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STATISTICAL ANALYSIS OF TRANSFORMER DIAGNOSIS METHODS BY OIL ANALYSIS

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1. INTRODUCTION

Due to the expensive replacement cost of power transformers, accurate methods to determine the condition and state of these machines have been developed and improved. The goal of these methods is, by means of the preventive maintenance, to avoid inopportune exits of service. These failures have directly costs associated the to the damage, but also costs associated to the problems caused by the energy lack of the clients. In competitive markets, the importance of knowing the real condition of the transformers is growing every day.

Many techniques have been developed for the determination of the conditions of the transformers. Routine field measurements are supplemented by tests carried out in laboratories on the insulating oil. Among them are: analysis of dissolved gases, contents of water in the oil, losses and breakdown voltage, interfacial tension, acidity, determination of furanic compounds or the grade of polymerization of a paper sample, when this is possible, through direct dew point measurement by the Recovery Voltage Measurements (RVM) method [1].

Different criteria have been used according to standards and other international publications. One of the problems of these methods is the difficulty to arrive to a diagnosis. Different criteria generally lead to different failure diagnostics. An expert opinion is necessary to select one.

Many field tests have also been developed and they are used when there is an indication of an incipient fault. Recovery voltage method, for measuring the percentage of water in paper, has been used in field tests to help in the process of making decisions when problems have been found, and also during transformer drying in repairing facilities. It has been very useful for the optimization of the drying process, where other techniques failed.

2. DISSOLVED GASES

This technique is based on the analysis of small quantities of gases dissolved in the oil, produced by internal defects. It is a very sensitive method and can distinguish between different causes of failures, but in some cases, it is not easy to interpret the analysis results.

Deterioration of the paper, through CO and CO_2 gases, can easily lead to wrong interpretation. Transformers with high paper deterioration (confirmed by other tests) did not appear as defective for this method. A 150 kV, 36 MVA power transformer with CO: 577 ppm and CO_2: 4010 ppm, had normal diagnosis results. However, the furanic concentration was 6 ppm. This high value shows paper degradation.

The ratio CO_2/CO calculation is a method recommended by the IEC Standard [2] for determining the deterioration of the paper insulation. According to this standard, values of the ratio greater than 3 may represent paper insulation in good condition. Nevertheless, Fig. 1 shows something different. In this figure data resulting from tests done in our laboratory are shown. Each point indicates the gas ratio (ordinate) and the furanic content (abscissa), for each transformer. There are many cases (17%) with excessive furanic compounds, indicating paper deterioration, which ratio values are greater than 3, which are supposed to be in good condition according to the standard.

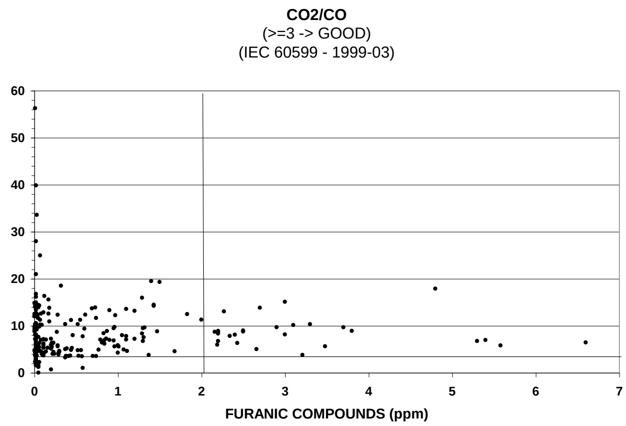

Fig.1 Ratio CO_2/CO versus furanic content.

Otherwise, about the CO_2/CO ratio the IEEE standard [3] says “This ratio is normally more than seven”, but it only considers cases with CO_2>5000 ppm and CO>500 ppm. This criterion reduce the total number of cases to those shown in Fig. 2.

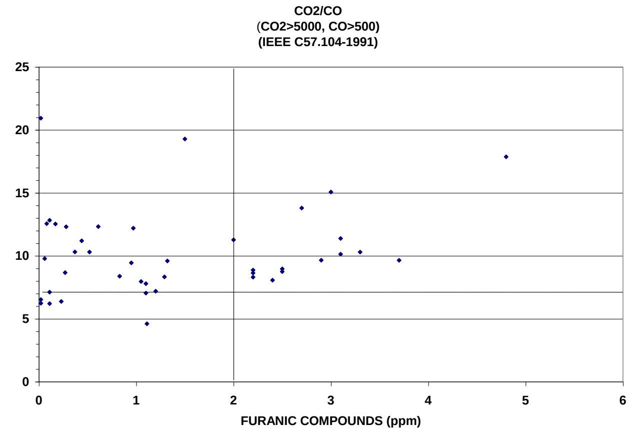

Fig. 2 Ratio CO_2/CO versus furanic content.

