Behavior of Paper oil insulation of transformers under copper corrosion

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Abstract: The problem of corrosion of copper conductors of transformers due to sulphur in oil is a serious issue concerning transformer design, quality of oil, and service conditions. Studies have been mainly focussed on the quality of transformer oil and efforts were made to mitigate the problem of copper corrosion due to sulphur. In this investigation, laboratory model studies have been carried out for better understanding of the mechanism of copper corrosion. A simple model is proposed to explain the mechanism of migration of copper sulphide on the basis of capacitance and resistive equivalent circuits. The results of capacitance and insulation resistance have been configured in the proposed model to explain how the process of migration can take place in a complex paper oil insulation of transformers.

1.0 INTRODUCTION

Sulphur in oil poses severe threat to the performance of transformers. Sulphur in oil reacts with copper conductor to form semi-conducting copper sulphide which migrates and settles in the windings of transformer's [1, 2]. The voltage distribution is altered in presence of copper sulphide and electrical stress across clean paper and oil starts gradually increasing. Temperature is the driving force for copper corrosion to occur and initially it leads to micro-discharges which over a period of time increases both in terms of number of discharges and magnitude of discharge [3, 6]. These discharges go unnoticed in a huge transformer because of their very low magnitudes and the conventional dielectric tests do not give any early warning signals about the occurrence of copper corrosion. However, in the laboratory models it is possible to understand the characteristics of PD occurring under sulphur corrosion. It is also possible to monitor subtle changes in dielectric parameters like capacitance and Insulation resistance in a small model windings of a transformer. However, it is extremely difficult to detect or monitor changes in a huge transformer system because of limitations of sensitivity of the measuring equipment's and imperceptible changes that take place in dielectric parameters**.**

In this paper the details of laboratory evaluation carried out to understand the mechanism of sulphur corrosion of copper and its influence on both dielectric and chemical properties are presented and discussed.

In addition to laboratory evaluation, a simple model to explain the mechanism of copper sulphide migration based on the measurements of capacitance and insulation resistance are proposed and its consequences are presented and discussed in this paper.

1.1 EXPERIMENTAL METHOD

The experiments are carried out in a standard laboratory, under ideal conditions of temperature: 25± 2 °C, humidity: 55±5 %, clean environment and very low ambient noise levels. Standard calibration and equipment maintenance practices were adopted and the calibration had traceability to International standards.

The samples used were either paper of 50 µm thickness which was impregnated with transformer oil or the conventional pigtail samples representing a portion of winding of transformer as shown in figure 1. The paper covered copper conductor used in power transformers was employed for preparing the specimens. The thickness of paper was 50 µm and there were five layers of paper on each conductor.

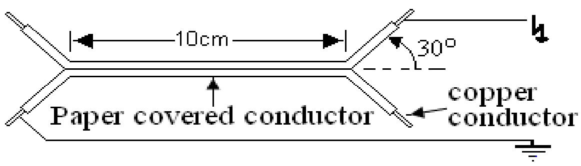

Figure 1: Specimen configuration for laboratory ageing studies

The samples were aged in specially designed bottles at temperature of 100° C to 120 ° C for long duration, till failure occurred or till the oil lost its colour and turned very dark.

For studies on simulation of the mechanism of copper corrosion due to sulphur in oil different specimen configurations were used. These are:

<u>Specimen 1</u>**:** Pigtail sample aged in transformer oil confirming to IEC.
<u>Specimen 2:</u> Pigtail sample aged in transformer oil containing 10 ppm of mercaptan sulphur by weight.

Specimen 3: Pigtail sample aged in transformer oil containing 20 ppm of mercaptan sulphur by weight.
Specimen 4: Pigtail sample aged in oil containing 30 ppm of mercaptan sulphur by weight.
Specimen 5: Pigtail sample aged in oil containing 40 ppm of mercaptan sulphur by weight

The dielectric parameters like capacitance, volume resistivity, insulation resistance, electric strength were carried out as per relevant ASTM methods.

The PD measurements are carried out using advanced precision PD measuring system of M/s Omicron Instruments, using the experimental set up shown in Figure 2. The PD measuring unit consists of Acquisition Unit MPD540, a fiber optic controller USB502 and a computer. The Acquisition Unit MPD540 through the coupling capacitor Cc senses the discharges from the test specimen and the fiber optic controller USB502 is used to interface the Acquisition Unit to the computer

