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# INTEGRATED PROGRAMME OF DIAGNOSTICS, DECONTAMINATION AND DETOXIFICATION OF FLEETS OF TRANSFORMERS IMMERSED IN OIL

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**Summary**

Management of oil insulated transformers and equipment in electrical energy Generation, Transmission, Distribution and Use represents, for Utilities and Users, a new technologic challenge of remarkable complexity. This situation may be specially critic in the case of equipment service breakdown with the subsequent direct damages (loss of assets), indirect (loss of production or service interruption) and environmental in the case of leakage of dangerous substances.

In order to assist to the maintenance management of such equipment fleets, this paper describes a maintenance and protection system integrated into three steps:

- o Predictive maintenance and transformer diagnosis by oil analysis and PCB inventory;
- o Decontamination treatments of the oil in order to restore the properties deteriorated by ageing and extend its end of life;
- o Dehalogenation and detoxification of oil and transformer should the oil is contaminated by polychlorobiphenyls (PCBs).

Oil analysis allows the diagnostic of transformer condition, because the oil retains as much as 70 % of the information needed. However, the interpretation of the analytical results must be done with due care as it is not an easy task, even when applying to the diagnosis the best known analytical techniques, such is the case of oils which have exhaustively been hydrotreated during its manufacturing process. To improve the efficiency of the diagnosis, new analytical procedures such as dissolved sulphur and metals are proposed in the maintenance programmes in order to allow for a much more precise knowledge about transformer functioning. Also, new techniques for trend analysis (forecast of the oil and transformer behaviour in the long term) and the influence of laboratory measurements uncertainties are discussed.

Treatment of the insulating oil is a practice which allows to improve oil properties during its service life and enables to extend the oil service life up to 300 %. Depending upon the type of contamination present in the oil, it is possible to perform two different types of treatments: reconditioning and reclamation. The state-of-the-art of this activity is discussed.

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Lastly, main available technologies for PCB decontamination of oil and transformers are discussed and a new technology for the safe dehalogenation, on site, in continuous, in closed loop is described.

**Keywords:**

Transformer – Oil - Polychlorobiphenyl (PCB) - Predictive maintenance – Diagnostic – Treatment – Decontamination – Detoxification - Asset – Environment - Risk assessment - Life Cycle Analysis (LCA).

## 1. Predictive maintenance of in-service transformers

Oil analysis is perhaps the most powerful tool for predictive maintenance of transformers and oil-filled equipment [1], however, it is possible to improve its efficiency by adding new analytical procedures to those already standardised and by using techniques of trend analysis in the long term associated with the uncertainty of individual measurements.

### 1.1 Proposal for new analytical procedures

During past years, several important problems have been found in oil-filled electrical equipment installed in the Spanish electrical network. Such problems include some catastrophic explosions of instrument transformers and the automatic disconnection to the grid of a nuclear power plant.

In-depth analysis of the oil of such equipment seems to indicate that sulphur containing compounds play an important role on their behaviour. Such sulphur containing compounds are naturally occurring products which are present in almost all crude oils of the world at concentrations which may be very high (more than 5 %). Refining techniques, solvent extraction and hydrogenation, reduce considerably the amount of sulphur containing compounds in petroleum refined derivatives, including mineral oils, but these techniques do not completely eliminate such compounds which, on the other hand, are natural anti-oxidants of the oil.

Case history: By the end of 1997, a Spanish nuclear power plant was automatically disconnected to the grid because the failure of one of its power transformers. DGA of the oil of this transformer performed in December 1997, just after the transformer failed, yielded the concentrations given in table I.

Table I.- DGA results

| $H_2$ | $O_2$ | $N_2$ | $CH_4$ | CO | $CO_2$ | $C_2H_4$ | $C_2H_6$ | $C_2H_2$ |
|---|---|---|---|---|---|---|---|---|
| 1752 | 12038 | 34917 | 1179 | 1514 | 1093 | 1512 | 103 | 1357 |

These results clearly indicate the existence of an important electrical fault with arcing.

During inspection of this transformer at the manufacturer facilities, it was found that several electrical contacts were coated by black flakes. This material was sent to the laboratory for further analysis.

