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DIAGNOSTIC TOOLS FOR TRANSFORMERS IN SERVICE

by

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SUMMARY

The maintenance of transformers in service is one of the most important problems in the field of distribution of electricity.

The physico-chemical analysis of the oil permits a good tracing of its aging behaviour, necessary to assure safe operation conditions of the equipment in service. In thispaper information will be given on measurements performed on 4000 transformers during the last 20 years in Switzerland, on the periodicity and on limits adopted for these controlls.

The chromatography of the dissolved gases generated in the transformers in service, permits the detection of occured stresses or failures not detectable by the physico-chemical analysis. This technique has increased and improved the possibilities of detection of abnormalities at a preliminary stage during service operation. Criteria adopted for decision making and practical cases are presented.

On-site-monitoring of gases might be adopted mainly for large or strategic units. Detection systems for Hydrogen are used in Switzerland. The experience shows that the precision of the results gives a limited level of confidence in the diagnostics.

Finally HPLC (High Performance Liquid Chromatography) is a new tool in the diagnostic technique for the determination of furanic compounds giving information on the ageing of paper insulation. The goal of this determination is to forecast the remaining life of the insulation. This technique has been introduced in Switzerland, and the results seem to be promising.

Keywords: Insulating oil, DGA, HPLC, ageing, diagnostic methods, monitoring, transformer, control periodicity, furane.

1. INTRODUCTION

The analysis of the cooling/insulating oil, as applied in transformers, is now widely accepted. The oil analysis can give information on the condition of the oil itself, or on the existence of faults in other parts of the equipment (winding, core, etc).

The insulation co-ordination of an electrical distribution system requires that each component of that system can assure a minimum level regarding the withstand voltage during the total service life. In that case, an acceptable failure rate (reliability) will be provided.

The ageing and other parameters of the oil (humidity, pollution with particles, etc) are the source of a reduction of the withstand voltage. Therefore the insulation co-ordination requires that controls of the oil (oil condition, dissolved gas, etc) should be performed with a certain periodicity depending on:

- the type of equipment,
- the type of operating conditions (overvoltage, overloading, etc),
- the environmental conditions (water zone protection, etc).

2. PHYSICO-CHEMICAL ANALYSIS OF THE OIL CONDITION

There are many tests which can be performed on the oil:

- colour/appearance,
- water content,
- breakdown voltage,
- acidity,
- dielectric dissipation factor/power factor tg δ,
- interfacial tension.

In general, these tests have to be made in a laboratory with testing procedures according to the standards. In the last 15 years more than 4000 oil analyses have been performed in our companies on power, distribution and instrument transformers. The Figures 1-4 show the measured data for the different parameters. The upper number on these figures gives the measuring range and the lower number represents the quantity of data in that range.

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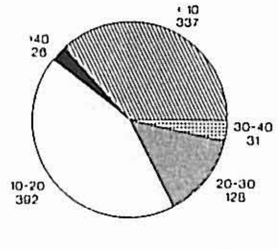

Fig.1 OIL ANALYSIS
WATER CONTENT (ppm)

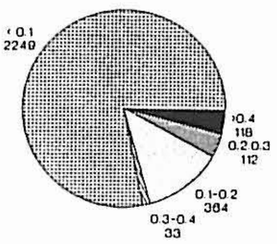

Fig. 2 OIL ANALYSIS
ACIDITY (mg KOH /g)

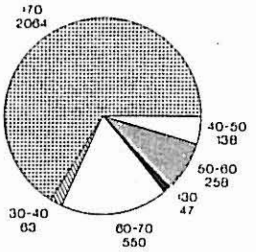

Fig.3 OIL ANALYSIS
BDV 50 Hz (kV)

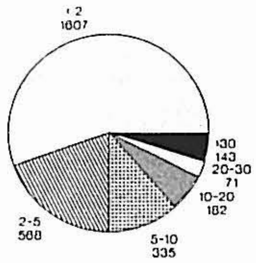

Fig.4 OIL ANALYSIS
POWER FACTOR (%)

It can be seen that 3-5% of the data represent critical values which are outside the fixed limits. The Figures 5-6 show two correlations between the data. The most significant observation is that no correlation exists between the ageing of the oil and the breakdown voltage.

