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ANALYSIS OF MAINTENANCE OPTIMIZATION IN A HYDROELECTRIC POWER PLANT

Francisco Javier Martinez Monseco*

Escuela Tecnica superior de Ingenieros ETSI-UNED, Madrid. Spain.
Manager of the hydroelectric plants of Barcelona and Girona (Ter Unit) of the company Enel Green Power Iberia Hydro. Spain.
jmartinez1638@alumno.uned.es

Abstract:

This article presents a guide to designing a maintenance plan for any industrial system. As an example, it develops a maintenance plan for highly reliable equipment, such as a hydroelectric power plant, where instant availability and reliability are crucial in its operation. The development of the proposal serves as a basis for the transversal development of any industrial system that has the same operational objectives (manufacturing lines), transport (trains, aircraft) and also involves safety and environmental aspects in its proper functioning. Today's society requires that there are more and more industrial processes in which the maximum availability of the systems must be guaranteed, and at the same time there must be a minimum number of incidents that prevent the unavailability of the process. The methodology used has consisted firstly of dividing the complex industrial system into systems to be analysed on the basis of the functions they have to perform, then on the basis of the fault history a list of potential faults to be analysed has been determined, taking into account the risk of the system itself. From here, the systems of the hydroelectric plant have been classified to determine the priorities of actions. The different maintenance techniques to be applied have been carefully considered, focusing on the need to analyse condition-based maintenance techniques, such as predictive techniques, which allow us to define the point of potential failure based on parameters, and thus be able to plan maintenance actions in a justified manner. In the specific case of a hydroelectric generation plant, the fundamental objective is based on the commitment to operate in the electricity market (high reliability and immediate availability), and the performance of maintenance actions imply in most cases the shutdown of the plant and therefore the loss of income from electricity production. Finally, a design of a justified maintenance plan for a hydroelectric power plant has been proposed based on the methodology explained.

Keywords: Maintenance; reliability, power plants, industrial processes.

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1. Introduction

In maintenance, the questions a technical maintenance manager asks in the course of his work are often:

- Am I really doing the right maintenance on the equipment?
- Could I do more to make the system more reliable?
- How could I improve the system's maintenance plan?

Many times the maintenance to be done of any industrial system is based on the "maintenance book" that exists in each industry and is untouchable, but the daily experience of maintenance has to serve us to have the necessary information to contribute to the improvement and modification of the own maintenance of the system.

This article analyses a complex industrial system such as a hydroelectric power plant based on the analysis of the different functional systems that make it up as well as the potential system failures and the maintenance techniques to be applied. It also reflects the importance of each system to fulfil the function and takes into account the condition-based maintenance techniques that will help us to make decisions on the frequency of maintenance actions.

2. Maintenance function

Maintenance is the set of actions necessary to conserve or restore a system in a state that guarantees its operation at a minimum cost. (Moubray, 2002).

According to the previous definition, different activities are deduced:

- Prevent and / or correct breakdowns.
- Quantify and / or evaluate the state of the facilities.
- Economic aspects (costs).

3. Maintenance plan for high reliability equipment (hydroelectric power plant)

3.1. Definition of systems, equipment, degree of criticality and maintenance model of a hydroelectric power plant

Firstly, the different functional systems that make up the hydroelectric plant are identified so that each can be analysed individually.

*Corresponding author: F.J. Martínez, jmartinez1638@alumno.uned.es

The systems of a hydroelectric plant are:

- Alternator.
- Turbine.
- Telecontrol system.
- Guard valve.
- High voltage electrical equipment.
- Voltage generator equipment.
- Protective equipment.
- Refrigeration equipment.
- Power transformer.
- Auxiliar equipment (CA-CC).

3.2. Failure modes and standard fault types of a hydroelectric power plant

To define the failure modes and types of failures associated to a hydroelectric power plant, an analysis was carried out based on several considerations (Moubray, 1997; Hattagandi, 2005). Historical data of incidents of the set of hydroelectric plants. Experience contributed in the historical maintenance of the hydroelectric power plants, as well as the incidents that occurred. (Professional experience of the maintainers of this type of systems). Analysis of maintenance strategies and their results in planning developments.

Table 1 is a list of the standard failure modes and failure types that have been typified based on the standard incident history of hydroelectric power plants. The criteria for this definition of failure modes and functional failures are based on the technical reasons that have caused the hydropower plant to be unavailable to perform its function (electricity generation).