Inspection of these layers by Electron Microscopy showed they are constituted by a material which is positioned in parallel lines, suggesting it is a polar compound which is orientated parallel to the electrical field lines (figure 1). Analysis by Microprobe X-rays Dispersive Energies gave the results shown in table II.

Basic chemical calculations show that this material is mainly silver sulphide ($Ag_2S$), what was confirmed by X-ray powder diffraction techniques. As the result of this analysis, transformer owner decided to change the oil of all twin transformers.

By way of conclusion, quantitative analysis of dissolved sulphur and, specially, dissolved metals in transformers in service is strongly recommended.

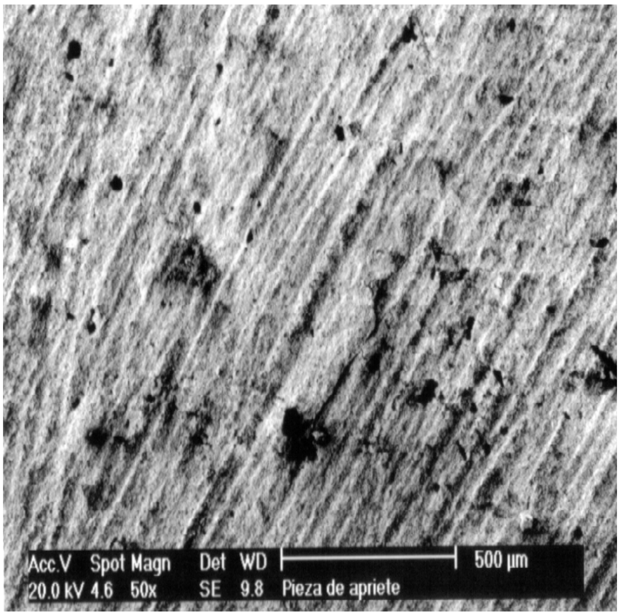


Figure 1.- Electronic photography of coated electrical contact.

Table II.- Quantitative analysis (% by weight) of the flakes which cover the electrical contacts

| Element | % weight |
|---|---|
| Ag: | 85,45 % |
| S: | 11,40 % |
| Mg: | 1,49 % |
| Si: | 0,52 % |
| Cu: | 1,15 % |

### 1.2 Effect of measurement uncertainty in trend analysis

Trend analysis is one of the most effective techniques to understand whether the conditions of a transformer (and, generally speaking, of any apparatus that needs an accurate "health" monitoring) are going towards a degradation or a failure state, and in what time this bad conditions will be reached.

This evaluation consist mainly in two steps:

- o Collection of at least three (but better more) experimental values, coming from in-field or laboratory tests, for the parameters to be monitored
- o Calculation of rate of increase of such parameters, or calculation of a "model" that fits mathematically the actual parameter's behaviour against the time.

Trend analysis, performed by the way described above, allows to forecast the value of some parameters in a fixed time (i.e. from some months to one year) and to consequently foresee, by a diagnostic interpretation, the degradation conditions of the fluid and the transformer that probably will be reached at that time.

The key factor in this evaluation is the word "probability". It is easily understandable that forecasting is a kind of extrapolation (made on the "time axis"), and is ruled by the laws of probability. It is well known (that means so obvious that sometimes we forget it) that any prevision of the value of a parameter in a future time is submitted to a lot of circumstances that must take place: operative conditions has to be maintained quite constants, any sudden failure (such as atmospheric damage) must happen, an so on. In any case the value we forecast is, in the best chance, the most probable to be verified.

The question is: how high is the probability to measure next time effectively the value we foresaw one year ago? Statistics help us in these extrapolations, especially with the so-called back-propagation of errors [2], a powerful mathematical technique to calculate the effect of initial errors in calculations of probability. What we need, in this case, is the knowledge of the error bonded to each test we made in the first step of our trend analysis study. The name that chemistry (and, more generally speaking, metrology) gives to this error is uncertainty [3].

Uncertainty can be defined as "an estimation of a reasonable range in which is probably situated the true value of a parameter", where the probability is quantified by the confidence level (95% to 99%).

