

AN APPROACH TO A PRACTICAL OPTIMIZATION OF RELIABILITY CENTERED MAINTENANCE. CASE STUDY: POWER TRANSFORMER IN HYDRO POWER PLANT

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Abstract:

Any industrial organization has to analyse the maintenance strategy that it is applying to ensure the maximum efficiency of the system. This includes to define the maintenance policy, a well-analysed maintenance plan, and correct maintenance management and operational procedures. The maintenance department in most industrial organizations has to be continuously justifying the costs associated with their activities to avoid the continuous cuts requested by management based on the economic business plan for asset management. This paper presents the bases of the reliability centered maintenance and describes a practical case referring to a critical electrical equipment of an electrical system, such as the power transformer of a hydroelectric power plant. The power transformer in a hydroelectric power plant constitutes a fundamental electrical equipment because a failure in its operation can generate a long lasting unavailability of the system in the electrical generation with the consequent losses associated to the business.

Keywords: reliability; reliability centered maintenance; RCM; preventative maintenance; system failure mode analysis.

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1. Introduction

Reliability centered Maintenance (*RCM*) is a systematic, objective and documented methodology of analysis, applicable to any type of industrial system, very useful for the development or optimization of an efficient maintenance plan. Its basic principles were developed in the 1960 for the American aeronautical industry. The airlines began to realize that their philosophies of maintenance were too expensive. This approach motivated this industry to launch a set of maintenance working groups with the mission of re-examining everything that was done to keep aircraft flying. These groups were formed by representatives of aircraft manufacturers, airlines and the FAA (Federal Aviation Agency).

In the early 80,s this methodology began to be transferred to other industrial sectors. In 1984, the *EPRI* (Electric Power Research Institute) identifies the RCM as a highly recommended methodology for its application in the nuclear field and initiates a series of pilot studies in different methodological approaches with the develop application guides and computer Support tools. Between 1985 and 1995, the RCM analyses are multiplied not only in the nuclear field as well as in the electric power plants, extending the application of this methodology in the last years, to other industrial sectors as Railway sector, the chemical industry or electrical networks and power plants.

The application of the RCM strategy in the maintenance department of a company can contribute to being able to defend against the plant management the costs of the application of the maintenance strategy to be implemented with justified criteria of actions to be taken and clear cost savings in terms of improving the physical asset to be maintained efficiently.

This study extends a particular analysis of highly reliable electrical equipment such as a power transformer in a hydroelectric power plant. The application of the RCM strategy allows us to evaluate if the maintenance actions that we are carrying out can allow us to verify if we can identify the state of the equipment, the parameters that serve us as condition monitoring and in short the improvement of the reliability of the equipment itself to avoid a breakdown that in the case of this equipment in question, can imply a great unavailability of the hydroelectric group.

2. Reliability centered maintenance

The main aspects that a maintenance manager has to control are:

- Select the most appropriate techniques.
- Control the different fault processes.

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- Develop the objectives set by the company in terms of physical asset management.
- In the most enduring and effective way in terms of costs.
- With the support and cooperation of all the people involved.

Therefore, in this chapter the theoretical analysis process of the RCM is presented taking into account the answer to 7 questions about the system or equipment to be analyzed, of the concepts that define it such as functions, functional failures, failure modes, failure effects, failure consequences and finally the maintenance tasks that have been selected and consequently prioritized.

2.1. Maintenance and RCM

As a basic definition of maintenance, we can consider maintenance as “ensure that physical assets continue to do what users want them to do”.

Furthermore, the requirements of the users will depend on how and when the asset is used (operational context). We can define RCM as “a process used to determine the maintenance requirements of any physical asset in its operational context”.

Based on the previous definition of maintenance, a more complete definition of RCM would be «a process used to determine what must be done to ensure that all physical assets continue to do what their users want them to do in their current operational context.»

2.2. RCM: The seven basic questions

The RCM process asks seven questions about the asset or system that we want to be analyzed:

- What are the functions and operating parameters associated with the asset in its current operational context?
- In what way does it fail to satisfy its functions?
- What is the cause of each functional failure?
- What happens when each failure occurs?
- How does each failure matter?
- What can be done to predict / prevent each failure?
- What should be done if an adequate proactive task is not found?

