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변압기 절연유의 열화 검출에 관한연구

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A new method for measuring the degradation level of transformer insulating oil in use

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ABSTRACT

Aging process in transformer insulating oil is studied by measuring the leakage current in ceramic sensor. The current of a sensor developed in this paper shows a close relationship with the acid value and the breakdown voltage of the transformer oil. The sensor has exellent physico-chemical reaction to the oil and stable adsorption of conductive impurities. Therefore the experimental data show good reproducibility. From the detailed analysis of the leakage current, it may be proposed that the condition of transformer insulating oil in service can be checked portably.

INTRODUCTION

It has been recognized that the transformer oil should be degraded by aging and/or various processes under long time service in spite of perfect fabrication of the oil.

Many studies have aimed to find degradation parameters of impurities, acid value and breakdown voltage of the oil. [1] [2] [3] The number of impurities in an oil is related to the breakdown voltage of the oil, assuming that the typical size of impurities is in the range of the 25 [μm] ~ 50 [μm]. [4] The tan δ and conductivity of oxidized mineral oils have been shown unambiguously to depend on the dissolved - copper peroxide, and soluable acidity contents. Changes in tan δ and conductivity with the oxidation time correspond to the appearance of these products in the oil. [5]

In this paper it is shown that the variation in acid value and breakdown voltage of the transformer oil with the oxidation time corresponds to products in the oil. It is also shown that the leakage currents of the ceramic sensor vary likewise as acid value and breakdown voltage with the oxidation process and normal condition.

ANALYSIS OF DEGRADATION OIL

Insulating oil containing hydrocarbons is resolved into various products by temperature, auto - catalysis of metal and contamination of impurity elements and light beam etc. Though the base oil is in either naphthenic series or paraffinic series, all of the insulating oil is composed of aliphatic, cyclo - aliphatic, aromatic hydrocarbons. These compounds create ROH, RCOR', RCHO, RCOOR', RCOOH by oxidation process. The reaction process occurs by free radical chain mechanism known as auto-oxidation. The degradation mechanism of the insulating oil is likewise as following examples.

For example : [6]

Free Radical Reaction

$$2RH \xrightarrow{O2} 2R^{o} + H_2O$$

Hydroperoxy Radical & Propagation Reaction

$$R^{o} + O_2 \longrightarrow RO_2^{o}$$

Termination Reaction

$$RO_2^{o} + RO_2^{o} \longrightarrow ROH + RCOR' + O_2$$

Non - solute parts are trace metals of copper, silver, iron, CO_2, CH_4, C_2H_4, CO, H_2 etc, and the last suspended products are carbon sludge.

Freecarbon Preserving Reaction

$$C_2H_6 \text{ (Ethane)} \longrightarrow CH_4 + \underline{C} + H_2$$

$$C_3H_6 \text{ (Cyclo - propane)} \longrightarrow C_2H_4 + \underline{C} + H_2$$

From this analysis it is evident that the carbon sludge [7] [8] take into the increase of power factor, acid component and other ionizable species in insulating oil.

SELECTION OF THE SENSOR MATERIALS

Basic design

It is suggested that after non - solute particles are adsorbed in a sensor, the leakage current across the sensor can be detected by meter. Fig.1 shows that the leakage current between two electrodes is measured at a constant voltage.

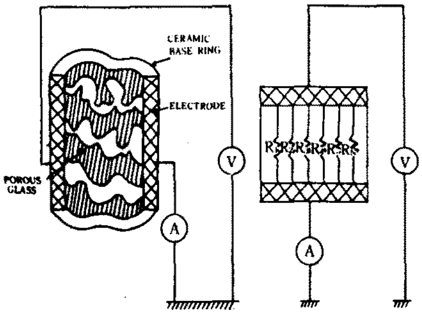


Fig.1. Equivalent circuit of sensor

The functions of sensor materials are as follows

. Porous glass (adsorbing plate): Adsorbing the conductive particles.
. Base ring : Supporting the adsorbing plate and electrodes.
. Electrodes (bipolar type) : Checking the leakage current