Using uncertainty to appraise the dispersion of values for each historical result is possible, with the appropriate mathematical models is possible to forecast the value of the parameters, and also its probability. This probability gives us two fundamental informations:

- What is the probability of the forecasted value
- What is the width of the probability distribution

In Figure 2 is described a case of forecast in two years for 2-FAL concentration. The most probable value was estimated as 3,95 ppm, but the uncertainty of the analyses, applied to the forecast gave a very wide distribution, with peak of probability of 23%. So the probability to have 3,95 ppm of 2-FAL was low, and the 95% of confidence the value had to be expected 1,8 and 8 ppm (wide range!). The actual value was measured at 2,35 ppm.

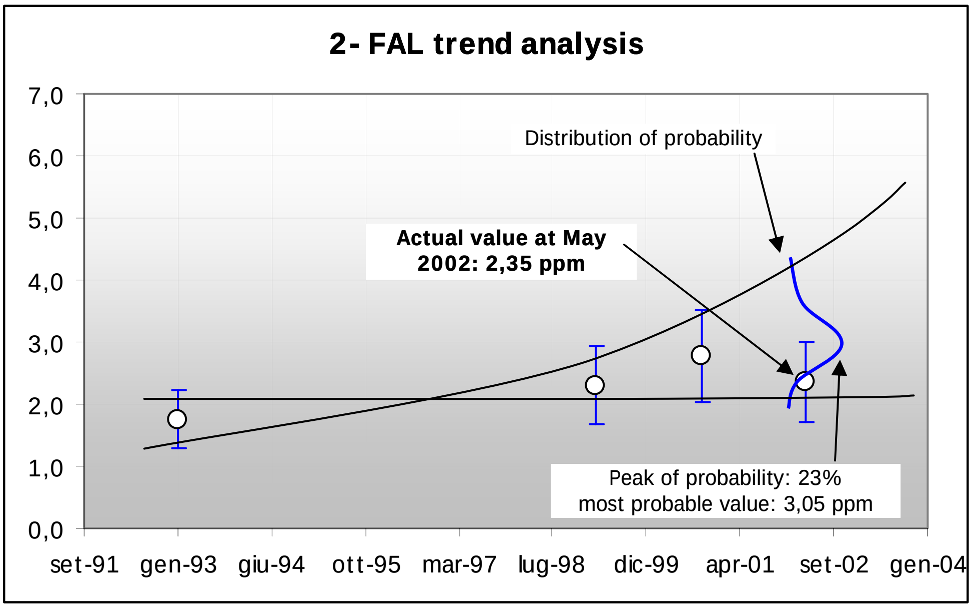


Figure 2.- Influence of Uncertainty in trend forecast.

The case in Figure 2 shows that the use of uncertainty avoids forecast mistakes, providing not just the most probable value, but also the probability related to that value. The probability is normally inversely proportional to the forecast time and proportional to the number of experimental points on which the model is based.

## 2.- Oil treatments

Once the diagnosis evidences some kind of oil contamination, oil filtration and reclamation is a widely used technique to restore the original properties of oils in service when they have lost such characteristics due to external contamination (water, particles) or ageing (polar compounds). The most widely used reclamation media is the so called Fuller's earth. However, in same cases, this adsorbent material is not enough to properly reclaim the oil, as is shown in the case history reported bellow.

Fuller's earth is an active material containing both internal and external polar active sites, which allow the non-polar components of the oil to pass trough without retention but which retains the polar contaminants or degradation compounds dissolved in the oil. Several different clays are available that have proven suitable for these purposes. The most widely used are of the sepiolite, bentonite, montmorillonite type. They are constitute of silicate anions $(Si_2O_2)_n$ condensed with octahedral layers of the type $X(OH)_2$ where X may be magnesium, aluminium, etc., thus the adsorption of polar compounds is made via Lewis acids interaction. For this reason, if the polar compounds present in the oil are not of the Lewis acid type, or the polar fraction of the molecule is sterically hindered by the non polar fraction, such compound is not retained by the Fuller's and the assistance of an auxiliary adsorbent is necessary.

Case history: An step-up transformer (15/130 kV, 21.000 kg mineral uninhibited oil) installed in a hydroelectric power station was submitted to a regular diagnosis programme due to its strategic condition because is the only generator transformer of the station. Such diagnosis programme showed an unusual high value of dissipation factor. In order to investigate the cause of such abnormal value, the oil was submitted to a further diagnostic programme and the analysis of dissolved metals indicated the presence of very high amounts of dissolved copper (table III and figure 3).