It is recommended to adopt a periodicity of 4 to 5 years for these tests. Tab. 1 defines the exceptable limits for distribution and power transformers for diagnostic purposes.

	STAND.	RATED VOLTAGE			
		< 36	37-170	170-300	> 300
BREAKDOWN VOLTAGE (kV)	CEI 156	> 40	> 45	> 50	> 55
POWER FACTOR AT 90 °C (o/o)	CEI 247	< 30	< 30	< 30	< 20
ACIDITY (mgKOH/g) - UNINHIBITED OIL - INHIBITED OIL	CEI 296	< 0.7 < 0.05	< 0.4 < 0.05	< 0.4 < 0.05	< 0.3 < 0.05
INTERFACIAL TENSION (mN/m)	ISO 2049	> 12	> 15	> 15	> 15
WATER CONTENT (ppm)	CEI 814 CEI 733	< 40	< 40	< 20	< 20

Tab. 1: Recommendations and limits for power transformers in service

3. CHROMATOGRAPHIC OIL ANALYSES

3.1 THE DISSOLVED GAS ANALYSES (DGA)

For many years the analysis of the gaseous decomposition products of the insulating oil has been of importance in the monitoring of transformers and other oil-insulated electrical equipment. It offers the only possibility of at least an indirect look into the normally hidden interior of a transformer. This technique is based on the observation that different decomposition products are split off under load from the insulating oil (=hydrocarbons). Typical products are: hydrogen, methane and other light hydrocarbons. All these components are gaseous and remain normally dissolved in the oil. The extraction and the analysis of these gases is standardized in the IEC-standard 567 [1], which has just been published in its revised version. The association of the different gases extracted from the oil to an electrical fault is regulated by the IEC-standard 599 [2]. This standard is an essential help for recognizing inherent faults such as hot spots, different kinds of discharges, etc.

However, there is one problem which leads often to dissensions in the interpretation of the results. It is a known fact that certain amounts of these

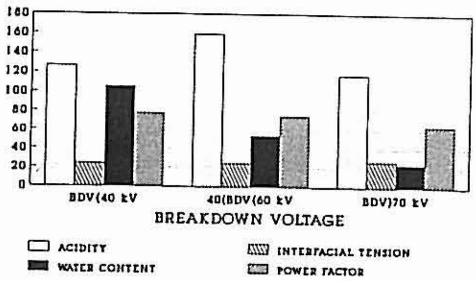

Fig.5 OIL ANALYSIS
CORRELATION

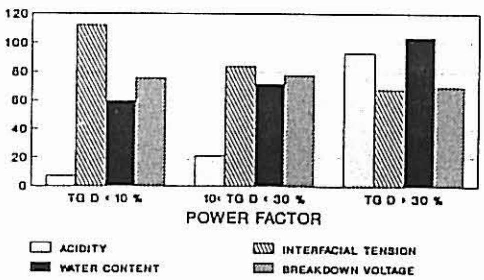

Fig.6 OIL ANALYSIS
CORRELATION

gase s are dissolved in the oil of each transformer. This applies also to fault-free transformers and even to freshly impregnated ones which have never been in operation [3]. During the first years of operation the level of gas concentrations is permanently rising, until, after a certain time, the loss of the gases is in equilibrium with their production. In a normal, fault-free power transformer this situation is reached after about 7 years of service. The amounts of decomposition gases in fault-free devices is still a matter of discussion. Praehauser et al.[4] published several data compilations of so called "maximum admissible" decomposition gas concentrations in different kinds of transformers and after different times of operations. Those data are based on experience of experts from 15 countries, "which does not mean that they are official values for that country." Our experiences of some thousands of dissolved gas analyses generally confirm the recommendations given by Dörnenburg and Hutzel[3] (Tab.2).

time of operation		concentrations in ppm by vol. 3 years	>7 years
Hydrogen	H_2	200	250
Methane	CH_4	100	200
Ethane	C_2H_6	100	200
Ethylene	C_2H_4	150	300
Acetylene	C_2H_2	15	35
Carbon monoxide	CO	500	1000
Carbon dioxide	CO_2	6000	11000