Table 1: Failure modes and standard functional faults analysed in a hydroelectric plant.

failure mode	functional failure
disarm	action of electrical protections group
	action of mechanical protections group
	camera level action
	channel level performance
	action forced pressure piping
	group synchronization lock
	lack of conditions in operation
	lack of parameters of group operation
	covering grids
overcapacity	external electrical protections
	water flood
	lack of water flow
group design-control	lack of communications
	lack of telecontrol
	automation operation failure
	automatism relay failure
	electronic card failure control
	automatic lock PLC
	operation sequences failure
civil work	pipe break
	water channel break
	break valve
	breakage of hydraulic gate
	grieet settlements
	pipe water leaks
	crack mechanical equipment
physical deterioration	oxidations
	throwings mechanical elements
	bad mechanical operation
	bad electrical operation
electrical deterioration	temperature trip
	lack of command
	lost parameters in regulation of turbine
	lost parameters of lubrication
	lost parameters of refrigeration
	lost parameters of guard valve
	lost transformation parameters
	lost operating parameters
	ca-cc magnetothermic trip
	high voltage switch failures
	electrical problems in tt / ti measurement and protection
	electrical drives
	lost parameters voltage regulation
mechanical deterioration	temperature trip
	lack of command
	lost parameters in regulation of turbine
	lost parameters of lubrication
	lost parameters of refrigeration
	lost parameters of guard valve
	lost transformation parameters
	lost operating parameters
	filter problems
	lost of speed detection
	breaks mechanical equipment
	valves failure
	coal joint fail
	lost parameters of voltage regulation
maintenance failure	problems of measurement equipment
	problems of control equipment
	low-high levels
	shoot measurement equipment
	shoot control equipment
	setting operating parameters
	final career failure
	circulators-flow faults
	soon detection anomalies

(Table 1, continues in next column)

(Table 1, continues from previous column)

3.3. Criticality analysis of hydroelectric power station equipment

After dividing the complex system into functional systems that can be analyzed, the criticality of each system must be taken into account to set priorities in maintenance actions. the economic management of the physical assets will always be limited by the management of the company.

The characteristics of the maintenance plan of each equipment of the hydroelectric power plant are indicated in Table 2, different types are based in the definition of criticality (Bloom, 2006; Sifonte, 2017).

Table 2: Characteristics of each type of equipment according to their criticality in operation.

high reliability system (c)	• safety and environment. - very serious accidents. - periodic reviews. - accidents have occurred. • production. - your stop affects the production plan. • quality. - it is key to product quality. - it is the cause of a high percentage of - incidents. • maintenance. - high repair cost in case of breakdown. - very frequent breakdowns. - consumes an important part of the resources of maintenance.
important system (i)	• safety and environment. - needs periodic (annual) reviews. - it can cause a serious accident. • production. - it affects production but is recoverable. • quality. - affects quality but is not problematic. • maintenance. - maintenance cost.
dispensable (d)	• safety and environment - little influence on security • production - little influence on production • quality - does not affect the quality • maintenance - low maintenance cost

In order to define the maintenance strategy to be used, it is necessary to justify the cost that we are going to propose in the analysis of the maintenance plan.

Depending on the degree of availability of the system to be analysed, we can define the maintenance modes to be performed (Table 3).

3.4. Maintenance objectives of the hydroelectric power plant

A hydroelectric power station constitutes a highly reliable equipment due to the need for instantaneous availability and reliability (operating conditions of the electricity market) and therefore the realization of a correct maintenance plan is crucial in its operation. Table 4 shows the conditions and criteria that are usually managed into account in current maintenance strategies, to define the maintenance objectives of the system to be analysed.

In most power plants, the maintenance developed involves making a series of “routines” included in the initial maintenance history book. but any maintenance department should analyze if what it is doing is useful for the objective of improving system reliability.

3.5. Maintenance operations according to the maintenance mode of the hydroelectric power station equipment.

We have defined the systems, equipment, degrees of criticality of each system as well as maintenance objectives of the hydroelectric power plant. The next step is to define the operations to be carried out within each maintenance mode to be implemented in the development of the maintenance plan in question (Table 4). In the following sections the actions to be implemented in the maintenance modes considered are developed (Calixto, 2016; Sifonte, 2017).

Table 4: List of maintenance operations in each equipment maintenance mode.

1.	corrective maintenance mode - inspection acknowledgments.
2.	conditional maintenance mode - inspection paths - conditional maintenance operations
3.	system maintenance mod - inspection paths - conditional maintenance operations - maintenance operations cyclical reconditioning - preventive maintenance operations.
4.	high reliability maintenance mode - inspection paths - conditional maintenance operations - maintenance operations cyclical reconditioning - preventive maintenance operations - predictive maintenance operations - redesign operations.