2.3. Functions and operating parameters

In the first place, can define what process to apply to determine what must be done so that any physical asset continues to do what its users want it to do in its operational context, we need to do two things:

- Determine what your users want you to do.
- Ensure that you are able to do what your users want you to do.

2.4. Functional failures

The maintenance objectives are defined by the operating expectations associated with the asset. The only fact

that can make an asset can't perform according to the parameters required by its user is some kind of failure.

The RCM process performs an analysis at two levels:

- First, identify the circumstances that lead to the failure.
- It then asks what events can cause the asset to fail.

2.5. Failure mode

After the functional failure has been identified, the next step is to identify all the facts that may have caused each failure state. These facts are called failure modes. Possible failure modes include those that have occurred in the same or similar equipment operating in the same context.

2.6. Failure effects

The fourth step of the RCM process is to list the effects of the failure, which describes what happens when each failure mode passes. This description must include all the necessary information to support the evaluation of the consequences of the failure, such as:

- What evidence exists that the failure has occurred.
- How it represents a risk to safety or the environment.
- How it affects production or operations.
- What physical damages have been caused by the failure.
- What must be done to repair the fault.

2.7. Consequences of failure

One of the main aspects of RCM is that it recognizes that the consequences of failures are more important than their technical aspects. In fact, it recognizes that the reason to do any kind of proactive maintenance is to avoid or reduce the consequences of failures.

The RCM process classifies these consequences into four groups, as follows:

- Consequences of hidden failures: hidden failures do not have a direct impact but expose the organization to multiple failures with serious and even catastrophic consequences.
- Environmental and safety consequences: a failure has consequences for safety if it is possible that it causes damage, death to any person or violates any environmental or corporate or regional, national or international regulation or regulation.
- Operational consequences: a failure has operational consequences if it affects production (quantity, product quality, customer service, or operational costs) in addition to the direct cost of repair.
- Non-operational consequences: failures that fall into this category do not affect safety or production; they only relate to the direct cost of repair.

2.8. Types of maintenance tasks

The process of evaluating the consequences of the failure also involves the analysis of the importance of the failure

on the operation of the equipment and the performance of the system and the organization. Consequently, with all the information obtained in the previous steps, the most appropriate maintenance strategy should be selected to implement the tasks to be defined in the maintenance plan.

Maintenance tasks can be classified into two categories:

- Proactive tasks.
- Failure finding tasks.

2.8.1. Proactive tasks

These tasks are undertaken before a failure occurs, to prevent the item from reaching the fault state. They cover what is traditionally known as “predictive” or “preventive” maintenance.

The RCM divides the proactive tasks into three categories:

- Scheduled overhaul tasks.
- Scheduled replacement tasks.
- Condition based maintenance tasks.

2.8.1.1. Scheduled overhaul and replacement tasks

Scheduled servicing tasks involve repairing a piece of equipment before a specific age limit, regardless of its condition at the time. Similarly, scheduled replacement tasks involve replacing a component before a specific age limit, beyond its current condition. These two types of tasks are generally referred to as preventive maintenance. This type of maintenance is the more useful of the proactive maintenance types.

2.8.1.2. Condition based maintenance tasks

Most new techniques are based on the fact that most failures give some kind of warning that they are near to occur. These warnings are called potential failures and are defined as identifiable physical conditions that indicate that a functional failure is about to produce. The new techniques are used to detect potential failures and to be able to act avoiding the possible consequences that would arise if they were transformed into functional failures. They are called condition-based maintenance tasks because the components are left in service provided, they continue to reach the desired operating parameters (Condition maintenance includes predictive maintenance, maintenance based on condition and condition monitoring).

2.8.2. Failure finding tasks

These actions interact with the failure state and are chosen when it is not possible to identify an effective proactive task. The Actions “in the absence of” include failure search, redesign, and maintenance to break (corrective).

The RCM recognizes three major categories of actions in the absence of:

- Fault search: Fault search tasks involve checking the functions to determine if they have failed.

- Redesign: redesigning involves making one-time changes to the initial capabilities of a system.
- Running to failure: as the name implies, no effort is made here to try to anticipate or prevent the failure modes to which it applies. In this way, the failure is simply allowed to occur, and then repaired.

3. The RCM task selection process

A main consideration of the RCM is the way in which it provides simple, accurate and easy-to-understand criteria to decide which of the proactive tasks is technically feasible in the context, and to decide who should do it and how often. If a proactive task is technically feasible or not, it depends on the technical characteristics of the task and the failure it intends to prevent.