Tab. 2: Upper limmits of decomposition gas concentrations in fault-free (power)transformers as a function of operating time [3]

These "limits" should only be regarded as approximate values. The most reliable method for a significant fault assignment is the periodic control of the gas formation in the insulating oils. The occurance of changes in the gas formation that means, forexample, a sudden increase of one or more compounds is in most cases a sure indication of a fault. On the other hand the different types of transformer design must also be taken into account. Especially when the oil of an on-load tapchanger communicates with the transformer oil. In this case of course discharges of high energy density are simulated. Distinct differences are also observable between closed and open breathing transformers.
In open transformers a permanent interchange of the gases between the oil and the atmosphere takes place. This leads in a fault-free transformer after a certain time to an equilibrium between formation and loss of the gases. In a closed transformer, however, all decomposition gases with the exception of hydrogen, which can easily diffuse through the rubber sealing, will accumulate in the course of time. This has to be considered when interpreting the results. On the other hand a closed system makes the diagnosis of a newly arising fault because of the high basic levels very difficult. Fortunately in our area of work only very few devices of that type are in operation.

Not the less complicated is the situation for the instrument transformers. In recent years in a series of more than 300 dissolved gas analyses from instrument transformers of different types, designs and manufacturers we have not been able to discover a consistent behaviour. Some of our observations are illustrated in the Tables 3 and 4.

Table 3 exhibits the distribution of the gaseous decomposition products detected in the oils of 3 different manufacturers after more than 20 years

	220 kV	220 kV	380 kV
H_2	8 (3-10)	40 (6-100)	10 (4-120)
CH_4	15 (12-17)	25 (15-40)	15 (3-120)
C_2H_6	10 (7-12)	50 (20-80)	100 (1-520)
C_2H_4	1 (1)	2 (1-3)	20 (1-40)
C_2H_2	< 1 (-)	< 1 (-)	< 1 (-)
CO	200 (140-260)	100 (60-140)	400 50-900)
CO_2	600 (450-710)	1900 (1300-2700)	1200 (350-5100)
age:	> 20 years	> 20 years	> 20 years
No:	6 devices	3 devices	58
sealing:	N_2-cushion	oil-filled metal bellows	N2-filled rubber bellows
manufacturer:	F	A	C

Tab. 3: Decomposition gas concentrations (ppm b.v.) in voltage transformers of different constructions and from different manufacturers In brackets: ranges of observed conc.

of service. Especially in the case of the 380 kV voltage transformers in Tab. 3 which are all of the same type of design and from the same-manufacturer, CH_4 concentrations have been observed varying from 3 to 120 ppm and much more in the case of C_2H_6, where a range from 1 to 520 has been detected. However we believe that all these devices are electrically sound and will perform satisfactorily.

	E	B	A
H_2	60 (20-140)	40 (4-70)	250 (40-320)
CH_4	5 (3-7)	5 (1-10)	6 (2-26)
C_2H_6	15 (3-20)	2 (1-5)	2 (1-3)
C_2H_4	1 (1)	1 (0-2)	5 (1-20)
C_2H_2	< 1 (-)	< 1 (-)	3 (0-14)
CO	160 (130-160)	100 (10-300)	200 (90-540)
CO_2	250 (130-500)	200 (90-240)	800 (400-1500)
age:	10-20 years	10-20 years	> 20 years
No :	7 devices	15 devices	12 devices
sealing:	oil-filled metal bellows	oil-filled metal-bellows	oil-filled metal bellows
	D	C	C
H_2	10 (3-11)	17 (15-19)	5 (2-10)
CH_4	8 (3-20)	2 (2-3)	50 (3-150)
C_2H_6	5 (2-11)	1 (1)	400 (1-900)
C_2H_4	4 (1-6)	1 (1)	20 (1-40)
C_2H_2	< 1 (-)	< 1 -	< 1 (-)
CO	200 (60-440)	100 (10-150)	500 (140-700)
CO_2	800(300-1200)	70 (50-80)	1500 (500-5000)
age:	> 20 years	10 years	> 20 years
No :	16 devices	3 devices	33 devices
sealing:	oil-filled rubber-bellows	oil-filled metal-bellows	N_2-filled rubber bellows

Tab. 4: Decomposition gas concentrations in combined measuring transformers (CT + VT) 220 kV from different manufacturers (A,B,C,D,E) and of different design. In brackets: ranges of observed concentrations.

