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Effect of Different Contaminants on Mineral Insulating Oil Characteristics

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***Abstract*—**Deterioration of insulating oil is a natural process that occurs during transformers operation. However, this process can be accelerated by some factors, such as oxygen, high temperatures, metals and, moisture, which rapidly reduce oil insulating capacity and favor transformer faults. Parts of building materials of a transformer can be degraded and yield soluble compounds and insoluble particles that shorten the equipment life. Physicochemical tests, dissolved gas analysis (including propane, propylene and, butane), volatile and furanic compounds determination, besides quantitative and morphological analyses of particulate are proposed in this study in order to correlate transformers building materials degradation with insulating oil characteristics. The present investigation involves tests of medium temperature overheating simulation by means of an electric resistance wrapped with the following materials immersed in mineral insulating oil: test I) copper, tin, lead and, paper (heated at 350-400 °C for 8 h); test II) only copper (at 250 °C for 11 h); and test III) only paper (at 250 °C for 8 h and at 350 °C for 8 h). A different experiment is the simulation of electric arc involving copper, using an electric welding machine at two distinct energy sets (low and high). Analysis results showed that dielectric loss was higher in the sample of test I, higher neutralization index and higher values of hydrogen and hydrocarbons, including propane and butane, were also observed. Test III oil presented higher particle count, in addition, ferrographic analysis revealed contamination with fibers and carbonized paper. However, these particles had little influence on the oil physicochemical parameters (dielectric loss and neutralization index) and on the gas production, which was very low. Test II oil showed high levels of methane, ethane, and propylene, indicating the effect of metal on oil degradation. CO_2 and CO gases were formed in the highest concentration in test III, as expected. Regarding volatile compounds, in test I acetone, benzene and toluene were detected, which are oil oxidation products. Regarding test III, methanol was identified due to cellulose degradation, as expected. Electric arc simulation test showed the highest oil oxidation in presence of copper and at high temperature, since these samples had huge concentration of hydrogen, ethylene, and acetylene. Particle count was also very high, showing the highest release of copper in such conditions. When comparing high and low energy, the first presented more hydrogen, ethylene, and acetylene. This sample had more similar results to test I, pointing out that the generation of different particles can be the cause for faults such as electric arc. Ferrography showed more evident copper and exfoliation particles than in other samples. Therefore, in this study, by using different combined analytical techniques, it was possible to correlate insulating oil characteristics with possible contaminants, which can lead to transformers failure.

***Keywords*—**Ferrography, gas analysis, insulating mineral oil, particle contamination, transformer failures.

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I. INTRODUCTION

POWER transformers are the main equipment in electric power transmission and distribution systems. The constant energy supply is highly dependent on correct transformer operation [1]. Replacing a transformer is an expensive process and can affect energy supply. For this reason, utility companies require scheduled maintenance to avoid sudden transformer faults and interruption in power supply for long periods [2], [3].

Power transformers use an insulating system composed of paper/oil and transformer useful life is extremely correlated to paper and oil condition during operation. Periodic analysis of insulating oil is the most appropriate procedure to assess equipment performance and extend useful life. Insulating oil degrades in service and this process is sped up by the presence of oxygen, high temperatures, metals, and moisture. Oil deterioration reduces insulating capacity and increases risk of faults [1]-[3].

Some transformer faults are known to be related to particle contaminating the oil. Parts of transformer building materials can be released in insulating oil due to equipment defect/fault, wear, oil, and solid insulation aging, resulting in soluble and insoluble compounds. Therefore, possible sources of insulating oil contamination are diverse, and these particles can be of different nature, such as rubber, copper, steel, tin, paper fiber, silica among other [2], [4].

Particle effect on oil characteristics depends on its amount and nature. Thus, knowing what materials are involved in the fault will help maintenance team choosing action to be taken. Dissolved gases analysis (DGA) is the method commonly used to diagnose thermal and electric faults in transformers. However, DGA does not inform about which specific part of equipment or particle is involved in the fault [2], [5]. Regarding this, this study aims to evaluate insulating oil contamination status through physicochemical tests, DGA (including propane, propylene, and butane), volatile and furanic compounds determination, as well as quantitative and morphological particle analysis, in order to correlate transformer building materials degradation with insulating oil characteristics.