Table III – Analytical results

| Sampling Date | Tg δ | Cu (mg/kg) |
|---|---|---|
| 05/02/02 | 0,944 | 37,76 |
| 18/09/02 | 1,085 | 38,09 |
| 03/03/03 | 1,168 | 43,11 |

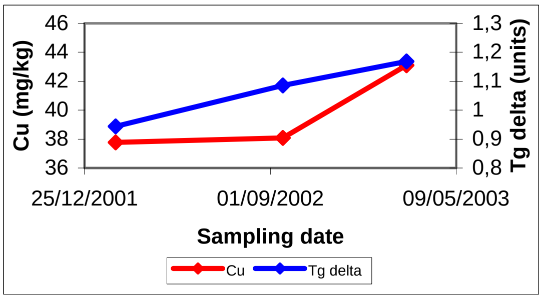


Figure 3 – Analytical evolution

Due to the above mentioned importance of this transformer, it was decided to submit the oil to a closed circuit reclamation process which enable to achieve following requirements:

- to decontaminate the oil and to restore its physical, chemical and dielectric properties;
- to remove dissolved and undissolved polar contaminants (depolarisation);
- to remove the sludge and precipitated material on the windings;
- to assure the possibility of a fast re-energising of the transformer on the case of necessity, during the decontamination process.

It was evident that the simple oil substitution, besides being more expensive, can not guarantee the fulfilment of such requirements, particularly the internal cleaning of the transformer.

However, initial reclamation tests carried out in the laboratory showed that the use of fuller's earth alone was not enough to restore the tg δ value, probably because the polar compounds responsible for such very high value are copper containing compounds of the type R-Cu or R-Cu-R', in which the organic groups R and R' are large enough to prevent the interaction between copper and the active sites of the fuller's earth.

In order to solve this problem, it was decided to add a relatively small amount, about 5 % by weight, of the Sea Marconi proprietary CDP reagent, which contains a mix of strong bases, to the fuller's earth. The aim of such solution was to destroy the copper containing compounds by chemical reaction with the reagent prior to its adsorption on to the fuller's earth. This new adsorbent showed, at laboratory level, a very high capacity to reclaim the oil, thus it was decided to use it in the field with a proprietary integrated configuration of a mobile decontamination unit (DMU).

The success of the treatment is demonstrated by the data shown in table IV, where the analytical results before and after the treatment are reported.

Table IV – Analytical results before and after oil reclamation

| Property | Before treatment | After treatment |
|---|---|---|
| Colour | 3 | 1 |
| Dissipation factor | 1,168 | 0,0742 |
| Copper concentration (mg/kg) | 43,11 | 0,85 |
| Breakdown voltage (kV) | 63,9 | 74,1 |
| Neutralisation number mg KOH/g oil | 0,213 | < 0,03 |
| Water content mg/kg | 14 | 11 |
| Total dissolved gases (%) | 9,06 | < 2 |

All these results were confirmed by a third independent laboratory.

### 3.- Deahalogenation and decontamination of PCB contaminated transformer oil

Environmental concern all around the world about the use of polychlorinated biphenyls (PCBs) and related compounds (PCT, PCBT), has posed an additional strength on transformer management. In Europe, for instance, Directive 96/59 obliges owners of oil-filled transformers contaminated with more than 500 ppm of PCB to eliminate or decontaminate them before the end of 2010. Those transformers contaminated by more than 50 ppm but less than 500 ppm can be maintained in service until their end of life, but then they must be securely eliminated or decontaminated.

Due to the environmental resistance and chemical stability of PCBs, there are only a limited number of technologies fulfilling legal requirements. The most important ones are indicated in Table V.