3.5.1. Inspection routes

The inspection routes are intended to detect accidental damage, to detect unexpected variations in fault behaviour, and also to detect problems due to cleaning and maintenance.

Table 3: Maintenance planning based on system availability.

availability >90%	high availability	low availability
.high reliability maintenance mode	systematic maintenance mode	conditional maintenance mode
legal maintenance	outsourced maintenance	
legal regulations	lack of means or knowledge	
very low indisponibility		
corrective maintenance mode		

Inspection routes are based on a visual inspection of the elements of a plant. Figure 1 shows a maintenance action observed through the inspection routes

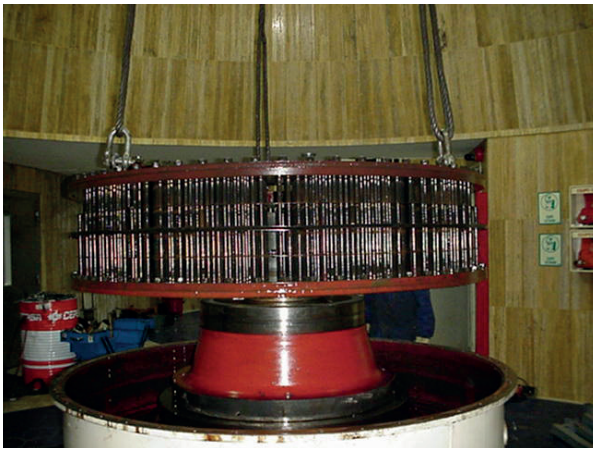

Figure 1: Repair work of the refrigerant circuit bearing by maintenance analysis through inspection paths and monitoring parameters (Enel Green Power-Endesa Generation).

3.5.2. Conditional maintenance operations

If a maintenance operation that reduces the risk of the associated multiple failure can't be found, a fault search task must be performed.

The search for failures is feasible if:

- It is possible to perform the task
- Homework does not increase the risk of a multiple failure
- It is practical to perform the task at the required interval.

It is worthwhile to perform the fault search if you reduce the probability of the multiple failure associated with a tolerable level.

The condition tasks consist of checking for potential failures so that action can be taken to prevent functional failure or avoid the consequences of functional failure. The P-F interval is the interval between the moment when a potential failure occurs and its decay until it becomes a functional failure.

Conditional tasks must be performed at intervals below the P-F interval

- It is possible to define potential fault conditions.
- Reasonably consistent P-F interval.

3.5.3. Cyclic maintenance operations

Cyclic reconditioning consists of reconditioning the equipment capacity before the defined age limit, regardless of its condition at that time.

Cyclic replacement tasks consist of discarding an element or equipment (the frequency is determined by the age at which the element shows a rapid increase in the conditional probability of the failure).

3.5.4. Preventive maintenance operations

Preventive maintenance is based in proactive tasks that they are carried out before the failure occurs in order to prevent the equipment from reaching the fault state. A maintenance operation is technically feasible if it physically reduces the consequences of a failure mode to an acceptable level. Figure 2 shows a redesigned maintenance action based on the preventive maintenance actions considered.

Figure 2: Assembly work of oil injection circuit to the pivot bearing of the hydroelectric group due to redesign by preventive maintenance analysis (Enel Green Power-Endesa Generation).

3.5.5. Predictive maintenance operations

One of the most important aspects in the analysis of the maintenance that is carried out is to have information at all times of the state of the system. This information is key to decide when to carry out the maintenance actions, optimizing the maximum period of availability of the plant and minimizing the losses due to stop and therefore no electrical production. For all this, the application of predictive maintenance techniques is very important due to their low impact in terms of hydroelectric plant shutdowns and because of the information we can obtain to make decisions on the application of maintenance actions.

The operation of the machines modifies their dynamic response, either by electrical or mechanical origin. Predictive maintenance attempts to diagnose the fault when it begins to manifest itself and is not yet serious for the system (Bloom, 2006). Its objectives are:

- Need for a reduction in maintenance expenses. Planning and reduction of catastrophic breakdowns.
- Need to increase availability.
- To do this, take advantage of:
- Potential of monitoring systems.
- Automation and remote control.
- Technological evolution of communication networks and their connection.
- This is a set of techniques that, duly selected, allow the monitoring and examination of certain characteristic

parameters of the equipment under study, which manifest some type of modification when an anomaly appears in it.