Therefore, it has been proposed that the degradation of oil can be defined by the current in a sensor. In order to select the best adsorbing material, it is considered two types of material, i.e. molecular sieve type material and a porous glass for adsorbing plate. On this basis the theoretical formula[9] of the particles' conductivity can be expressed with ideal model and conductance g. Fig. 2 represents the apparent conductance(σ_1) of nonsolute particles in degradation oil.

$$\sigma_1 = \frac{\gamma_c'/\gamma}{1+(2\sigma_s \cdot \rho_b/\pi \cdot \gamma_c'}\sigma_s + \frac{\pi/2\gamma}{\ln(2\gamma/\gamma_c')}\sigma_f \quad \text{---(1)}$$

γ : particle's radius (cm)
γ_c' : Effective contact radius ($\gamma_c + \Delta\gamma_c$)
(In the case of capillary condensation γ_c' equals γ_c, but in high humidity γ_c' equals $\gamma_c + \Delta\gamma_c$)
σ_s : particle's substance conductivity (℧/cm)
σ_f : particle's film conductivity (℧)
ρ_b: boundary unit resistance per square (Ω - cm^2)
ln : natural logarithm
π : 3.14

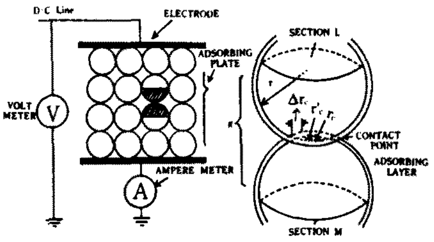


Fig. 2. Ideal model and conductance g.

In Eq [1], the parameters γ, γ_c', σ_s, σ_f, ρ_b are variable to the materials of sensors and the adsorbed nonsolute particles. But in the case of porous glass which is irregular, it is possible to apply the equation by regarding the shape factor.

Design of sensor

It is proposed that the change rate of acid value and dielectric strength in insulating oil equals that of leakage current in a void volume of the sensor.
Therefore assuming the sensor's leakage current as follows, following equations can be suggested.

$$\frac{d(\mu A)}{dt}\ (\text{sensor}) = \frac{d(A.V)}{dt}\ (\text{insulating oil}) \quad \text{---------(2)}$$

$$\frac{d(\mu A)}{dt}\ (\text{sensor}) = \frac{-d(D.S)}{dt}\ (\text{insulating oil}) \quad \text{---------(3)}$$

A.V : Acid value in oil
D.S : Dielectric strength in oil
μA : Sensor's leakage current

The sensor's adsorbing capacity (sensor volume) can be estimated in Eq. (2) and Eq. (3)
The base ring is composed ceramic materials, Al_2O_3 , which butts against the adsorbing layler and 2 electrodes. The physical properties of base ring which distinguish the excellent physico - chemical properties and stability for the insulating oil are represented as follows.

. Alumina (Al_2O_3) content : 96%
. Colour : white
. Specific gravity : 3.72
. Bending strength : 2600 ~ 3500 Kg/cm^2
. Safety temp (continuous) : 1600℃
. Thermal conductivity : 0.05 cal / cm, sec, ℃
. Volume resistivity : 10^{14} $\Omega \cdot cm$
. Dielectric strength : 13 KV / mm
. Dielectric constant (1 MHZ 25℃): 9.6

In order to measure the amount of conductive species in oil, it is used 3 different adsorbing laylers, molecular sieve sphere type (MSS - 4AFT - 1), molecular sieve pellet type (MSP - 4A) and porous glass type (PG - 120).
Base ring can be applied to all of the adsorbing plates and the electrodes are made of stainless wire mesh type #20, connecting to base ring with inorganic adhesive materials, aron ceramic, at 150°C in electricity furnace.

Adsorbing plate of molecular sieve type sensor

The properties of molecular sieve materials represent in Table 1. The size of the molecular sieve sphere type is 2 mm in radius and pellet type is 3 mm in length and pore size is commonly 4Å. All of this substances are packed in the base ring for measuring the degradation oil.