Table V – Comparison of PCB destruction technologies

| **Technology** | **Oil change** | **Sodium or lithium** | **KPEG** |
|---|---|---|---|
| Allows to reuse decontaminated oil | NO | NOT recommended | NOT recommended |
| Risk of fire or explosion | NO | VERY HIGH | HIGH |
| Can be carried out in continuous mode | NO | NO | NO |
| Can be performed with the transformer in service | NO | NO | NO |
| Allows decontamination of all PCB/PCT/PCBT | YES | YES | NO |
| Needs to drain the transformer | YES | PARTIALLY | PARTIALLY |

To overcome all these difficulties, a new technology[4] which uses an intrinsically safe and non toxic reagent, can be used on site, in continuous mode, in closed loop and perform the dehalogenation at temperatures below 100 ºC has been developed. Its most important scientific and technical advantages are described bellow.

#### 3.1 Scientific features

The reagent used by this technology is a mixture of polyethylene- and polypropyleneglycols of high molecular weight, a mixture of strong bases, a radical initiator or catalyst and particle supports. Such reagent is able to progressively react with the organochlorine compounds present in the oil, including the most stable ones like PCB, PCT, PCDD and PCDF, substituting the chlorine atoms by hydrogen atoms trough a nucleofilic substitution reaction mechanism.

The efficiency of this process is demonstrated with the data of figure 4, which shows the case history of the decontamination of one transformer, 250 MVA, 400 kV, having an initial concentration of 107 mg/kg PCB and 85.400 kg of oil.

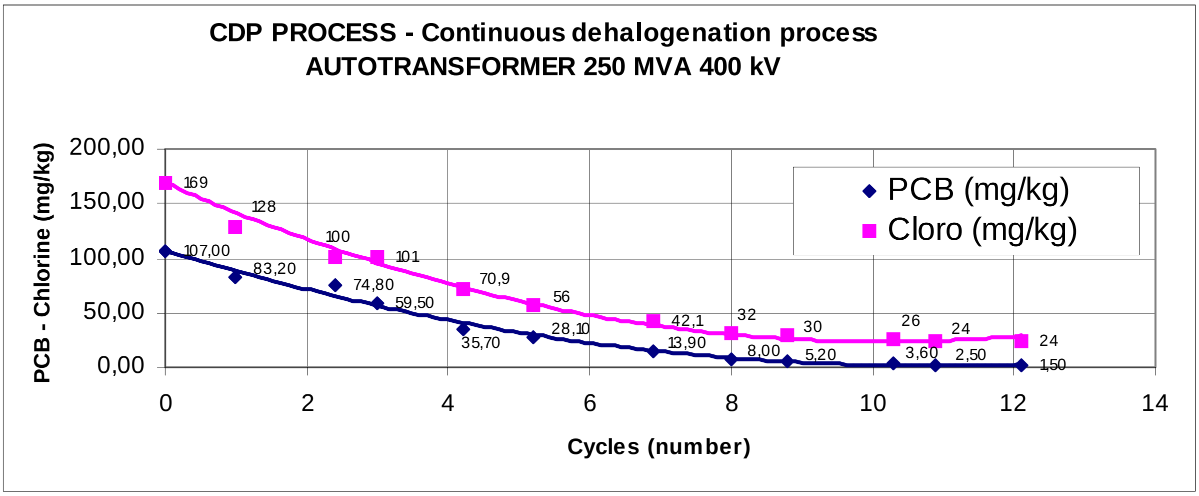


Figure 4 – Evolution of PCB and chlorine concentrations during dehalogenation process

During the reaction, the chlorine present in the oil as PCB is converted into innocuous sodium and potassium chlorides, which remain adsorbed onto the solid support, thus the waste is neither toxic nor dangerous.

Another additional advantage of this process is that the solid support of the reagent is the same material used to reclaim the oil, thus at the same time the oil became dehalogenated is reclaimed, removing as well the oxidation and ageing compounds, as shown in table VI which indicates the evolution of the physical and chemical properties of 186 transformers analysed one year after treatment[5].

Being a closed-loop, continuous process, the solvent capability of clean oil is used to extract more quantity of PCB absorbed onto the porous material of the transformer: insulating paper, pressboard, wood, etc., thus the efficiency of this technology is much higher than that of any other described above as demonstrated by figure 5 which shows the evolution of PCB content on the 186 transformers mentioned before.