II. MATERIAL AND METHODS

Tests of medium temperature overheating simulation were performed. Test set up used an electric resistance wrapped with different materials immersed in insulating mineral oil and heated at different temperatures and periods. Oil containing vessel was immersed into ice to cool the system and avoid oil aging (Fig. 1).

- Test I: Resistance wrapped with copper, tin, lead, and paper. Temperature was controlled (300-350 °C) for 8 h.

Fig. 1 System set up of overheating simulations

- Test II: Resistance wrapped only with copper and temperature kept at 250 °C for 11 h.
- Test III: Resistance wrapped only with paper, heated at 250 °C for 8 h and at 350 °C for 8 h.

A different experiment was carried out to simulate an electric arc involving copper. For this purpose, copper was immersed in insulating mineral oil and by means of an electric welding machine, distinct energy strength (low and high) was applied to the system, as illustrated in Fig. 2.

Fig. 2 System set up of electric arc simulations

After above mentioned tests, insulating mineral oil was characterized by different techniques as follows.

(a) Physicochemical analyzes including:
- Interfacial tension (25 °C) measured in an interfacial tensiometer Kruss (model 8600).
- Total acidity number (TAN) using a titrator Titras PRO (613-5287).
- Dielectric loss factor (100 °C) determined in an equipment of dielectric loss measure Tan delta Huazheng (model HZJD-3Z) and dielectric strength using an equipment from Huazheng, model HZJQ-X1.

(b) DGA (including propane, propylene, and butane) measured in a gas chromatograph Agilent (model 7820A) with Headspace sampler and detection by flame ionization (FID) and thermal conductivity (TCD).

(c) Volatile compounds determined in a gas chromatography Agilent (model 7820A) with Headspace sampler and detection by mass spectroscopy (GC-MS).

(d) Furanic compounds using a high-performance liquid chromatography (HPLC) Agilent 1220 Inifinity LC with UV/Vis detection.

(e) Elementary analysis: particle count measured in a Spectro Scientific, LaserNet model SpectroLNF Q200, magnetic particle quantification index (PQI) using an equipment from Parker, model Analex PQL and metals using an atomic emission spectrometry using rotating disc electrode (Spectroil)) from Spectro Scientific, model Spectroil Q100.

(f) Particle nature, shape, and size by ferrography, using an analytical ferrograph Spectro INC, model T2FM and a Bioptika microscope.

III. Results and Discussion

Results of physicochemical analysis, PQI index and particle count for overheating simulations are presented in Table I.

TABLE I
PHYSICOCHEMICAL ANALYSIS, PQI INDEX AND PARTICLE COUNT OF OVERHEATING SIMULATIONS

Parameter	Sample					
	Test I[a]	Test II[b]	Test III[c]		Electric arc	Electric arc
	300-350 °C 8 h	250 °C 11 h	250 °C 8 h	350 °C 8 h	low energy	high energy
PQI index	9	13	30	31	14	26
Particle count (ISO)	-	21/20/18	25/24/21	27/24/18	22/19/13	24/23/19
Dielectric loss factor 100 °C (%)	10,3	0,1	2,8	0,1	-	-
TAN (mg KOH g^{-1})	0,32	0,03	0,03	0,03	-	-
Interfacial tension 25 °C (mN m^{-1})	-	-	43	37	-	-

[a] Test with paper + resistance + metals; [b] Test with resistance + copper; [c] (paper + resistance)

Not all samples were analyzed using the same technique, however, relevant information was acquired. Results pointed out that paper causes higher particle release, since particle count significantly increased in test III, which used only resistance and paper. By comparing low and high electric energy discharges, particle count and PQI index were higher in high energy.

Dielectric loss factor was higher in test I than in other due to metals presence in high temperature. TAN was substantially high in test I, showing that presence of several particles favors oil degradation. Interfacial tension measured in test III indicated temperature effect on reducing this parameter even in metal absence.

DGA results related to common gases are presented in Table II. Hydrogen content was increased as temperature and time increase, as expected. The highest hydrogen, methane and ethane levels were reached in test I, confirming effect of diverse particles on oil degradation. Electric arc of high energy released more acetylene, which is a characteristic gas for this type of fault.

