal evolution of this pressure differential is indicative of the occurrence of deposits on the filter and can be used as a parameter for applying the practice of predictive maintenance.

To improve the system´s reliability is important to follow each one of the recommended maintenance tasks, in order to reduce the failure rate of the component and increase the availability as well. According to the maintenance policies is important to install sensors in the pump to allow the use of the monitoring system for checking the pump´s vibration, the oil´s temperature and the flow. Also carry out the oil´s analysis monthly with the objective of identify the presence of the metallic particles in the fluid that wear the pump and valves seal. With the result of diagnoses of the oil´s analysis can decrease the failure rate of the most critical components which are: the proportional, distribution and emergency valves. Doing this reduction of the failure rate in those component, the result was the improvement the system´s reliability achieved the value of 94,9%.

5. CONCLUSIONS

Firstly it can be concluded that the method developed to elaborate the model for selection of maintenance policies of speed governing system was adequate to the purpose of study. It highlights the importance of following the flowchart proposed in Fig.1, showing the sequence of activities that allow making a detailed and reliable analysis because they are used and organized in a logical order.

This paper shows that the FMEA analysis can be used for the survey of all the failure modes that can be potentially eliminated or controlled by maintenance actions. The effect of failure modes serves as basis for evaluating their consequences on the safety of operators, environment and performance of the main function of the hydraulic speed regulator.

The results of FMEA and FTA analysis provide subsidies for development of maintenance procedures (corrective and preventive) and even for a monitoring system (predictive maintenance).

In the sequence it was performed the application of quantitative and qualitative analysis of the fault tree. The qualitative analysis identified the minimal cut sets that will cause the top event –The total stop of speed governing – as shown in Eq.1. With the identification of the cut sets, carry the quantitative analysis was executed, resulting in the failure probability of 8.1% for an operating time of 2000 hours. Hydraulic fluid change every 2000 hours, will ensure a reliability of approximately 90%.

Finally applying the suitable maintenance policies is possible to decrease de failure rate of the valves, consequently it can improve the reliability of the system obtaining a value of 94,9%.

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