- Most machine failures appear incipiently, to a degree where detection is possible before it becomes an accomplished event with irreversible repercussions on both production and maintenance costs. It is necessary to establish a follow-up of those parameters that can notify us of the beginning of an impairment and establish for each of them what level we will admit as normal and which inadmissible, so that its detection triggers the relevant action.

The monitoring and control of the parameters can be done through periodic surveillance, in which case it is important to establish a frequency that allows us to detect deterioration at a time between P and F, and that it is not too late to react.

It can also be done through continuous monitoring which avoids the previous inconvenience, but it is not always feasible, and, in any case, it is more expensive. So finally, the parameters to be controlled and the form depends on economic factors:

- Importance of the machine in the production process
- Instrumentation necessary for control.

The equipment to which different state control techniques can be applied with proven efficiency are:

- Rotative machines
- Electric motors-Static equipment
- Electrical shield
- Instrumentation.

The advantages of this type of maintenance are that, when the state of the equipment is always known, it allows detecting failures in an incipient state, which prevents it from reaching undesirable proportions. Also, we can consider it allows to increase the useful life of the components, avoiding replacement before they are damaged. And finally, when the status of a defect is known, the stops and repairs can be programmed, providing for the necessary spare parts, which reduces the unavailability times (Bloom, 2006).

Tables 5,6 and Figures 3 and 4 summarize the techniques and parameters currently used for the state control for different types of equipment.

Table 5: Predictive maintenance techniques and characteristics.

maintenance management	damage and wear detection
vibratory tracking	repair control
oil analysis	avoid harmful operating condition.
alternators diagnosis	identification of vibration problems due to design or assembly
transformers diagnosis	reduction of maintenance costs
thermographs	increase availability increase intervals without repair

Figure 3: Power transformer replacement work due to predictive maintenance data analysis (dielectric oil analysis) (Enel Green Power-Endesa Generation).

Table 6: Predictive maintenance techniques used in high reliability equipment.

penetrating liquids. it is a non-destructive inspection that is used to find superficial cracks or internal failures of the material that present some opening in the surface. the test consists in the application of a special dye and subsequent treatment with absorbent liquid, marking the pores or superficial cracks.
magnetic particles. this is another non-destructive test based on the magnetization of a ferromagnetic material when subjected to a magnetic field. it is subjected to a magnetic field and magnetic particles are spread, oriented in the existing flow lines (defects marked by discontinuities).
radiographic inspection. technique used for the detection of internal defects of the material (by radiography) such as cracks, bubbles or internal impurities. especially indicated in the quality control of welded joints.
ultrasound. detection by means of frequency waves, of the presence of cracks (especially in thick or bulky materials).
analysis of lubricants. the quality level of the lubricating oil is an important parameter in the operation of the equipment. the properties of the lubricating oil such as degradation, contamination, etc. are analyzed by physical-chemical analysis of the samples.
vibration analysis. the vibratory level is increased if, in addition, there is a defect such as misalignment, mechanical imbalance, inadequate clearances, defective bearings. for this reason, the vibratory level can be used as a functional control parameter for the predictive maintenance of machines, establishing an alert level and an inadmissible level from which the fatigue generated by the alternating forces causes the imminent failure of the affected organs.
pressure measurement. the lubrication pressure can detect functional deficiencies in the bearings or problems in the seals due to insufficient pressure.
temperature measurement. in bearings and sliding bearings there is a significant increase in temperature when deterioration occurs. excessive elevation of the coolant temperature denotes the presence of a machine anomaly (friction, slack, etc....).
thermography. infrared photography technique to detect hot areas in devices. it is usually used in control of power lines.
shock impulses. it is used to control the condition of the bearings by controlling the speed difference between the speed of collision between rolling elements and the raceways. these impacts generate ultrasonic pressure waves in the material (shock impulses).

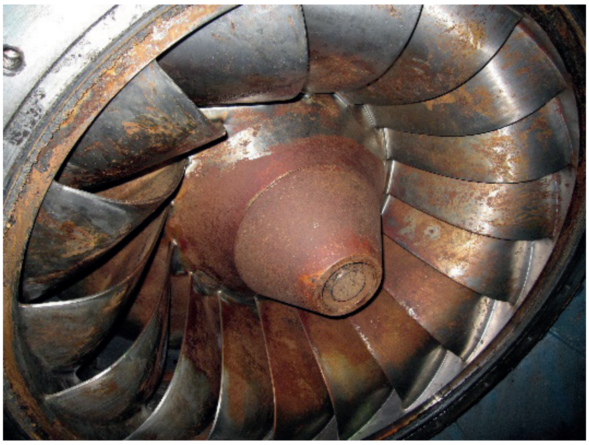

Figure 4: Mechanical disassembly of the hydroelectric group turbine due to predictive maintenance analysis (vibration and cavitation analysis) (Enel Green Power-Endesa Generation).