Figure 5 – Evolution of residual PCB concentration after one year of the treatment

Table VI – Evolution of selected physical and chemical properties after oil treatment

| Property | BT | AT | YT |
|---|---|---|---|
| Colour | 3,0-4,5 | 0,5-1,5 | 1,0-2,0 |
| Moisture | 8-32 | 6-9 | 9-14 |
| Tan delta | 0,04-0,19 | 0,02-0,04 | 0,01-0,06 |
| BV | 47-63 | 70->75 | 62-69 |
| Acidity | 0,03-0,19 | <0,03 | 0,03-0,04 |

BV breakdown voltage; BT before treatment; AT just after treatment; YT one year after treatment

### 3.2 Technical features

PCB decontamination process is a very tricky job which must be done with due care to protect the workers health, to prevent damages to the customer installations, to fulfil local regulations and to protect the environment.

To achieve all these requirements, decontamination mobile units (DMU) shall be equipped with:

- a self-cleaning configuration to avoid cross contamination;
- safety vessel, to recover eventual spillages;
- anti-dropping valves and safety pipes to connect the transformer to the DMU;
- suitable filters to avoid release oil dissolved gases onto the atmosphere;
- different sensors, pressure, flow, temperature, etc., to precisely control process parameters and to allow to stop electronically the DMU in the case of any problem.
- the possibility of use remote control facilities is strongly recommended.

In addition, personnel in charge of the process must be exhaustively trained in the use of the DMU in order to eliminate personal injuries and minimise environmental risks.

Another important problem is the protection of the customer's assets. The use of sodium, lithium and derivatives constitute an unreasonable risk of fire or explosion because the reagent may react explosively with free water or produce hydrogen by reaction with dissolved water or other oxidation components of the oil and the oil needs to be heated at temperatures (150-300 ºC) over its flash-point (several accidents associated to the use of sodium have been reported in the American press). As a consequence of such very high temperatures, the oil produces very high amounts of sludge and the natural sulphur containing compounds inhibitors are destroyed, thus making quite inconvenient to re-use the decontaminated oil in electrical equipment [6].

In summary, main advantages of this technology are the functional recuperation of transformer and insulating oil, preserving non renewable resources whilst avoiding production of dangerous waste; improves the physical, chemical and dielectric properties of the oil in service, warranting characteristics fulfilling the most stringent requirements of international standards (IEC 60422:2003); allows to perform the treatment with the transformer in service or guarantee the possibility of rapid re-energisation of the transformer in the case of emergency or grid requirements; is a safe and controlled process which does not represents risks of explosions or fires typical of those processes which use sodium, lithium or derivatives which need to operate at temperatures (150-300 ºC) above the oil flash point; is an efficient process for both oil and impregnated solid insulation materials which are decontaminated thanks to the solvent capability of the oil, minimising PCB contamination during service after the treatment; is in compliance with the European principles of safety, proximity, self-sufficiency and functional recovery; improves the company’s eco-balance and environmental protection policy (ISO 14001); improves the availability of assets (extending the life cycle) and the relationship cost/benefit in transformer and oil-filled equipment management (OAM – Oil Assets Management).

## 4. Future tendencies

Oil analysis, physicochemical properties and DGA, is one of the most powerful tools for transformers predictive maintenance. Although international standards, i.e. those from IEC TC 10 and ISO TC 28, are well founded, a proper diagnosis needs the assistance of new analytical techniques, specially analysis of dissolved sulphur and metals.

Precise determination of measurement uncertainties and the use of mathematical calculations in combination with oil and paper degradation models will have a relevant role in the determination of long term trend analysis.

Before initiating an oil treatment process, is strongly recommended to carry out a laboratory simulation to assure that the adsorbent material used is able to properly reclaim the oil. The use of adsorbent materials other than fuller’s earths or in combination with fuller’s earth should be considered.

Moreover, the increasing attention paid to environmental matters, will make necessary to investigate techniques for the decontamination of oils in service having relatively high concentrations of polyaromatic hydrocarbons (PAH). Preferably, this techniques should work in parallel with PCB decontamination ones.

Due to the current grid demands, which make difficult to stop a transformer even for preventive maintenance, it will be very important to consider the possibility to use integrated techniques able to decontaminate the PCB contaminants and to reclaim (depolarize) the oil in one step.

Finally, reclamation and decontamination processes will be done by using microunits in order to access to all operative scenarios, including underground substations.

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