More or less similar is the situation observed in a series of 86 combined 220 kV-measuring transformers(CT + VT) in Table 4. These transformers are from 5 different manufacturers and of different designs regarding the sealing. Understandable are in some cases the high hydrogen contents in the devices which are sealed by metal bellows compared to those sealed by rubber bellows. It is not possible to explain, however, the large variations of the ethane concentrations in the oils of these devices. When applying the IEC-guide 599[2] one would argue a thermal fault in the range 150 °C - 300 °C. We do not believe that this is true. In our opinion these instrument transformers are also in a satisfactory condition. This statement, which at first appears unusual, is confirmed in the results given in Tab.5

	ppm	range
H_2	7	3- 9
CH_4	50	37- 56
C_2H_6	230	150-340
C_2H_4	12	10- 12
C_2H_2	1	-
CO	150	110-180
CO_2	620	460-720

Tab. 5: Decomposition gas concentrations in combined measuring transformers (CT + VT) 220 kV sealed by N_2-filled rubber bellows. Between 20 and 30 years old, never been in service Manufacturer C as in Tab. 4. These data are not included in Tab. 4.

In that table the DGA-results are listed from 4 devices of the same age and design and from the same manufacturer. They have never been in operation. There is no significant difference to the corresponding types of Table 4, which in the contrast to these 4 objects have been in service for more than 20 years.

These observations mentioned above make the diagnosis very difficult. To consider all these peculiarities in a general guideline makes the planned revision of the IEC-standard 599[2] complex. On the other hand these examples demonstrate that an individual judgment of the DGA results is still necessary and cannot be replaced by an automatic mechanism.

3.2 THE HPLC ANALYSES OF THE INSULATING OIL

It is known that not only decomposition products deriving from the insulating oil are observed but also products which are the results of the degradation of the solid insulation, i.e. the cellulose. During natural ageing of the cellulose mainly carbon dixide (CO_2) is produced and in lower amounts also carbon monoxide (CO). A CO_2/CO-ratio in the range 7 indicates normal paper ageing. An anomalous paper degradation produces significantly lower CO_2/CO-ratios. On the other hand the oxides of carbon are also produced by a general oxidation of the insulating oil, when in direct contact with air. That means that they are not a definitive indication of the decomposition of paper With the application of the HPLC in analyzing the insulating oil, however, it is possible to detect indications of an anomalous paper degradation [5] Furanic compounds such as:

- 5-hydroxymethyl-2-furfural
- 2-furfurylalcohol
- 2-furfural
- 2-acetylfuran
- 5-methyl-2-furfural

are formed by anomalous ageing of cellulose. If these compounds are detected in the oil of a transformer or another oil-paper insulated electrical device it is a significant indication for anomalous paper dedradation. A new IEC-document [6] gives instructions for that kind of oil analysis. A status report of the work done in the CIGRE WG 15-01 Task Force 03, which is dealing with this problem, is given by de Pablo et al.[7] during this conference. In our companies this technique is applied in the monitoring of electric equipment either when there are indications from the DGA of anomalous paper degradation because of unusual amounts or ratios of the carbon oxides or when a high temperature is indicated, to be sure that no paper insulation is involved.

Since we started our activities in this field about six years ago several hundred HPLC-analyses of the oils of different electrical equipment have been made in our laboratory. In contrast to the DGA where always certain gaseous oil decomposition products as the result of the natural ageing are detectable, the HPLC-analyses exhibit only in the most exceptional cases a positive result. This is in fact one of the most distinct differences compared with the DGA: only in those cases when a real paper deterioration has occured will one be able to detect furanic compounds in the oil. Mainly we found in such cases the compound 2-furfural but only in very low concentrations, that means in the low ppm range. Some of the other compounds which are mentioned above have been present as traces only. So only in four cases have 2-furfural and traces of 5-hydroxymethyl-2-furfural and 5-methyl-2-fufural been found. In about 60 HPLC-analyses of instrument transformer oils we have not been able to detect any furanic compounds at the detection limit of 0,1 ppm (i.e. mg/kg), even in cases where the DGA yielded high concentrations and/or unusual CO_2/CO-ratios e.g. 1 to 3.