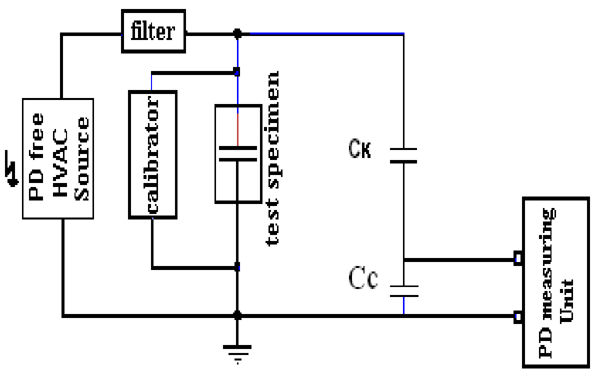

Figure 2: Partial discharge measuring circuit

The PD Software had the following features:

a) Statistics:
The software is based on IEC 60270. Details of Apparent charge (q or Q_{IEC}), Peak discharge (Q_{Peak}), Average discharge (Q_{Avg}), Pulse repetition rate (n), Average discharge current (I or I_{Dis}), Discharge power (P or P_{Dis}), Quadratic rate D are displayed on the window. The software gives flexibility to define the time interval (T_{ref}) of measurements and the minimum and maximum of PD magnitudes to be considered for computation of PD statistical parameters.

b) 2D histogram:
This gives the variation of PD magnitude with phase.

c) 3D histogram:
This is a three dimensional representation. Itt gives information about PD events/s, magnitude and phase and their correlation.

Mercaptan sulphur by potentiometric titration

Mercaptans sulphur is one form of sulphur which is very reactive. Although it is very less in quantity in case of fresh oils, it is consumed during high temperature and its value goes down from 1ppm to almost zero level when thermal ageing is carried out. The corrosive oils have shown random variation in Mercaptans sulphur content. The deleterious effect of Mercaptans sulphur is clearly exhibited by the presence of "2-Mercapto Benzo Thiozole" in transformer oil.

1.2 Results and Discussions

The important parameter which can give maximum information about copper corrosion and its intensity is the partial discharge parameters. However, the magnitude of these discharges is very small and imperceptible under service conditions and the ambient conditions which prevail limit the measurement of small PDs. Since this was a laboratory model, it was possible to measure PD's of very low magnitude.

1.2.1 Measurement of Partial Discharges

The 3-dimensional histogram of PD of clean paper oil insulation and insulation with different levels of penetration of copper sulphide into paper layers and contamination of oil have clearly demonstrated that PD activity is different under these conditions. For all PD measurements, only pigtail samples have been used.

In figure 3, the three dimensional histogram of PD for clean paper oil insulation is shown at a preset voltage of 1.5 kV. There are very few discharges and the magnitudes are also very small. The X-axis is phase, y axis gives the number of PD's/sec (n) and other shows the magnitude and polarity of recorded PD's.

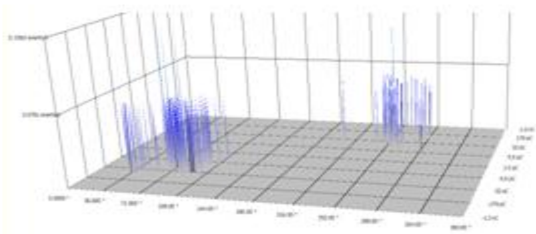

Figure 3: 3-D histogram of PD of clean paper-oil insulation

Figure 4 shows the PD activity when one layer of paper is contaminated and in this case an increase in magnitude of PD and number of PD's per second is observed. This also clearly indicates that progressive formation and migration of copper sulphide can be observed by constant monitoring of partial discharge activity. However, in addition to "n", the distribution of PD's over the phase also provides vital information about the activity in presence of copper sulphide.

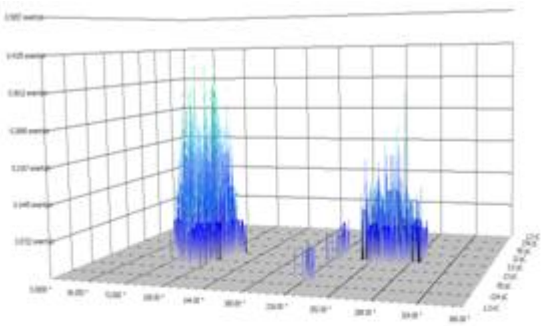

Figure 4: 3D histogram of PD of paper-oil insulation with 1 layer of contamination

The PD activity is also characteristic of the condition of oil used. Figure 5 gives typical case of clean winding in highly contaminated oil which was removed from a failed transformer.

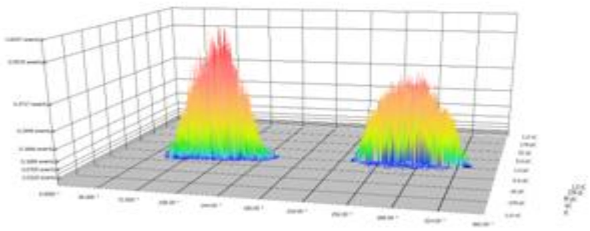

Figure 5 3-D histogram of PD of clean pigtail sample in contaminated transformer oil of failed power transformer

Hence PD activity is very important parameter and a careful monitoring of the PD statistical parameters will be very beneficial in understanding of the process of migration of copper sulphide into different layers of paper.

1.2.2 Modelling of copper corrosion in paper-oil insulation by simulation

The influence of corrosive sulphur on the dielectric parameters of paper-oil insulation was studied through thermal and electrical ageing of a set of pigtail samples. The pigtail samples are aged at a temperature of 120°C and are simultaneously subjected to 1200 Vac. The capacitance (C) and insulation resistance (R) were measured. Mercaptan sulphur was intentionally added to see its influence in the dielectric parameters.