Table 1 : Properties of molecular sieve type

Materials		Type	Pore size	Chemical composition
Molecular sieve	Ball and Pellet type	3A	3[Å]	$K_9Na_3[(AlO_2)_{12}(SiO_2)_{12}]XH_2O$
		4A	4[Å]	$Na_{12}[(AlO_2)_{12}(SiO_2)_{12}]27H_2O$
		5A	5[Å]	$Ca_{4.5}Na_3[(AlO_2)_{12}(SiO_2)_{12}]30H_2O$
		13X	13[Å]	$Na_{86}[(AlO_2)_{86}(SiO_2)_{106}]276H_2O$

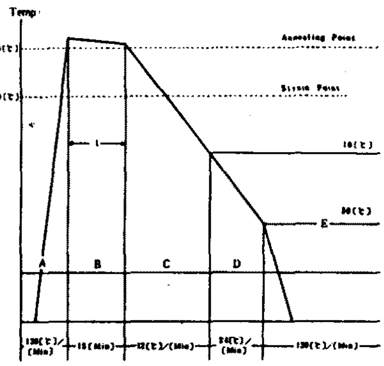
Adsorbing plate of porous glass type sensor

The chemical composition of porous glass layer is analyzed in Table 2.

Table 2 : Chemical composition of porous glass

Chemical Composition	SiO_2	B_2O_3	Na_2O	K_2O	Al_2O_3	Fe_2O_3	CaO	MgO
%	80.6	12.6	4.2	0.1	2.2	0.04	0.21	0.05

The porous glass plate (PG - 120) is solidified by the optimum annealing schedule. [10] Fig. 3 shows the annealing process of the porous glass layler. Borosilicate glass which was used for the adsorbing plate is classified as a simple glass the minimum constituents of which are silica, boron, alkalies and alumina. It is virtually free from heavy metals. High quality sand, dehydrated borate boric acid, alumina and salt are used in its manufacture and strick control is applied to ensure the stringent specifications for purity and consistency of these materials are maintained. Because of its resistance to heat, corrosion and thermal shock borosilicate glass is used extensively in this study.
So it is confirmed that the electrical values of the sensor are taken place only by conductive particles.
The annealing of glass is the process by which it is heated to and held at a stresses. Careful cooling under controlled temperature for a defined period to relieve internal controlled conditions is essential to ensure that no stresses are reintroduced by chilling.



A : Heating to 5 [°C] above annealing (heating rate ; 130 °C/min)
B : Holding temperature for time t (15 min)
C : Initial cooling to X below strain point (X ; 10°C)
D : Cooling next 50 [°C] (cooling rate ;12 °C/min)
E : Final cooling (cooling rate ; 130°C / min)

Fig. 3. Annealing process

The sectional morphology of the completed layler is taken by SEM (JEOL Model JSM - 35 CF).
Fig. 4 shows the section of porous glass, 120 μm, taken by 100 times before the test. Fig. 5 shows the porous glass taken by 54 times after the test.

The physical properties of porous glass is represented as follows. It is shown that volume resistivity is 10^{15} Ω-cm at 20° C of which value is higher than base ring.

. Specific heat : 750 [J / Kg°C] at 20°C
. Thermal conductivity : 1.13 [W / m° K] at 20°C
. Density : 2.23 x 10^3 [Kg / m^3]

Fig. 4. Section of porous glass by SEM before test (120 μm x 100)

Fig. 5. Section of porous glass by SEM after test (120 μm x 54)

. Knoop hardness : 550 [Kg / mm^2] with 500 gram load
. Dielectric constant : 4.6 at 1 MHZ, 20°C
. Volume resistivity : 10^{15} [Ω- cm] at 20°C
. Surface resistivity : 10^{13} [Ω - cm] at 50% humidity

Fig. 6 shows the outside view of sensors. Each sensor contains base ring, adsorbing layler and electrodes.

