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A2-206

Session 2004

EXPERIENCES IN MANAGING TRANSFORMERS THROUGH MAINTENANCE OPERATIONS AND MONITORING SYSTEMS

J.C. BURGOS*[(1)], E. PAGÁN [(2)], B. GARCÍA [(1)],J.I. ANGUAS [(2)], A. RAMOS [(3)], D. MONTÁVEZ [(2)], E. PEREZ [(3)]

[(1)] UNIVERSIDAD CARLOS III DE MADRID
[(2)] RED ELECTRICA DE ESPAÑA, S.A.
[(3)] UNIÓN FENOSA DISTRIBUCIÓN

(Spain)

1. INTRODUCTION

Nowadays, the population of transformers within the transmission and distribution systems worldwide is aging. Utilities are concerned, and it is necessary to manage the remaining life of the units in operation and assess the impact of a predictable increasing failure rates in the next future as the transformer population approach their end of life [1].

Maintenance operations are focused in techniques allowing to get information to diagnose the state of the transformer, which combined with an established policy allow to handle the transformer life.

This paper will deal with policies and experiences referring these maintenance operations, giving information about how to manage and improve the condition assessment of transformers (RED ELECTRICA's policy) and practical examples about how to get direct information from the transformers (UNION FENOSA DISTRIBUCION's transformer monitoring system).

KEYWORDS: Transformer life managing, Transformer monitoring system, Transformer diagnostic techniques

2. TRANSFORMER LIFE ASSESSMENT AT RED ELÉCTRICA DE ESPAÑA (REE)

REE own and operate nearly all the transmission grid of Spain. The transformer population is basically composed of transformers 220/400 kV, rated from 300 up to 900 MVA.

For managing life of transformers REE consider technical, economic, and strategic criteria.

- The *technical* criterion comprises the real state of the transformer (including accessories such as bushings or tap changers), taking into account data got from maintenance operations.

- *Economic* considerations will be decided keeping in mind the accountant's measure used to quantify asset value in utilities accounts. It will also be necessary to evaluate if such a transformer is worth saving: replacement costs, maintenance costs, etc.

- Finally, *strategic* criterion will deal with system security, short circuit capability, overloading, etc.

Focussing on the technical criterion the transformer life could be estimated from the analysis of internal and external issues that affect directly and that it should taken into account for determining the maintenance operations to schedule at a reasonable cost.

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main autor's email address: jcburgos@ing.uc3m.es

Once those parameters (issues) are identified, it should be analyzed which are the key factors associated with them, and finally, search for the technique which help to manage the factor.

Next table resumes the *parameters*, *key factors* and *techniques* identified by REE:

PARAMETER	EXTERNAL	INTERNAL	KEY FACTOR	HOW TO MANAGE? (TECHNIQUE)
Transformer design	X	X	Standards application	Current Specifications
			Characteristics of design (core, shell)	Historical Data Maintenance Manufacturing knowledge
Quality process		X	Manufacturing process	Manufacturing process check points Materials control quality, Drying process
Solid insulation of windings		X	Characteristics	Oil analysis
			Temperature	Winding temperature
			Dielectric tests	Dielectric tests
Oil		X	Temperature	Thermometer, Winding temperature
Windings		X	Characteristics	Dissolved gases analysis
			Winding resistance	Winding resistance measurement
			Current	Bushing current measurement Winding temperature monitoring
			Movements	FRA, Power factor test
Bushings		X	Dielectric Status	Dielectric tests, Thermography
Magnetic Core		X	No-load losses	Excitation current measurement, Thermography
LTC			Voltage regulation	LTC maintenance, Thermography
Clamping structure		X	Dielectric Measurements	FRA, Leakage reactance measurement
Clamping blocks for the leads		X	Dielectric Measurements	FRA, Leakage reactance measurement
Gaskets		X	Characteristics & heating	Inspection
Oil level indicator		X	Oil level	Ordinary Inspection
Pressure relief device		X	Oil pressure	Ordinary Inspection
Radiators		X	Cooler system	Inspection, cleanness, treatment, Thermography
Pumps		X	Oil flow	Current measurement
Fans		X	Heat transfer	Inspection, Current measurement
Oil temperature monitoring		X	Oil temperature	Ordinary Inspection
Breather		X	Transformer operation	Ordinary Inspection
Current transformers		X	Current	Connections checks, Insulation, Current measurement
Other valves		X	Oil flow	Ordinary Inspection
External protection devices	X		Transformer operation	Protection Philosophy
Paint		X	Maintenance	Ordinary Inspection
Transport	X		Transformer operation	Shock recorder, Dielelectric measurements
Maintenance	X	X	Transformer operation	Maintenance Policy
Lightning overvoltages	X		Isoceraunic level	Transformer protection
Other overvoltages	X		Transformer operation	Insulation coordination