4. FREQUENCY OF THE OIL TESTS

In co-operation with other Swiss electrical power utilities and during the past 30 years the following frequency of oil checks has been tested and established. Essentially our experiences are in in accordance with the recommendations given in the IEC-standard 422 [8].

4.1 POWER TRANSFORMERS

>170 kV

A complete examination of the oil (physico-chemical properties, DGA) is made after energizing and then at four- to five-year intervals.

<170 kV

Usually these transformers are checked on a random basis, about every ten years (physico-chemical properties, DGA)

General

If any of the oil tests, regardless of the equipment voltage, yields suspicious results, the time period between further tests is reduced. On the other hand, even such transformers with lower voltages than 170 kV but which are situated in a strategically important place or function are also examined at shorter intervalls, as required. Additionally it is our practice to examine the oil of large power transformers especially those in the nuclear power stations every year. This is done a sufficient length of time before the annual refueling break, so that any necessary actions can then be carried out.

4.2 INSTRUMENT TRANSFORMERS

Because of the large number of instrument transformers in service it would be very expensive to check all devices by routine oil examinations. In a well-proven procedure we select from each production series 3 to 6 individual devices which are checked regularly, to represent the whole series. This works well for all instrument transformers >170 kV. Such a routine examination includes

- the physico-chemical properties,
- the DGA, and recently also
- the HPLC - analysis.

This examination is generally performed every 10 years. If any suspicious observations are made, the time period between the tests is reduced. Our experience with this procedure has been positive.

During the last twenty years only 3 failures have occured, whereby one of them was caused by a direct lightning strike.

5. MONITORING OF TRANSFORMERS IN PRACTICE

Among those cases where the monitoring of transformers by examination of the insulating oil was able to prevent a fault during service the example of the following 1000 MVA transformer group in a nuclear power plant is very impressive. The strong rise of the ethylene content in the oil of one pole (phase R) of that transformer after the first year of service indicated a hot spot (Fig. 7). The fault has been found in some metal parts which were

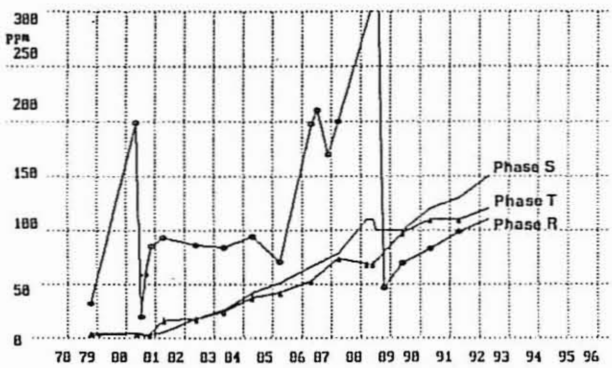

Fig.7 ETHYLENE-CONTENT (ppm) as function of time in a 1000 MVA-420 kV-Transformer group

heated by eddy currents. After elimination of this fault the transformer operated for 6 years without problem. Then a sudden content again indicated a hot spot. The simultaneous increase of the acetylene content indicated this time a much higher temperature fault. Several attempts to locate the hot spot from outside failed. Therefore the transformer was opened during the regular refueling outage of the power plant and a nearly molten grounding connection was detected. This fault would have lead with certainty to a failure within a short period of time. The poor contact could easily be eliminated and the transformer went back into service after the regular outage without any problem.