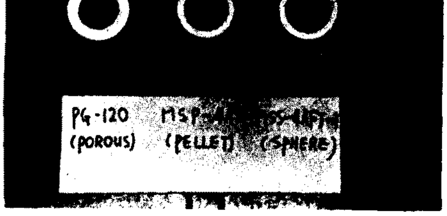


Fig. 6. Outside view of sensors

Sensors' tentative dimensions are as follows

. Diameter : 55 mm
. Thickness : 7 mm
. Electrodes : Mesh type (# 20), binary poles
. Pore size :
  - Molecular sieve type : 4 Å
  - Porous glass type : 120 μm

TEST PROCEDURE

Experimental facilities

Fig. 7 shows the experimental layout. Facilities located inside are the aging tank, load controller and resister box, and a test transformer with sensors is installed at outside fields. Aging tank is equipped with heater (AC 200 V, 22A) and the aging oil is allowed to flow from a main storage tank to the system and back again. An loop system with a housing, a tank and a pump, is placed in series.
The setting temperature of the oil is 70 ℃ and the test oil was used aged oil (about 4years) to save time and know early the phenomenon, which is meaned to check the acid value, breakdown voltage and sensor's leakage current in transformer oil at the same time.

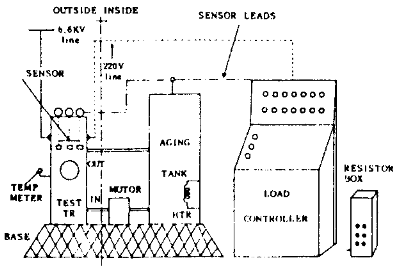


Fig. 7. Experimental facilities.

Aging process

The aging periodic process is performed by the short time overload schedule. Fig. 8 shows the overload cycle considering ANSI C57. 91. This load is supplied by the secondary terminal in the transformer.

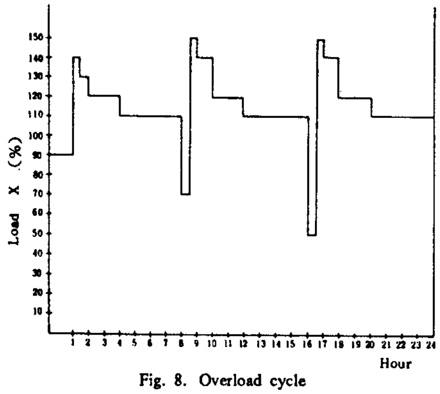


Fig. 8. Overload cycle

Measuring apparatus

- GPC (Gel Permeation Chromatography)

A WATERS associates model 510 liquid chromatography is used for detecting molecular weights in transformer oil. The GPC columns are consisted of μ- bondagel E-500/ μ - styragel 100 Å and μ- porasil 60 Å setting in 32°C. GPC analysises of various products, ranged from new oil to degraded oil, have been shown in this present study.

- PSA (Particle Size Analyzer)

Automatic particle counting is performed with a HIAC particle size analyzer model 4100. The counter is equipped 6 channels, but in this study pre-selected to 5 channels; 5 ~ 15 μm, 15 ~ 25 μm, 25 ~ 50 μm, 50 ~ 100 μm, 100 ~ 150 μm, for detecting spherical and non-spherical particles.

- Sensor's leakage current

A DC high voltage tester is used. In this study DC 2KV was supplied to the sensors to check the current. This meter is ranged 0 ~ 25 KV voltage and 10μA / 100 μA / 1mA / 10mA.

- Dielectric strength

A 50 KV oil tester consisting of electrodes with 2.5 mm gap is used. The voltage rate of rise is 3000 [volt] per second. The test was conducted in accordance with KSC 2101.

- Acid value

An automatic titrator (Mettler DL 40 GP MEMO titrator) was used. The test is carried out according to ASTM D664.