Once the diagnostic of each transformer is known through the results of diagnostic techniques, the next step is to schedule those others maintenance operations that will allow to recover as many as possible the original features of the transformer. These activities could be as easy as changing a bushing in bad state or on the contrary need an economical and/or technically inaccessible work.

As an example of these activities, the recovery of oil properties is explained: For improving oil properties lost due to normal aging process (oxidation and production of acids), operations such as filtering, oil degassing and drying can be effective and extend the transformer life. In short, the established criteria for deciding which is the best treatment are shown in Figure 1.

Due to restrictions of the network, many of these operations should be done with the transformer in service. REE have developed procedures that allow to reduce drastically the outage filtering, reclaiming and degassing on line, and in addition taking the advantage of oil and winding temperatures while in service (specially during winter).

Before programming a reclamation process, it should be proved that oil can be treated and recovered up to its original standard. In order to verify it, an oil sample is reclaimed, and then viability, oxidation

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main autor’s email address: jcburgos@ing.uc3m.es

and accelerated aging tests are done. The results will help to decide if the reclamation is feasible and also which products should be added to the oil.

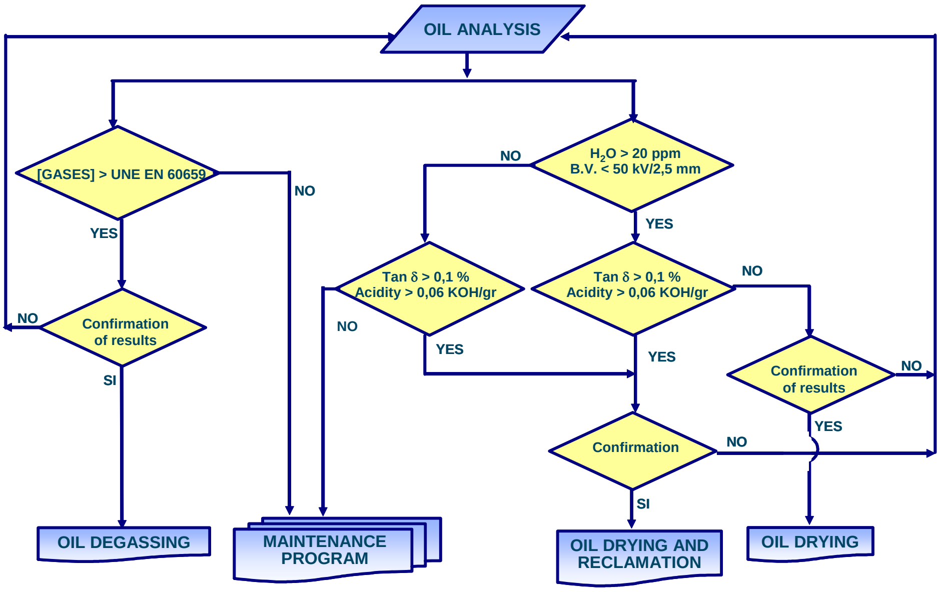

Figure 1. Criteria for maintenance - oil treatment

Briefly, the steps for reclamation by the percolating system are:

1. The oil is drawn out using the lowest valve, and then it passes through thick filter (diameter 0.15 mm) to remove fibres, particles and sludge.
2. The oil goes trough the heater.
3. Afterwards, it circulates through the chambers where the adsorbent earths are (zeolite).
4. The oil passes through fine filter (diameter 3 μm).
5. It enters a vacuum chamber for removal of dissolve gases and water.
6. The oil passes through fine filter (diameter 1 μm).
7. The oil returns to the transformer through the lower part of the conservator.
8. Finally, inhibitor is added

Economical and technical benefits are obtained doing this kind of treatment on line: To reclaim the oil of a 500MVA transformer could take more than 21 days, which is usually too much time for the grid. However, the on-line reclamation only needs that the transformer is out of service less than one hour, before and after the treatment, in order to connect and disconnect the oil processing plant to the transformer.

From the technical point of view, by using this technique, the equilibrium process between moisture in the solid insulation and in the oil can be maintained, since the internal transformer temperature is kept. Under high temperatures (full load operation) the moisture goes from the solid insulation to the oil, being removed in a more efficient way.

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main autor’s email address: jcburgos@ing.uc3m.es

But during the oil reclamation on-line process, some problems may appear. In the next table, most common concerns are shown, as well as how to try to avoid them.

DESCRIPTION PROBLEM	HOW TO AVOID IT
Air bubbles generation	Oil treatment process should not be stopped Oil processing plant outlet hose must be connected to the lowest part of the conservator Buchholz relay activation.
Drop of oil level	Refilled of transformer (an estimated loss of 5% is usual)
Oil flow rate	Low flow rate, less than 6000 litres per hour
Drop of oil temperature	Heater resistors are connected to raise the oil temperature up to 60ºC
Colour and the dielectric dissipation factor do not recover the expected values	Low efficiency in the adsorbent earth. The adsorbents should be replaced
Oil pressure before the filter goes up	Low efficiency in fine filter (0.1 µm). It should be replaced
Water content does not go down	Oil temperature and vacuum level in chamber should be reviewed Adsorbents could be in bad conditions. It has to take care of humidity in the adsorbents
Safety of personnel	All tasks must be done at accessible height from the ground

3. TRANSFORMER MONITORING SYSTEM AT UNION FENOSA DISTRIBUCIÓN

3.1 Monitoring system description

Union Fenosa Distribucion owns and operates part of the distribution grid of the center and northwest of Spain with a transformer population of more than 700 power transformers.

Union Fenosa in collaboration with Carlos III de Madrid University, has developed a transformer monitoring system whose scheme is shown in Fig 2.

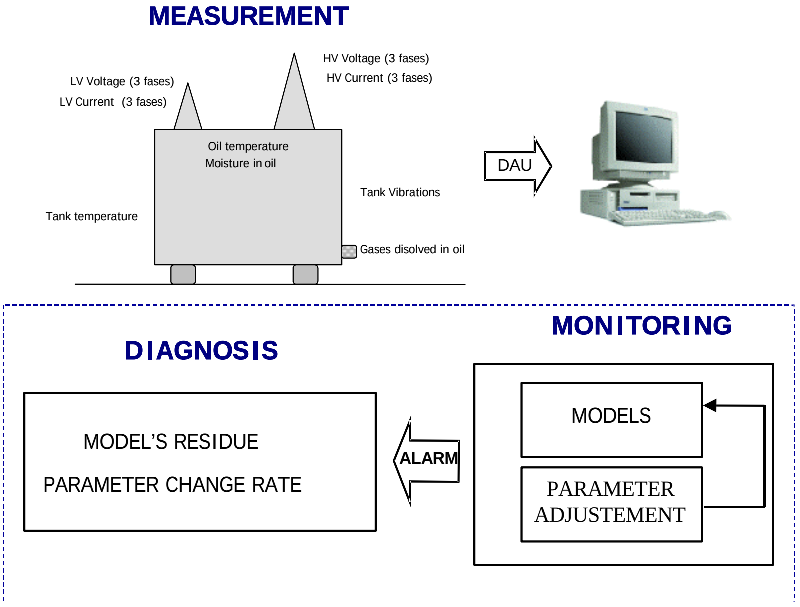

Fig.2 Monitoring system structure

The monitoring system includes four transformers behaviour models: thermal model, moisture model, dissolved gas model and tank vibration model. In every moment, from a set of input measured