Also using this last standard, some cases appear as bad to the standard but good according to the furanic test, and on the other hand many cases have gas ratios greater than 7 (good paper condition) but their furanic content is greater than 2 (bad condition of the paper).

For other gases diagnosis, a similar situation occurs. As multiple interpretation criteria exist, it is not an easy task to conclude which is the right one. Most common criteria are IEC, IEEE, Rogers, Duval and Dornemburg [2 to 7]. Some of them almost always lead to a failure diagnosis, and others generally lead to no diagnosis. This happens because the gas ratios do not fit to the ranges managed by the criteria. Also an international criterion, as IEC, cannot detect some defective cases.

As an example, a 500 kV, power transformer with high concentration of H_2 appeared as normal under some criteria, when really it had an important partial discharge defect. The results of the chromatographic analysis are shown in Table 1. According to IEC and Rogers the diagnosis is normal aging. Others do not reach to any diagnosis.

TABLE 1
Dissolved gas concentration of a 500 kV transformer

GAS	CONCENTRATION (ppm)
Hydrogen (H_2)	1060
Methane (CH_4)	135
Carbon Monoxide (CO)	44
Ethylene (C_2H_4)	1595
Ethane (C_2H_6)	14
Acetylene (C_2H_2)	0

Fig. 3 shows a comparison between all mentioned criteria. For each one, the figure shows the number of transformers versus the type of diagnosis (Normal, Partial Discharges, Arcing Discharges, Thermal Defect or No Diagnosis).

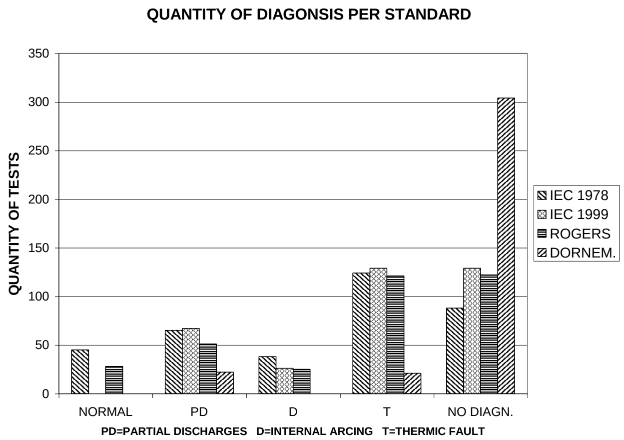

Fig. 3 Comparison of four different diagnosis methods

For this study, 347 transformer tests realized in our laboratory were analyzed. Different results arise if different criteria are used.. Diagnosis results from the to IEC standards (1978, 1999) present minor differences except that the last IEC standard provides no diagnosis for normal condition of the transformer. Rogers method does not differ greatly with those of the IEC, although it diagnosis few less cases and has more cases as NO DIAGNOSIS. Meanwhile, Dornemburg method diagnosis much less cases than the other methods, with large differences in the results.

Nowadays the situation is that the interpretation by an expert is necessary to arrive to a diagnostic. Neural network computer programs are being developed to assist the diagnosis [14], but they cannot replace the human experts at the moment.

3. OIL TESTS

Many physical and chemical properties of the oil are observed to assure this insulation media maintains good conditions. In this way, periodic tests on breakdown voltage, delta tangent, interfacial tension and neutralization value, are done. According to the standard IEC 422 [9] there are certain limit values for each one that may indicate problems for the transformer and its isolation if they are surpassed. Data from oil tests were analyzed. The cases were divided according to the maximum transformer voltage. Table 2 shows transformers for systems voltage greater than 420 kV, Table 3 for voltages between 72.5 kV and 170 kV and Table 4, lower than 72.5 kV. In each table the mean value and the standard deviation are calculated for each test. They are compared to the Standard limits.

TABLE 2
Results of oil tests for transformers of 500 kV

	Categ. 0 : >420 kV (**500 kV** - 51 cases)			
	standard limits	mean values	standard deviation	mean +/- 2 std. dev.
breakdown voltage (kV)	> 50	76	14	**48 ***
water content (ppm)	<= 20	13	7	**27 ***
delta tangent (%)	< 20	3	3	**9**
interfacial tension (mN/m)	> 15	36	6	**24**
neutralization value (mgKOH/g)	< 0.5	0,06	0,04	**0,14**

Results show that mean values of operating transformers, plus or minus 2 standard deviations (depending on the sign of the limit of the standard), that correspond to a confidence level of approximately 95%, differs from those indicated by the standard as to be the acceptable limits. In some cases, the difference between our calculated limit values and those of the standard is great enough as to call the attention of our clients in our certificates. Delta tangent is one of the parameters in which large difference exists. For example, for transformers of 500 kV (Table 2), the standard admits values up to 20 %, while our experience is that this value is, in a great proportion of the cases, less than 9 %. For transformers up to 170 kV, the standard admits values up to 100% while our experience indicates a mean value around 2% and a limit (confidence 95%) of 10% for transformers between 72.5 kV and 170 kV.