A few years later the same transformer group again caused problems. The content of carbon dioxide rose to values which were unusually high. The calculation of the total gas saturation using the solubility coefficients given in IEC 567 [1] gave values of about 100 %. Particularly the contineous increase of CO_2 in all 3 single phase transformers (Fig. 8) indicated an over saturation which would unquestionably lesd to a Bucholz-alarm. The 3 oils were examined by HPLC-analyses to be sure that this unusual increase in CO_2-contents is not the result of an anomalous paper degradation. Fortunalely no furanic compounds could be detected which excluded an anomalous paper degradation. As a consequence of these observations, oil degassing was carried out during the next planned outage.

In spite of all these difficulties this 1000 MVA transformer group is still in operation thanks to the various oil examinations.

On the other hand 11 instrument transformers have been taken out of service during the past 20 years as a result of oil examinations: 6 because of alarming results of the DGA and another 5 because of critical dissipation factors. As a result of our action we have been able to limit the number of faults to only 3 during the same period of time, whereby one was caused by a direct lightning strike.

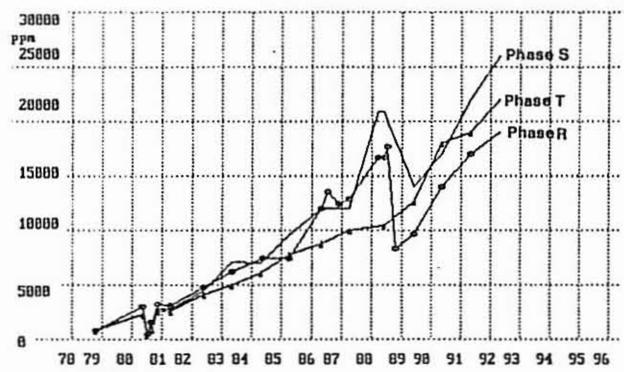

Fig. 8 CO_2-CONTENT (ppm) as function of time

In relation to the large number of devices which are supervised by our companies this may be regarded as a success.

As a further activity in transformer monitoring a few selected devices have been equipped with a Teflon probe for on-site measurements of the hydrogen content with a comercially available device. The disadvantage of this instrument is that one can only detect the hydrogen content dissolved in the oil. Other decomposition products, however, are not indicated. The agreement of the hydrogen contents measured with this detector compared with those determined by the classical IEC-method is limited. This is mainly a result of the low hydrogen contents in the transformers tested. The true values are in the range between 10 and 20 ppm. Such low hydrogen contents are at the limit of the measuring accuracy.

It is planed, however, to continue these activities and to further improve the results.

6. CONCLUSIONS

Both, physico-chemical and chromatographic analyses (DGA and HPLC) of insulating oils are an essential help in the monitoring of transformers and other oil-insulated electrical equipment.

The successes of the techniques applied confirm the invested efforts ensuring reliable electrcal supplies. An improvement of the on-site and on-line monitoring devices, however, would be desirable for the future.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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RESUME

La maintenance des transformateurs en service est un des problèmes importants dans le domaine de la production d'électricité.

L'analyse physico-chimique de l'huile permet de suivre l'évolution vieillissement de l'huile, gage du bon fonctionnement de l'appareil. On présentera une statistique des résultats de mesure accumulées en Suisse depuis 20 ans sur 4000 appareils ainsi que la périodicité et les limites adoptées pour ces contrôles.

L'application de l'analyse par chromatographie gazeuse des gaz dissous, formées dans le transformateur en service, a permis de déceler des contraintes que les méthodes mentionnées précédemment ne mettent pas en évidence. Cette méthode a accru et affiné les possibilités de détection de défauts à leur naissance ou en cours d'exploitation. On présentera ici les critères adoptés pour la prise de décisions ainsi que des exemples tirés de la pratique.

La surveillance en continu a pris de l'importance pour ce qui concerne les grosses unités ou certaines autres unités d'importance stratégique. Des appareils de détection permettant de doser H_2 sont utilisés en Suisse. L'expérience montre que la précision des résultats ne permet pas de donner un diagnostique sûr.

Finalement, nous présenterons la nouvelle application de la chromatographie liquide pour doser le vieillissement du papier. La finalité étant prévoir la fin de la vie de l'isolation, partant de celle du transformateur. Cette technique est déjà utilisée en Suisse et les résultats semblent prometteurs.