The key principles of the task selection process is the following:

- In the case of hidden failures, the proactive task is correctly applied if it significantly reduces the risk of multiple failures of that function to a tolerable level. If this is not possible, a troubleshooting task must be performed.
- In the case of failures with environmental or safety consequences, a proactive task is only carried out if it reduces the risk of failure to a very low level, or eliminates it. If a task cannot be found that reduces the risk to acceptably low levels, then the component must be redesigned, or the process modified.
- If the failure has operational implications, a proactive task is only worthwhile if the total cost of carrying it out during a given period is less than the cost of the operational implications and the cost of repair in the same period.
- If a failure has non-operational consequences, it is only worth performing a proactive task if the cost of the task over a period is less than the cost of repair in the same time.

4. An analysis of a power transformer in a hydroelectric power plant

The power transformer constitutes a critical equipment, whose possible failures can cause important economic costs (loss of profit of the electric generator system, high period of unavailability of the system due to the inexistence of spare parts due to its high economic cost, costly repairs both technically and temporarily, as well as in many cases very hard conditions for operation and continuous overloads and location to the outdoor).

The transformer can also cause major failures, severe environmental consequences (discharge of large volumes of oil and / or large fires).

4.1. Operational environment

In power plants, medium voltage energy is generated, at levels between 6 and 20 kV depending on the type of alternator. In order to connect these power plants to the electricity network, the voltages need to be

increased for their transport or distribution in high voltage, depending on the network to which they are going to connect. For this, in the power plants there are elevating substations where the transformer is the fundamental element.

Tables 1, 2 and 3 and Figure 1 describe different parts of a power transformer, as well as its functional characteristics (functions) and the protection systems associated with the transformer that form the basis of safety in the event of a major or catastrophic failure.

Table 1: Parts of the transformer. (Fraile Mora, 2002).

<ul style="list-style-type: none"> The terminals AT and MT, which are easily identifiable by the insulators, being those of AT greater size than those of MT
<ul style="list-style-type: none"> The tank, which contains the oil and the internal parts of the transformer.
<ul style="list-style-type: none"> Radiator and fans, to refrigerate the transformer itself.
<ul style="list-style-type: none"> Expansion tank, which absorbs the dilation of the oil from the VAT due to heat. Its interior normally carries a separate compartment for the voltage regulator oil.
<ul style="list-style-type: none"> Voltage regulator, automatic or manual operated by remote control, in charge of adjusting the voltage within certain limits varying the transformation ratio.

Table 2: Functional characteristics of a transformer. (Fraile Mora 2002).

<p>Cooling method. It is usually carried out by natural oil circulation through natural air-cooled radiators, type ONAN (Oil Natural-Air Natural), and forced type ONAF (Oil Natural-Air Forced). Forced air circulation through the radiators is carried out by fans.</p>
<p>Short circuit voltage. It is a % relative to nominal voltage that is reached in one trial applying nominal intensity on one side with the other shorted. Indicates the internal impedance of the transformer, referring to the nominal power and the central position of the load-changer.</p>
<p>Overdrive. The magnetic circuit is designed to supply permanently and without premature ageing, the power assigned with a higher voltage of 10% at the assigned voltage.</p>
<p>Possibility of overload. The terminals, connections and other auxiliary elements of the main circuit must be able to withstand a permanent overcurrent of 20%, even considering the position of work in the most unfavourable outlet.</p>
<p>Isolation level. The insulation levels of the AT and MT windings correspond to the specifications in the table of characteristics. The high-voltage neutral has the same level of insulation as the AT-coil.</p>
<p>On-load tap-changer. It usually consists of an electro-mechanical system (Jansen system) that uses a motorized rotary switch, insulated in its own oil.</p>

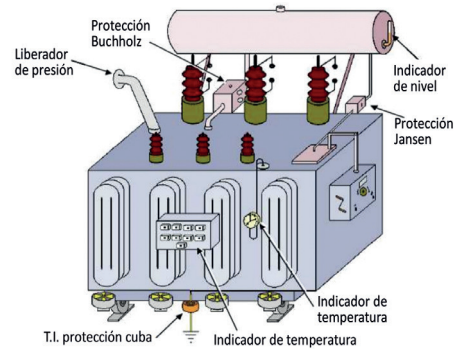


Figure 1: Parts of a transformer. (Fraile Mora, 2002).