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main autor's email address: jcburgos@ing.uc3m.es

variables, each model estimates how the value of a certain output variable should be if the transformer were healthy. This output variable is also measured, so the difference between the estimated and the measured value of this variable (the so called «residue») can be calculated giving an indication about transformer internal failures.
As can be seen in Fig.1 all the measured variables can be measured on-line by external and non-intrusive sensors, what makes the system applicable both to new and to in service transformers. The required data are, mainly:

- A.T. and B.T. currents
- A.T. and B.T. voltages
- Tank vibrations
- Dissolved gas in oil (as read by gas sensor)
- Moisture in oil (as read by moisture-in-oil sensor)

As the geometrical data of the transformer are usually not known, model parameters are adjusted after a learning period. To take into account transformer changes due to ageing, the parameters of the models are periodically readjusted.

3.2 Monitoring Software

All the functionalities of the system have been included in a monitoring software. The user interface allows a no experienced user to make consults easily in the system. Fig. 3 shows one screen with different menus.

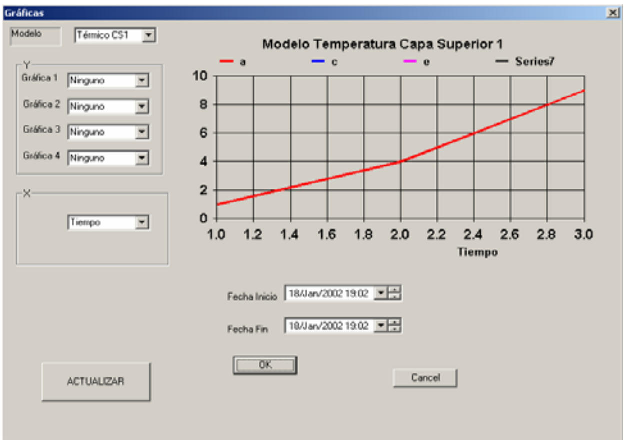

Figure 3: User interface

The monitoring software carries out the following tasks:

- Communication with the database
- Initial parameter adjustment
- Periodical executions of the models
- Alarms emission
- Parameter readjustment
- Historic consults
- Diagnostic system

3.3 Models

As can be seen in Fig.1 the system incorporates four behaviour models: Thermal model, vibration model, moisture model and gasses dissolved in oil model

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main autor’s email address: jcburgos@ing.uc3m.es

Thermal model

The inputs of the thermal model are load current, ambient temperature, bottom oil temperature and status of the oil pump. The output of the model is the top oil temperature. As the characteristics of the refrigeration system are very different depending on the status of pumps and fans there are different models that takes into account these subjects. Error of the model is below 1ºC on average value. Under sudden load changes and under low loads model predictions are slightly poorer.

Vibrations model

The inputs of the vibration model are voltage, load current, top-oil temperature and status of the refrigeration system. The outputs of the model are the real and imaginary part of the 100 Hz component of tank vibration. Tank vibration is different whether the oil pump is ON or the refrigeration system is OFF, so there are two Vibration Models, one of them to be used when the pump is OFF and the other one when the oil pump is ON. In the case of more cooling combinations (two groups of pumps or fans) there would be more thermal models.

Moisture model

The objective of moisture model is to estimate moisture in oil as a function of time and temperature. The inputs of the moisture model are top-oil temperature, estimated hot spot temperature and oil pump status. The output of the model is an estimate of moisture in oil, as read by a moisture sensor. The model makes use of Oomen curves, but also includes equations relating moisture dynamics.