TABLE 3
Results of oil tests for transformers of 150 kV

	Categ. B : 72.5-170 kV (**150 kV** - 114 cases)			
	standard limits	mean values	standard deviation	mean +/- 2 std. dev.
breakdown voltage (kV)	> 40	84	14	**56**
water content (ppm)	<= 40	12	13	**38**
delta tangent (%)	< 100	2	4	**10**
interfacial tension (mN/m)	> 15	39	6	**27**
neutralization value (mgKOH/g)	< 0.5	0,04	0,04	**0,12**

TABLE 4
Results of oil tests for transformers lower than 72.5 kV

	Categ. C : <72.5 kV (**<=60 kV** - 193 cases)			
	standard limits	mean values	standard deviation	mean +/- 2 std. dev.
breakdown voltage (kV)	> 30	74	17	**40**
water content (ppm)	no free H20	14	10	**34**
delta tangent (%)	< 100	4	12	**28**
interfacial tension (mN/m)	> 15	38	6	**26**
neutralization value (mgKOH/g)	< 0.5	0,05	0,09	**0,23**

Similar situation exists with the neutralization value. The standard allows values as large as 0.5 mg/g, while our mean values are around 0.05 mg/g, (10 times lower).

3.1 Parameters tendencies

Analyzing the same transformer during its aging process, the previously mentioned parameters measured in the oil, change in a steady way upwards or downwards. Results for a set of 76 transformers, are shown in Table 5, where the average value of the slope and the standard deviation of that value are indicated for the sample of transformers analyzed.

TABLE 5
ANUALE SLOPES

	Breakdown voltage (Kv/year)	Water contents (ppm/year)	Delta tangent (%/year)	Interfasial tension ((mN/m)/year)	Neutralization value ((mg KOH/g)/year)
PROMEDIO:	3,20	-0,42	0,07	-2,74	0,001
DESV. EST:	15,72	9,54	2,25	10,51	0,021

Transformers which had at least three consecutive oil analyses done without an oil treatment in-between were chosen. The linear regression of each parameters for each transformer, finding the slopes of the lines, were calculated. The table shows the average value of each parameter and its standard deviation.

It is remarkable that, although the slope in most cases has the expected sign, many years are necessary to reach the value of the standard deviation. That means that the behavior of the analyzed set of transformers has large dispersions comparing to the annual variation.

4. WATER IN PAPER

High moisture contents in the isolation paper can mean paper deterioration, and on the other hand it accelerates the deterioration reducing the lifetime of the transformer. A simple test to determine this parameter can be done measuring the water contents of the oil. However, the transformer must be at constant temperature during many hours previous to the extraction of the sample to assure water equilibrium between the solid insulation and the oil. If this condition is not achieved, there is no relation between the water contents in the oil and the water contents in the paper. Even, if the equilibrium has been reached, there are different criteria to relate percentages of water in paper isolation to the oil water contents.

Other methods to calculate the paper moisture contents are based on measuring the Dew Point [10] at the gas phase, and electric methods using polarization spectrums from recovery voltages. An automatic implementation of this last method, controlling all the equipment by a computer, has been developed at our laboratory.

Four different methods of calculating the water contents in the paper are compared: RVM, IEEE [11], Dew Point and Oommen [8]. Figures 4 to 6 show the relations found in a sample of 16 transformers (1.5 MVA to 10 MVA, 6 kV to 30kV) where these tests were done. All had their active parts oil covered. Fourteen had the rest of the cube filled with nitrogen. The two remaining transformers were completely immersed in oil.

Fig. 4 shows the relation between IEEE and Oommen methods. They are based on the same test (determination of water in oil). So that, no difference exists between them in the physical determination. Only the proposed relation between the water contents in oil and paper differs. The tendency of the straight line is around 0.5 (with low dispersion). This means that the same contents of water in oil leads to double value of water in paper using Oommen criterion than using IEEE criterion.

Tests on samples were done at our lab to find out which one adapts better to reality. The samples consist of transformer papers in oil baths. Similar ratio between amounts of paper and oil than in real transformers were used. Oil and paper were carefully dried, and after that a measured weight amount of water was put in the paper. The samples were hermetically closed and placed at controlled constant temperature. Samples with water-in-paper percentages between 0.5% and 4% were created at temperatures between 20°C to 60°C. For all cases the Oommen results were more close to reality than IEEE. On the average, the actual moisture contents were 20% lower than the Oommen results. So, the error of the IEEE forecasts is around -40%.