Table 3: Power transformer protections. (Fraile Mora, 2002).

Oil temperature thermometer	There are normally two types of devices that work according to the temperature of the oil: thermometers and thermostats. Due to the high thermal inertia of the transformer (they are heated and cooled with some slowness); these devices are mainly used for protection against permanent overloads.
Thermal imaging devices (winding temperature)	The system is basically formed by a trafo of toroidal intensity located in one of the phases, whose secondary feeds to a small coil. This coil is a kind of scale model of the main winding, receives an intensity at scale, and is immersed in the same oil of the VAT. Consequently, it is estimated that its thermal situation should be a scaled image of what happens in the main winding. Through a probe connected directly to the coil, the temperature signal finally reaches a thermometer similar to the oil temperature measurement.
Oil level Indicator	They are used to control the level of oil in the Transformers. They are usually mounted on the sides of the expansion tank. Two are usually installed, one to measure the oil level of the windings and the other for the oil level of the regulator in charge.
Pressure release	The release system consists of a balance chimney that ends in a membrane or over-pressure valve.
Buchholz Relay	An internal fault can lead to small electric arcs that break down the oil or result in the combustion of the insulators, resulting in a more or less significant release of gas in the form of bubbles. The Buchholz relay detects this detachment, whose magnitude is proportional to the importance of the breakdown and decides two types of actions: alarm or fire
Protection of Cuba	This protection is exclusive to the AT/MT distribution transformers and protects the equipment against current derivations through its casing, for example, the breakage of bushings insulators. The Transformers AT/MT ground wire is passed through a toroidal current transformer whose secondary feeds the protection relay from Cuba.
External protections.	They are those that are not part of the transformer itself but work through auxiliary equipment such as measurement transformers and protection relays. <ul style="list-style-type: none"> Grounding resistance and homopolar protection (ground faults). Differential protection. Over-current protection.

4.2. RCM analysis of the power transformer

After having explained the theoretical process of analysis of the RCM (Sections 2 and 3), as well as the technical and operational context of the equipment to be analyzed (in our study it would be the power transformer of a hydroelectric plant in Section 4), in the following table (Table 4), the functions, failures, failure modes and effects of a power transformer are analyzed, and the possible definition of the maintenance action to be developed and its frequency to be applied is included.

Please note that in the definition of the functions in the table, values of the different control electrical parameters

are not indicated since the study presents a generic analysis of equipment. In a particular analysis of an equipment it is necessary to include the control values in the fulfillment of the defined functions.

4.3. Maintenance strategies and tasks selected

Based on the information collected in the RCM analysis sheet of the transformer, a period of actions is obtained in order to avoid the failures analyzed and therefore to increase the reliability of the operation of the equipment, in addition to being able to have updated information on the "state" of the asset, in order to define the maintenance strategy and actions to be carried out.

Table 4: Functions, failures, failure modes and effects of a power transformer.

Function	Functional failure	Fault mode (cause of failure)	Effect of the fault.	Maintenance action	Frequency
1 transforming the machine voltage (bt kv) to line voltage (at kv) ±5% mva power	a it does not convert the machine voltage (bt kv) to line voltage (at kv) ±5%	1 open switch for actuation protection buchholz relay by low insulation coiled by aging.	the insulation of the windings wires when subjected to thermal changes, excess force and overvoltages, is degrading, losing its physical and chemical properties and the oil. these degradations are externalized by the generation of gases that will provoke the performance of the buchholz relay, leaving the group unavailable.	task on condition. it is detected by analysis of dissolved gases in the oil. action in case of detection: you can opt for the repair of the insulation and regeneration of the oil or replace the transformer	annual
		2 switch open for actuation protection buchholz relay by hot spot in joint coiling of the lv terminal due to lack of tightening	the increase of the punctual temperature provokes the generation of gases being able to come to act the buchholz relay and the unavailability of the group, it is detected by the degradation of the observed oil by means of dissolved gases analysis.	task on condition. it is detected by analysis of dissolved gases in the oil. action in case of detection: hot spot repair and oil regeneration. the time spent on your repair 1 week 3 workers	annual
		3 open switch for actuation protection buchholz relay by presence of air in cuba after partial emptying and subsequent replacement.	failure produced after a maintenance operation.	no scheduled maintenance. verify gases and normalize buchholz relay 1h 2 operators	random. inspection procedure maintenance
		4 switch open for actuation protection buchholz relay by low level of oil tank by local level fault.	local level fault that is externalized by the performance of the buchholz relay when the oil level is lowered to that relay.	fault search. action in case of detection: replace level detector and replenish oil level. 2 operators 3h	annual
	b transforms tensions but does not reach electrical power specified	1 coils in short circuit by insulation defect degraded by ageing.	overloads and over-voltages over time lead to degradation of insulator properties, which, when shorting between whorls, cause an increase in the temperature of the oil and windings, pollute the oil and decrease the transformer performance shortening the service life.	condition based maintenance techniques. it is detected by analysis of dissolved gases in the oil. action in case of detection: group unavailability time from 6 weeks to 3 months	annual
			2 coils in short circuit by insulation defect degraded by ageing.	overloads and overvoltages provoke efforts in the nucleus that can cause defects such as deformations, short circuits between sheets or slides with the appearance of air gaps, causing heating, gas generation, etc. shortening the life of the transformer.	task on condition. it is detected by analysis of dissolved gases in the oil. depending on the results regenerate or change the oil. 3 weeks of unavailability