Gas dissolved in oil model

The gas dissolved in oil model estimates the gas sensor reading (as a function of time and temperature) if the transformer were healthy. In this sense it must be taken into account that most of the gas sensors (e.g. hydran sensor) only measure some of the combustible gasses generated by internal faults.

3.4 System validation

A test facility was used to test the monitoring system. The test facility includes a 1500 kVA, 15000/400 V, OFAN transformer specially designed so in certain aspects has the same characteristics than a 60 MVA grid transformer (disk windings, etc). Fig. 4 shows the test facility electrical scheme.

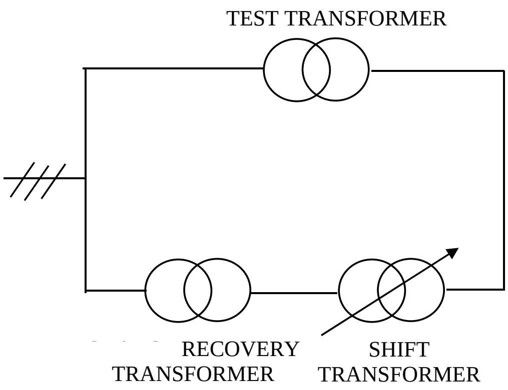

Figure 4: Test facility electrical scheme

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main autor’s email address: jcburgos@ing.uc3m.es

With the aim of acquire knowledge about the transformer internal behavior, and correlate the internal and external measures, during the development period more than forty sensors both internal and external were fitted in the Test Transformer (in the final version of the systems only external sensors are placed on). The measured variables in the Test Transformer during the development period were temperatures, vibrations, moisture in oil, gas in oil, voltages and currents.

Three kind of tests were performed in the Test Transformer, measuring all the aforementioned variables during tests:

- Normal work*:* The Test Transformer worked with several loads and power factors, testing the models ability to predict the transformer healthy condition.
- Accelerated aging: The Test Transformer worked with a high load and temperature with the aim of ageing its insulating paper. Hot spot temperature was computed so aging in paper in one month was the same as that of the paper from a grid transformer in thirty years.
- Work with failures in the transformer: Failures were simulated in the transformer to test the models ability to detect it. The failures simulated where: a winding axial deformation, radiator obstruction, pump failure, hot spot, and leak in the tank with the consequent increase on moisture.

In this experimental period all the models were tested in healthy as in failure condition comparing the model response in both situations. All the models get good results while the transformer was healthy, but when failures were simulated in the transformer the residue increases significant, allowing to detect the failures.

Next, as an example of the validation of the models, are shown some vibration model results.

In figures 5 and 6 the validation of the vibrations model is shown. Figure 5 shows the tank vibration estimated by the model vs. the measured one in a period where the transformer worked under normal condition submitted to variable load. The vibrations are estimated in real (left of the figure) and in imaginary part (right of the figure). As can be seen a good accordance appears between measured and estimated vibrations. Figure 6 shows the model response when a winding deformation was simulated on the test transformer. As can be seen the estimated and measured vibrations differs significant.