TABLE II
DGA – COMMON GASES

Gas (ppm)	Sample					
	Test I[a]	Test II[b]	Test III[c]		Electric arc	Electric arc
	300-350 °C 8 h	250 °C 11 h	250 °C 8 h	350 °C 8 h	low energy	high energy
H_2	1031	769	5	49	8	105
O_2	9964	14182	16115	24723	8584	23170
N_2	84954	74567	45182	83567	22775	61853
CH_4	14996	6308	33	677	16	25
CO	574	273	287	37	15	8
CO_2	6561	801	3590	444	193	438
C_2H_6	14293	1429	29	1815	13	22
C_2H_4	685	68	52	1289	15	97
C_2H_2	151	0	0	0	29	296
CO_2/CO	11	3	13	12	13	55

[a] Test with paper + resistance + metals; [b] Test with resistance + copper; [c] (paper + resistance)

CO_2 and CO were formed in a higher proportion in tests that used paper, as expected. CO_2/CO ratio is commonly used to check paper involvement in faults. However, in this study, the lowest CO_2/CO ratio was achieved in test II (without paper). This is justified, however, by lower total concentration of these gases when compared to tests using paper.

DGA containing propane, propylene and butane was performed and its results are showed in Table III.

TABLE III
DGA – PROPANE, PROPYLENE AND BUTANE

Parameter	Sample					
	Test I[a]	Test II[b]	Test III[c]		Electric arc	Electric arc
	300-350 °C 8 h	250 °C 11 h	250 °C 8 h	350 °C 8 h	low energy	high energy
C_3H_6	11345	25770	0	4647	1	86
C_3H_8	10871	3180	70	820	45	9
C_4H_{10}	19128	5895	34	610	5	88

[a] Test with paper + resistance + metals; [b] Test with resistance + copper; [c] (paper + resistance)

Good correlation was found between propylene and ethylene, since they were formed in a higher concentration in test I. Propane and butane were higher in test I, following the trend of higher hydrocarbon contents in this sample.

GC-MS analysis indicated some volatile compounds, which are acetone, benzene, and toluene in tests I and III, in addition to methanol in test III. Acetone and benzene may be related to oil oxidation, whereas methanol is associated with paper degradation.

Elementary analysis through Spectroil (Table IV) showed lead in test I, arising from metals that were wrapped in resistance, which suggests that high temperature favors lead particles formation. Copper was identified only in electric arc tests, showing that high energy level is required to these particles' formation. Silicon, probably from external contamination, was detected in test III.

Ferrographic analysis allowed to identify more particles in the samples. Fibers, carbonized paper, and dark particles were observed in test I sample (Fig. 3). In test II, copper and dark particles were noticed (Fig. 4). In test III (Fig. 5), fibers and dark particles were identified and, especially in test carried out at higher temperature (350 °C), a gelatinous material similar to sludge was observed. Ferrography of electric arc tests (Fig. 6) showed copper pieces and spheres, in addition to red oxides.

TABLE IV
METALS DETECTED BY SPECTROIL

Metal (ppm)	Sample					
	Test I[a]	Test II[b]	Test III[c]		Electric arc	Electric arc
	300-350 °C 8 h	250 °C 11 h	250 °C 8 h	350 °C 8 h	low energy	high energy
Si	0	0	2	2	0	0
Cu	0	0	0	0	0	2
Pb	1	1	0	0	0	0

[a] Test with paper + resistance + metals; [b] Test with resistance + copper; [c] (paper + resistance)

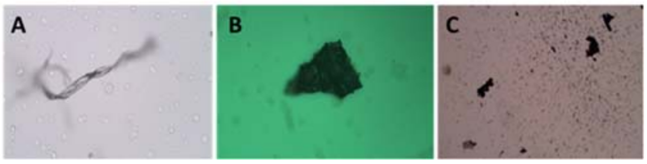

Fig. 3 Ferrograms of test I samples. A: fiber. B: Carbonized paper. C: Dark particles

Fig. 4 Ferrograms of test II samples. A and B: Copper. C: Dark particles

Fig. 5 Ferrograms of test III samples. A: Dark particles. B: Fiber. C: Gelatinous material

Fig. 6 Ferrograms of electric arc test samples. A: Copper sphere. B: Copper piece. C: Red oxides

IV. CONCLUSION

This study showed that it is possible to evaluate insulating oil contamination through different analytical techniques. The proposed methodology can be an alternative for the identification of insulating oil contamination source and, therefore it can be useful as an indication of maintenance actions for better operational and financial planning.

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