(Table 4, continues in next page)

(Table 4, continues from previous page)

Function	Functional failure	Fault mode (cause of failure)	Effect of the fault.	Maintenance action	Frequency
2 isolate the live parts of the windings from the tank	a it does not insulate the parts in tension from the coils, from the tank.	1 oil with high levels of aging oil contamination.	oil aging reduces its electrical properties group unavailable for the performance of the buchholz or the differential. confirm degradation by oil analysis.	task on condition. it is detected by analysis of dissolved gases in the oil. action in case of detection: depending on the results regenerate or change the oil. 3 weeks of unavailability.	annual
		2 oil with high levels of water pollution. by silica gel dehumidifier air inlet tank saturated expander.	the accumulation of water in the oil reduces its electrical properties. group unavailable for action by buchholz.	task on condition. it is detected by physico-chemical analysis of the oil. action in case of detection: depending on the results regenerate or change the oil. 3 weeks of unavailability.	annual
3 contain the oil inside the transformer tank.	a does not contain	1 leakage by aging joints in the bt terminal.	shot by buchholz. there is no pollution to the environment, group unavailable.	cyclical replacement. adapt the terminal. 2 days of unavailability.	5 years
		2 aged joint leakage of buchholz relay.	shot by buchholz. there is no pollution to the environment, group unavailable.	cyclical replacement. repair of buchholz relay gaskets. 1 day of unavailability.	5 years
4 transmit a maximum and continuous current of ampers and a voltage of bt kv±5% from the winding of bt, to the cable, without a temperature increase of 10°C higher than that of the ambient	a it does not transmit a maximum and continuous current of x a from the bt winding to the cable.	1 terminal junction open for human failure.	unavailability of the group. depending on the number of unions left unconnected, the behavior of the group's protections would vary.	no scheduled maintenance. normalize unions 2 workers 2h	random. inspection procedure maintenance.
		b transmits a maximum and continuous current of ampers from the bt winding, to the cable, with a temperature increase of 10°C higher than the ambient.	1 hot spot on external terminal due to lack of tightening.	the temperature changes and the vibrations affect a loss of tightening of the joints, causing an increase in the temperature of the union. it is detected by oil analysis.	condition based maintenance techniques. thermal inspection. action in case of detection: retighten borna. 3 hours 2 workers.
	c it does not withstand a voltage of bt kv±5%	2 hot spot in terminal inside terminals due to lack of tightening.	the temperature changes and the vibrations affect a loss of tightening of the joints, causing an increase in the temperature of the union. it is detected by oil analysis.	condition based maintenance techniques. thermal inspection. action in case of detection: repair borna. 3 hours 2 workers.	annual
		1 partial discharges (glow) in terminals due to dust and moisture.	group shot by imbalance of intensities.	condition based maintenance techniques. transformer diagnosis (etp). action in case of detection: 3 horas 2 operarios.	annual
	2 cracking of the insulating material of the terminals.	group shot by imbalance of intensities.	condition based maintenance techniques. transformer diagnosis (etp). action in case of detection: substitution of terminals. 2 days 3 workers.	annual	
		5 transmit a maximum and continuous current of ampers and a voltage of at kv±5% from the winding of at, to the cable, without producing a temperature increase of 10°C higher than the ambient	a it does not transmit a maximum and continuous current of ampers from the at winding to the cable	1 terminal junction open for human failure.	unavailability of the group. depending on the number of unions left unconnected, the behavior of the group's protections would vary.