TEST RESULTS

Measurement value

The characteristics obtained from each sample are shown in Fig. 9. It is clear that the porous type sensor (PG-120) has a good sensing property nearly closest to the dielectric strength and acid value. The transformer is breakdowned on 175 aging days.
As result it indicates that the transformer oil is throughly aged until the condition of dielectric breakdown voltage ; 22.6 KV, acid value ; 0.895 mg-KOH/g sensor's current; 5.1 μA, which means that impurity particles in oil decrease the dielectric strength and

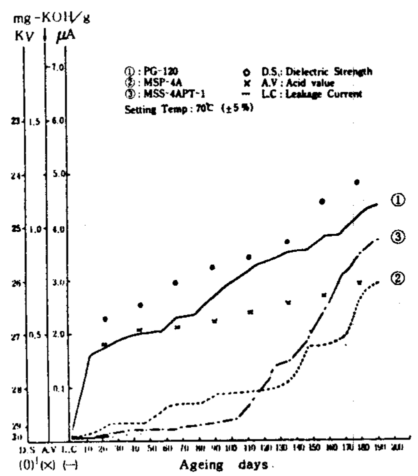


Fig. 9. Characteristics of dielectric strength, acid value and sensor's current.

increase the acid value. The breakdown value is strongly dependent on the particle size and its numbers. With conducting metal or partially conducting particles (carbon and sludge) is significantly greater for sensor's current than the acid value. In Fig. 9 the variation rate of PG 120 sensor's current is closely related to the acid value, but after 50 degradation days more related to the breakdown voltage in oil. According to the effect, following equations are suggested.

In 50 degradation ;

$$\frac{d(\mu A)}{dt}\text{(sensor)} \approx \frac{d(A.V)}{dt}\text{(insulating oil)} \quad \text{———— (4)}$$

after 50 degradation ;

$$\frac{d(\mu A)}{dt}\text{(sensor)} \approx \frac{-d(D.S)}{dt}\text{(insulating oil)} \quad \text{———— (5)}$$

By considering the information about particle numbers in Table 3 and mol weights in Table 4 in reference to the breakdown voltage and PG - 120 sensor's current, the acid value, it is possible to recognize the relationship which influence the degradation in oil.

Table 3. Comparison of characteristics in insulating oil (I)

Degraded days	Impurity particles [EA]	Leakage current in PG - 120 [μA]	Dielectric strength [KV]	Acid value [mg - KOH/g]
36	17,689	2.2	26.1	0.571
50	18,833	2.3	25.6	0.598
96	24,680	3.5	25.1	0.675

Table 4 Comparison of characteristics in insulating oil (II)

Degraded days	Molecular weights	Leakage current in PG - 120 [μA]	Dielectric strength [KV]	Acid value [mg - KOH/g]
60	867	2.6	25.6	0.598
140	875	4.35	23.9	0.748
170	884	5.1	22.9	0.895

From this data it is ensured that the sensor current is valuable to compare with acid value and breakdown voltage. From this detailed examination of the current (5.1 μA) in the PG - 120 sensor, the attention level of the insulating oil can be proposed. Fig. 10 shows the examples of recording paper, which are known the sensor's current and degradation level of transformer oil.

As shown the values are very stable and normal, which means that the sensor has good stability and good reproducibility for the adsorbed conductive impurities.

Table 5. Degradation changes at normal temperature

	Bofore test			After test		
	Acid value [mg-KOH/g]	Dielectric strength [KV]	Leakage current [μA]	Acid value [mg-KOH/g]	Dielectric strength [KV]	Leakage current [μA]
new oil	0.05	29	0.25	0.06	28.5	0.75
aged oil	0.65	26.5	1.75	0.76	25.3	2.51