4. Maintenance frequency of a hydroelectric power plant

The previous chapters have analyzed the systems that make up the hydropower plant, the failure modes that have occurred in historical failures, the priority in terms of risk and consequences of the failures and the current maintenance techniques of a hydropower plant emphasizing the development of condition-based and predictive maintenance to plan the right time to stop the plant to carry out maintenance.

The following is a design of a justified maintenance plan in order to defend the costs associated with such actions before the company's management.

Once defined the actions to carry out the maintenance plan, we can define the periodical maintenance plan of the hydroelectric group based on the hours of operation. The temporary actions to be performed are divided into:

1. Every 72 hours of operation.
2. Every 4300 hours of operation.
3. Every 8700 hours of operation.
4. Every 50000 hours of operation.

Temporary actions 2-3-4 involve the management of a group shutdown by means of electric and hydraulic discharge (safety conditions of absence of electric voltage and water pressure according to regulations, work with high voltage electrical hazards).

It should be noted that in addition to the type of maintenance and periodical maintenance operations, it is necessary to make a control report of the different parameters of the hydroelectric group in order to define the feasibility and the technical-economic analysis for the realization of a large revision of the hydroelectric group (cost-opportunity investment and improvement of the system to maintain).

5. Definition of the periodical maintenance plan of a hydroelectric power plant

Attached is the list of systems, equipment, criticality consideration as well as its maintenance mode once the plant has been analyzed through the guide presented in this article.

Table 7: Definition of maintenance in the hydroelectric power plant.

system	equipment	criticity	maintenance mode
alternator	alternator	c	high reliability
alternator	measurement and control	c	high reliability
alternator	excitement	c	high reliability
alternator	ventilation-heating	i	programmed
alternator	braking	i	programmed
alternator	fire protection	i	additional schedule
turbine	speed regulator	c	high reliability
turbine	turbine	c	high reliability
turbine	drain	i	programmed
turbine	lubrication	i	on condition
turbine	media and control	c	high reliability
guardian valve	gate valve	i	maintenance condition
voltage generator equipment	disconnector	i	programmed
voltage generator equipment	switch	c	high reliability
voltage generator equipment	measures and protection	i	programmed
high tension equipment	disconnectors	i	programmed
high tension equipment	switches	c	high reliability
high tension equipment	measures and protection	i	programmed
Protected system	mechanics	i	programmed
Protected system	electric	i	programmed
refrigeration	cooling circuits	i	a.c.
refrigeration	measurement and control	i	a.c.
Power transformer	transformer	c	high reliability
telecontrol system	control-remote	i	programmed
auxiliar equipment	ac	i	additional schedule
auxiliar equipment	dc	i	additional schedule

Finally, the strategic table of the maintenance to be carried out in the development of the Maintenance Plan of a hydroelectric power plant is presented.

Table 8: Strategy for the maintenance plan of the hydroelectric power plant.

operation hours	type of maintenance	maintenance operations
72	periodic maintenance	inspection paths
		conditional maintenance operations
		operation monitoring
4300	preventive maintenance	cyclic overhaul operations
		preventive maintenance operations
		non-critical corrective actions
		performance of redesign actions
8700	predictive maintenance	preventive maintenance operations
		predictive maintenance operations
		redesign operations-new jobs
		regulatory maintenance
		annual report power station status
50000	planning improvements / redesigns	analysis of the annual reports of the state of the plant
		technical assessment of completion of major revision
		economic valuation of realization of great revision
		cost-opportunity valuation great investment work

6. Conclusions

In summary, this article has developed the methodology for designing a maintenance plan for a complex industrial system such as a hydroelectric plant, taking into account the parameters:

- The division of the hydroelectric plant into functional systems.
- Study of the failures and definition of the failure modes to define the importance of each failure in the operation of the complex system, in order to justify the cost of the actions and to define its priority, since the cost in the maintenance will always be limited by the management of the company.
- Definition of the existing maintenance techniques, making an explanation about the trend of the development of the condition-based maintenance techniques, as well as the predictive maintenance techniques
- Application of all these criteria to make a justifiable design of a maintenance plan for the complex system

This developed methodology can easily be applied to any industrial system to be maintained, and implies the justification in the proposal of the maintenance costs within the industrial company.

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