(Table 4, continues in next page)

(Table 4, continues from previous page)

Function	Functional failure	Fault mode (cause of failure)	Effect of the fault.	Maintenance action	Frequency
transmit a maximum and continuous current of ampers and a voltage of at kv±5% from the winding of at, to the cable, without producing a temperature increase of 10°C higher than the ambient	b transmits a maximum and continuous current of ampers from the at winding, to the cable, with a temperature increase of 10°C higher than that of the ambient.	1 hot spot in connection terminals due to lack of tightening.	temperature increase union. detection by oil analysis terminals.	condition based maintenance techniques. thermal inspection. action in case of detection: dismantling and repairing terminal. 1 week 3 operators.	annual
	c does not withstand a voltage of at kv±5%	1 partial discharges (glow) in terminals due to dust and moisture.	group shot by imbalance of intensities.	condition based maintenance techniques. transformer diagnosis (etp). action in case of detection: cleaning of terminals. 3 hours 2 operators.	annual
		2 cracking of the insulating material of the terminals.	group shot by imbalance of intensities.	condition based maintenance techniques. transformer diagnosis (etp). action in case of detection: substitution of terminals. 2 days 3 workers.	annual
		6 measure in local temperature oil	a it does not measure in local oil temperature.	1 fault thermometer.	loss of local information temperature oil.
7 have local indication level oil tank expansion transformer within a range of 10% of the real	a no local indication level oil tank expansion transformer within a range of 10% of the real.	1 sedimentation buoy binding oil paraffin.	loss of local information. failure of the level control may result in the performance of the buchholz relay.	cyclic replacement. Replace Level 2 operators 4h	5 years
8 shoot the group if the oil temperature is >90°C	a do not fire the unit if the oil temperature is >90°C.	1 bad calibrated thermostat (thermometer) transformer temperature.	excessive heating of the oil can degrade the oil and subsequent performance of buchholz by gas formation.	cyclic overhaul. check and tare thermostat 2 operators 4 h	trimestral
		2 internal fault thermostat (thermometer) transformer temperature.	excessive heating of the oil can degrade the oil and subsequent performance of buchholz by gas formation.	cyclic overhaul. replace thermostat 2 operators 6 h	5 years
9 give alarm if the oil temperature is >80°C	a no alarm if the oil temperature is >80°C	1 bad calibrated thermostat (thermometer) transformer temperature.	loss of information does not affect the operation of the group but prevents a transformer problem	cyclic overhaul. check and tare thermostat 2 operators 4 h	trimestral 5 years
		2 internal fault thermostat (thermometer) transformer temperature.	loss of information does not affect the operation of the group but prevents a transformer problem	cyclic replacement. replace thermostat 2 operators 6 h	5 years
10 shoot the group if there is gas formation inside cuba	a do not fire the group if there is gas formation inside cuba.	1 internal fault buchholz relay.	loss of transformer protection does not fire the unit and can lead to a fire in the transformer	cyclic replacement. replace buchholz relay 2 operators 5 h	5 years
11 give alarm if there is gas formation inside the transformer tank.	a it does not give alarm if there is gas formation inside the transformer tank.	1 internal fault buchholz relay.	loss of information does not affect the operation of the group but prevents a transformer problem	cyclic replacement. replace buchholz relay 2 operators 5 h	5 years



Figure 2: Adequacy of power transformer (Endesa Generación-Enel Green Power).

The actions that have been mainly indicated as a function of the analyzed faults, indicate a series of actions grouped in:

- Fault search actions.
- Conditioned tasks actions.
- Cyclical substitutions.
- Cyclical reconditioning.

Up next are the different periodical roadmaps of the maintenance actions to be implemented.

4.3.1. Tasks to condition. Surveillance

Every three months there will be a face-to-face monitoring where we will analyze the visual status of the asset, as well as the status of the different levels, leaks, status of parts of the equipment, etc. This vigilance is necessary because there is no technical maintenance that can give us remote information of the surveying parameters considered.

Table 5: Check List of monthly surveillance.