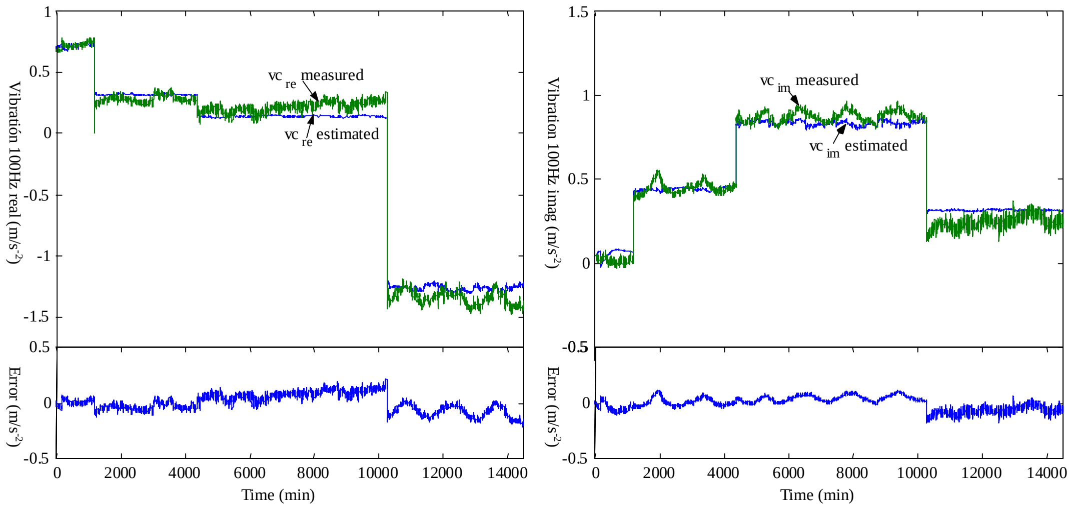

Figure 5. Validation of the vibrations model in normal condition

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main autor’s email address: jcburgos@ing.uc3m.es

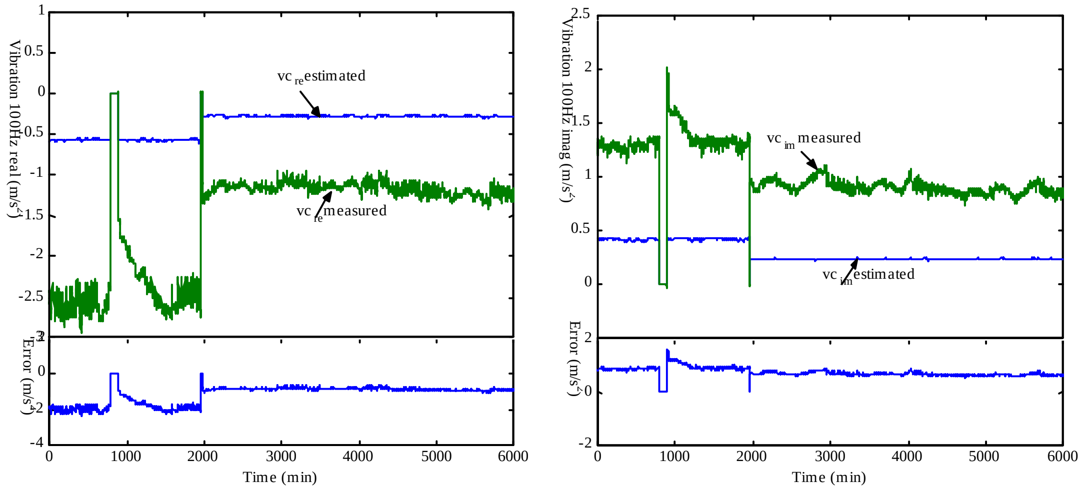

Figure 6. Validation of the vibrations model after deformation

4. CONCLUSION

This paper shows some of the maintenance policies of two Spanish utilities (RED ELECTRICA and UNION FENOSA DISTRIBUCION).

Analysis of key factors and continuous improvements in procedures have allowed RED ELECTRICA to improve strongly the quality of works, to reduce the outage time due to maintenance and time required to restore the oil properties, to improve maintenance costs and to increase the remaining life of installed power transformers and reactors.

UNION FENOSA developed a model based monitoring system to reinforce transformer maintenance tasks on very critical transformers. In the present state, the monitoring system includes four transformer models that deal with different physical aspects, with the aim to detect transformer failures with different origin. The monitoring system is modular, so some of the models could be suppressed or new models can be included. All the measurements required by the system, can be done without installing any internal sensor in the transformer. The system functions have been included in a monitoring software with a friendly graphical interface that allows to a no expert user use it easily.

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main autor's email address: jcburgos@ing.uc3m.es