Fig. 5 and 6 show the relation between RVM versus Oommen criteria and Dew Point versus Oommen. For these cases, different measuring techniques are used for each one. All transformers were out of service at the field. The temperature variation from day to night was from 25°C to 18°C approximately.

In Fig. 5, data shows a slope of 0.8 between RVM and Oommen methods, although the dispersion is high. This means that RVM is very close to reality.

For the comparison case Dew Point versus Oommen, the slope of the straight line decreased to 0.28 (Fig. 6). This value means that significant differences exist between both methods. For the Dew Point method in operating transformers, were a large part of the active part is immersed in oil, it is difficult to reach a complete equilibrium. Possibly, the difference found may result from incomplete paper-water/water-oil transference and incomplete oil-water/water-gas transference due to the variations of temperature. Anyway, erroneous conclusions can be arrived at if this method is used.

Other simple technique for verification of water in paper is the measurement of the isolation resistance. No relationship was found between isolation values (measured at dc voltages between 1000 V and 2500 V) and water contents. Obviously, when the water contents is very high (as occurs at the beginning of the drying process on repaired transformers), the isolation value is low; but after that, even over 1000 MΩ, a large water contents may remain.

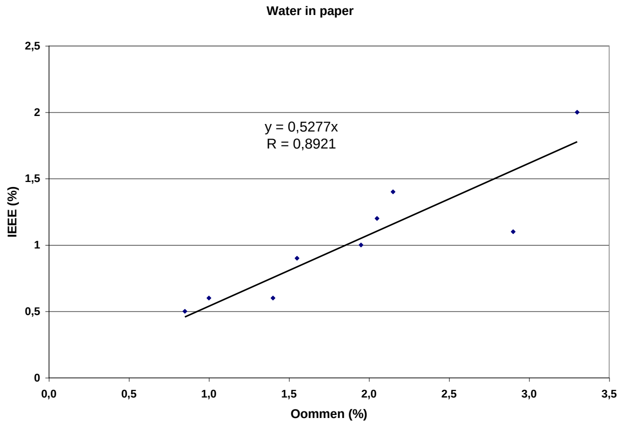

Fig. 4 Relation between IEEE and Oommen criteria

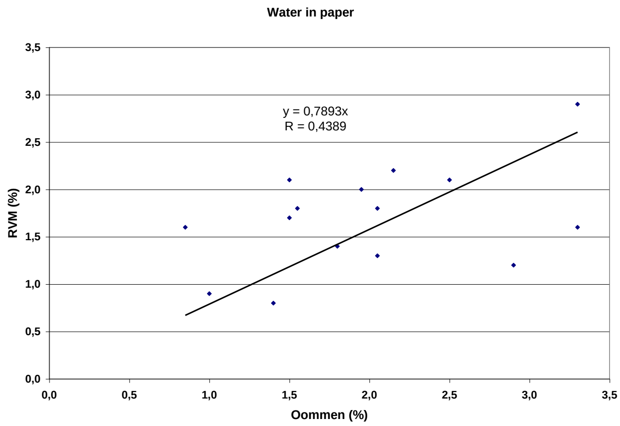

Fig. 5 Relation between RVM and Oommen criteria

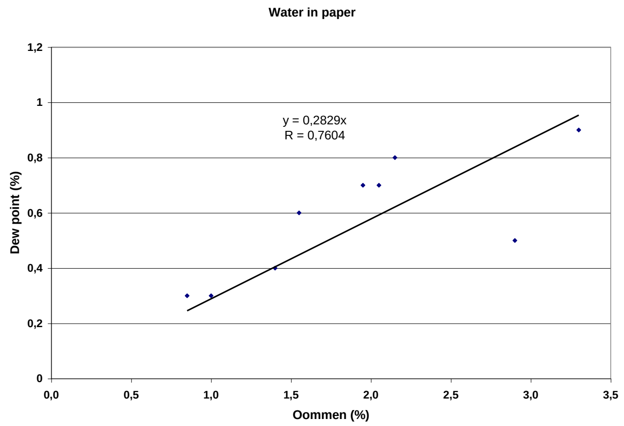

Fig. 6 Relation between Dew Point and Oommen criteria

5. CONCLUSIONS

All these techniques as a whole have been used by the authors to determine problems in power transformers. The information has been valuable for determining minor failures before they lead to a catastrophic ones, and to know the extent of the repair to be done.

A continuous comparison between chemical determination (Oommen) of oil moisture and polarization results shows a good agreement. However, there are cases with significant differences. When chemical methods show large paper water contents, the electrical method is proposed to confirm the result. From experiments done on installed transformers, only partially oil emptied, dew point method gives much lower results respect to the other method.

All failure prediction methods used require at last the intervention of an expert person for the interpretation of the results of the tests and their diagnosis, despite the programs developed for that purpose.

6. REFERENCES

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