1	Physical access
2	Access door
3	Transformer appearance
4	Oil level
5	Insulating state
6	Electric busbar appearance
7	State Silicagel
8	Temperature of transformer
9	Oil leaks
10	Noises and vibrations
11	Other anomalies

4.3.2. Preventive maintenance

Every year it,s necessary to carry out another action routine through a periodical roadmap, but in this case it will be necessary to de-energize the equipment and develop the electrical discharge operations (electrical safety conditions by opening, interlocking and signaling the possible sources of stress affecting the transformer,

as well as the grounding of the Work area to protect workers in the development of maintenance activities).

Table 6: Check list three months surveillance.

1	Physical access
2	Correct oil leaks.
3	Check the oil level (it is in the expansion tank).
4	Check the integrity of the transformer and the neutral ground connection of the tank.
5	Revision of terminals and retightening.
6	Review of hot spots in electric circuit.
7	Magnetothermics Review.
8	Trip alarms check.
9	Check the colour of the silicagel
10	Tighten screws.
11	Inspection of wires and terminals of thermostats and thermometers.
12	Inspection, cleaning of bushings.
13	Verification and inspection the state of paint and possible leakage of oil by the different lids and radiators.
14	Visual inspection of the state of the ground and verification of the tightening of the terminals.
15	Inspection of the electrical cooling circuit from the control room to the local frame terminal of the Trafo.
16	Inspection and retightening of the local power box and load regulator.
17	Inspection, testing, tare of thermostats and thermometers.
18	Inspection and verification of condition of the chimney and check valves.
19	Inspection and verification of Bucholz relay.

4.3.3. Predictive maintenance

Annually it is also necessary to carry out a diagnosis of the electrical equipment, by means of techniques that allow us to analyze the state of the transformer, as well as the severity of the indications that we can find in the diagnosis, in order to know the time limit to be able to perform an action “before having a power failure of important consequences.

The predictive maintenance techniques to apply for the transformer that we have considered are:

- Dielectric oil analysis.
- Thermal analysis.
- Analysis and electrical diagnosis of the transformer.

4.3.3.1. Dielectric oil analysis

The “Insulating oil”, “dielectric oil” or “Transformer oil” is an oil that is generally used in electrical equipment and

exhibits characteristic and essential dielectric properties to oppose the passage of the electric current the function Physics is the cooling, dissipating the heat generated during the operation of the unit. The electrical function is to act as a dielectric medium (insulator) to prevent arcing between two conductors with high potential difference.

Oil is a key element in the operation of the power transformer and the one that will determine its remaining lifespan is its dielectric.

The dielectric is divided into dielectric liquid (usually oil) on which we will have some degree of manipulation through possible treatments, and solid dielectric (paper) on which our actions are limited exclusively to the verification external and indirect state.

Advantages of dielectric oil:

- Increased oxidation stability.
- Has excellent fluidity at low temperature.
- It is free of moisture and particulate matter.
- High electrical resistance and great thermal stability.
- High flash point.
- Do not contain any type of corrosive sulphur.

Insulating oils are essential components of a large number of electrical equipment, particularly for power and measuring transformers. The evaluation of the state of the insulating oil in service is carried out according to the following control indices:

- Appearance and colour.
- Water content.
- Neutralization Index.
- Dielectric loss Factor.
- Rupture voltage.
- Number of particles per size are counted.

4.3.3.2. Dissolved gases in oil analysis

One of the diagnostic methods that provides an early indication of malfunctions in their functional behaviour and allows to determine the measures that should be taken before the equipment suffers major damage is based on the chromatographic analysis of decomposition gases of the insulating oil by excessive heating of certain points of the transformer or by electric shocks inside.

Depending on the temperature of the hot spot the energy of the discharges, the proportions in which the different decomposition gases are produced are different.

By effect of thermal or electrical request, the insulating oils give rise to decomposition gases as a hydrogen, methane, ethane, ethylene, acetylene, monoxide, carbon dioxide, oxygen and nitrogen.

Determining the content of each gas, the overall valuation and the relationship between the concentrations of different gases and their evolution, it is possible to know not only the existence of a defect, but also the type of the same and its importance.