Sensor's current at normal temperature

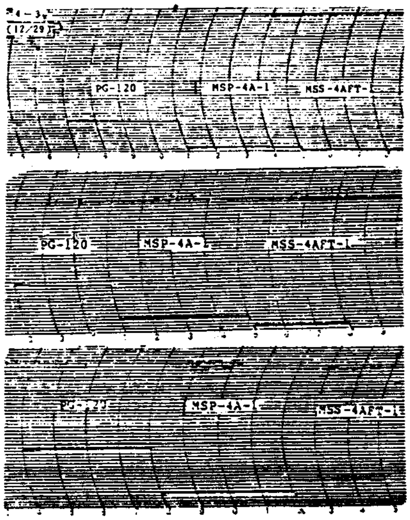


Fig. 10. Example of sensor current in recording paper

The visual observation in Fig. 11 is as instructive as Fig. 9. The sensor's current at normal temperature is about the same as for a clean oil and an aged oil. According to the plots of Fig. 11 the current of aged oil is more variable than the new oil, which is suggested to be caused by auto - oxidation in oil. Table 5 shows results of variation in degraded oil, which shows the acid value, dielectric strength and sensor's current.

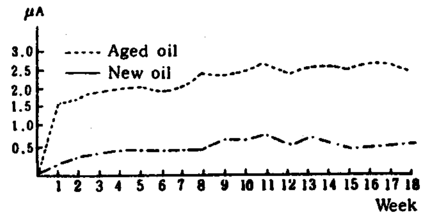


Fig. 11. Sensor current's curve at normal temperature

Temperature effect

In order to understand further knowledge of the temperature effect of the PG - 120, sensor currents are measured at variable temperatures, 20°C, 40°C, 75°C, and 95°C at the aging tank, which is caused that the impurity particles move more actively according to the increased temperature. Fig 12 shows the variations of the sensor's current at the temperatures.

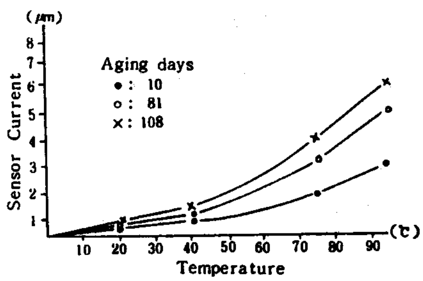


Fig. 12. Sensor current curve at variable temperature

From the relationship between sensitive effect of the sensor and temperature, the reproducible data can be obtained by compensating meter. It can be suggested following idea to compensate the meter. Fig. 13 shows the compensating circuit. It knows that current sources are consisted of high voltage source and sensor's leakage current, at that time the temperature of insulating oil being checked. All values are inputed to the micro-processor after amplifing and converting.

Progress has been made in characterizing the sensor's current and the temperature of transformer oil in micro-processor, which comparing this standard level with the pratical current in field.
The parameter memorizing in micro-processor can be defined as the characterization of the sensor. However, the processor may be responsible for the apparently contradictory test data that have obtained in same cases.

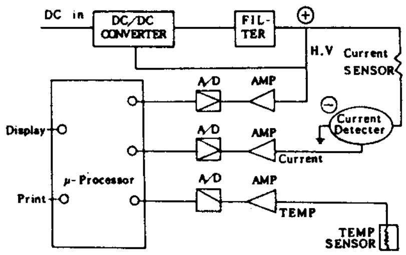


Fig. 13. Compensating circuit

CONCLUSIONS

Results from measuring the degradation insulating oil in transformer by using ceramic sensors are reported in this paper. Insulating oil containing hydrocarbons is resolved into various products by temperature, auto-catalysis of metal and contaminated by impurity elements. . From detailed examination of the conductive species in the transformer oil to the breakdown voltage, the newly developed ceramic sensor in this study is useful to measure the degradation of the insulating oil. Important conclusions are given below.

(1) As GPC (Gel Permeation Chromatography) and PSA (Particle Size Analyzer) tests are performed, so it is shown that impurity particles are distributed almost 50～100 [μm] size.

(2) Simulation tests were performed by a transformer with three kinds of sensors developed in this paper (ball and pellet type in molecular sieve, porous glass type). The sensor's currents were measured simultaneously with acid value and breakdown voltage of the oil.

(3) The current of the porous glass sensor (PG-120) is closely related to the acid value and breakdown voltage of the oil.

(4) PG-120 sensor has the excellent physico-chemical properties for example nonreacting against the oil, stability of adsorbed conductive impurities etc, therefore, the experimental data have good reproducibility.

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