4.3.3.3. Thermal analysis

Thermovision inspections are carried out on the characteristic elements of each installation. These inspections are carried out by specialized companies, which will issue the corresponding reports. After a subsequent analysis of them, the recommended actions will be executed

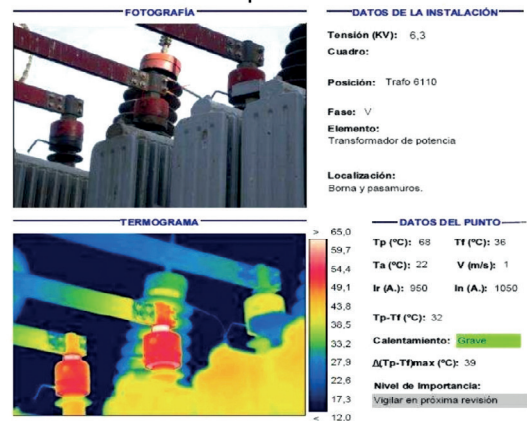


Figure 3: Thermal inspection. (Endesa Generación-Enel Green Power).

5. Diagnosis of transformers

To carry out a correct diagnosis in the transformers, the tests are carried out Evaluation of power transformers (ETP). This type of tests defines the state of the transformers in terms of electrical, magnetic, dielectric or geometric circuit.

In this way we will have the ability to detect and confirm possible breakdowns.

By means of this type of tests it would be possible to detect defects classified according to the circuit in which they occur. In the Table 7, 8 and 9.

Table 7: Defects detected in a power transformer by location in the different circuits (electrical and dielectric).

Electrical circuit	Dielectric circuit
Hints of shorting between whorls	Abnormal Aging
Regulatory problems	Insulation pollution
Loose of connections or hot spot on the winding.	
Open Winding	

Table 8: Defects detected in a power transformer by location in the different circuits magnetic and geometric).

Magnetic circuit	Geometric circuit
Scrolling windings	Scrolling windings
Core loosening	
Head Detachment	

One of the key elements in the operation of the power transformer and the one that will determine its remaining useful life is its dielectric. The dielectric is divided into liquid dielectric (usually oil) on which we will have some degree of manipulation through possible treatments, and solid dielectric (paper) on which our actions are limited exclusively to the external and indirect verification of its state.

Table 9: Control Techniques and parameters of electrical equipment.

Indicator Parameters	Techniques
Phase Equilibrium	Voltage and intensity measurements
Anomalous consumption	Intensity and power measurements
Winding state, eccentricity, imbalance	Current and vibration spectrum
Severity of Service	Control and counting of starts and maneuvers
Insulation resistance	Resistance measurement, polarization index
Windage pollution	Absorption and leakage current
Winding temperature	Temperature measurements, Thermographies
Isolation failures	Dielectric loss Factor, partial discharge analysis

Table 10: Characteristics EDAS tests (they define the insulation in terms of humidity, pollution and dielectric degradation of rotary electric machines).

Reversible parameters	Reversible problems (Simple operations, cleaning, drying and painting)
- Polarization index	- Surface pollution
- Time constant	- Surface humidity
- Leakage Current Index	- Internal humidity
- Leakage current Ratio	
- AC-DC Capacity	
Irreversible parameters	Irreversible problems (High cost operations: rewinding, replacing)
- Resorption Currents	- Problems in the binder
- Normalized resorption current to thickness	- Dielectric degradation
- AC-DC Capacity	- Aging
- Hours of operation	- Ionization

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6. Conclusions

Through this article, a guide has been presented for the implementation, revision or modification, based on RCM, of the maintenance strategy of an industrial equipment, using as an example a power transformer of a hydroelectric power plant in which the instantaneous availability and reliability are crucial for its operation, as well as the state of the equipment, in order to plan the appropriate actions in case of a catastrophic failure that may cause an environmental, safety or unavailability problem with the corresponding economic loss due to loss of profit in electricity generation.

The development of the strategy presented in the article can also be adapted to any industrial system that has the same operational objectives (manufacturing lines), transport (trains, aircraft) and that also involves safety and environmental aspects in its proper functioning. Today's society demands that there are more and more industrial processes in which the maximum availability of the systems must be guaranteed and, at the same time, that there must be a minimum of incidents to avoid the unavailability of the process.

It should also be remembered that at present, any maintenance section of an industrial system must continuously justify its "economic cost" based on the operations it performs, and analysis based on the MCR of the system or equipment to be maintained is good practice to justify the maintenance strategy being followed.

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