The measured values of capacitance (C) and Insulation resistance (R) are shown in Table 1. In the beginning of thermal and electrical ageing, the value of C decreases and resistance increases. With continuation of ageing, C starts increasing and IR values show decreasing trend. The data of percentage variation of capacitance and resistance with thermal and electrical ageing are shown in the Table 2 and Table 3.

Table 1 Variation of Capacitance and Insulation resistance of specimen with ageing

Day	Specimen 1		Specimen 2		Specimen 3	
	C (pf)	R (TΩ)	C (pf)	R (TΩ)	C (pf)	R (TΩ)
01	22.05	22.46	22.35	20.68	22.71	20.36
07	21.32	22.86	21.85	21.10	22.21	21.06
14	21.33	22.82	21.84	20.83	22.30	20.26
22	21.58	22.70	22.12	20.26	22.78	21.90
30	21.78	22.56	22.53	19.16	23.56	17.78
45	22.54	22.40	24.18	16.36	25.81	13.75
60	23.64	21.60	27.46	14.90	28.54	12.94
90	24.13	20.60	29.00	13.04	30.80	12.08

Day	Specimen 4		Specimen 5	
	C (pf)	R (TΩ)	C (pf)	R (TΩ)
01	24.45	21.16	21.26	22.72
07	23.82	21.68	21.02	23.02
14	24.36	21.13	21.13	21.37
22	25.00	19.76	22	18.41
30	25.57	16.14	22.87	15.09
45	29.92	12.86	27.31	14.30
60	33.14	12.62	28.63	13.54
90	33.94	11.76	30.67	12.57

From the table it is observed that capacitance increases with ageing by about 20% in case of specimen 1 in which pure transformer oil was used. On other hand resistance value remains unaffected and the pigtail specimen has a constant R value of 22 TΩ. With addition of mercaptan there is a 30-45% increase in capacitance and resistance starts decreasing.

It is very clear that there is a 30-45% increase in capacitance which can be measured with a deal of accuracy. Though in laboratory it is possible to measure Insulation resistance accurately, it is difficult to correlate variations in R to the presence of mercaptan in oil and to understand its interaction with copper to form sulphurous by-products because of difficulties in measuring the R values at any given instant of time since IR can be influenced by other conditions. Compared to “R”, measurement of C is much easier because of its consistency.

The C and R of specimen 4 before commencement of ageing and after completion of 180 days of ageing were measured for different combination of paper-oil insulation by the process of layer-wise unwrapping of paper. The data is shown in the Table 2 The layer-wise values of C and IR are computed from these measurements and are shown in the Table 3

Table 2. Capacitance(C) and resistance (R) of specimen 4 with various paper layers

Layers	Un-aged		Aged specimen	
	C(pF)	R(GΩ)	C(pF)	R(GΩ)
01	290.24	2000	412.35	453
02	139.93	4150	202.26	941
03	90.03	6100	123.15	1499
04	64.36	8290	83.21	2499
05	48.93	10580	61.42	3500

Table 3. Computed values of C and R per layer of paper from Table 2

Layer-wise	Un-aged		Aged specimen	
	C(pF)	R(GΩ)	C(pF)	R(GΩ)
01	290.24	2000	652.35	453
02	270.21	2150	605.35	488
03	252.43	1950	530.23	558
04	225.73	2190	348.36	1000
05	203.52	2290	348.31	1001

Proposed Model

Each partly contaminated paper-oil insulation layer is represented by parallel combination of contaminated section and uncontaminated section. Accordingly they are represented by respective resistances in resistive equivalent circuit and capacitances in capacitive form as shown in Fig.5. This model is simplified and is applicable when copper corrosion is initiated and the values of C and R are predominantly controlled by copper sulphide. It is assumed that the conventional complex model simplifies to the present form only under copper corrosion and not otherwise. With this assumption the present simple model is proposed.

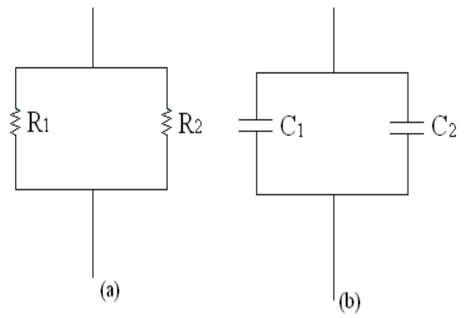

Fig.5 Equivalent circuit representation of copper sulphide partly contaminated single layer paper –oil insulation in

(a) Resistive form (b) Capacitive form.

Suffix:

1=copper sulphide contaminated single layer of paper

2= remaining clean paper insulation of single layer.

The equivalent circuit components and respective ratios of area to thickness of capacitance formed due to each paper-oil insulation layer (a/t) were evaluated by iterative methods using a computer program. Flow charts of the programs are shown in Fig.6 and Fig.7.

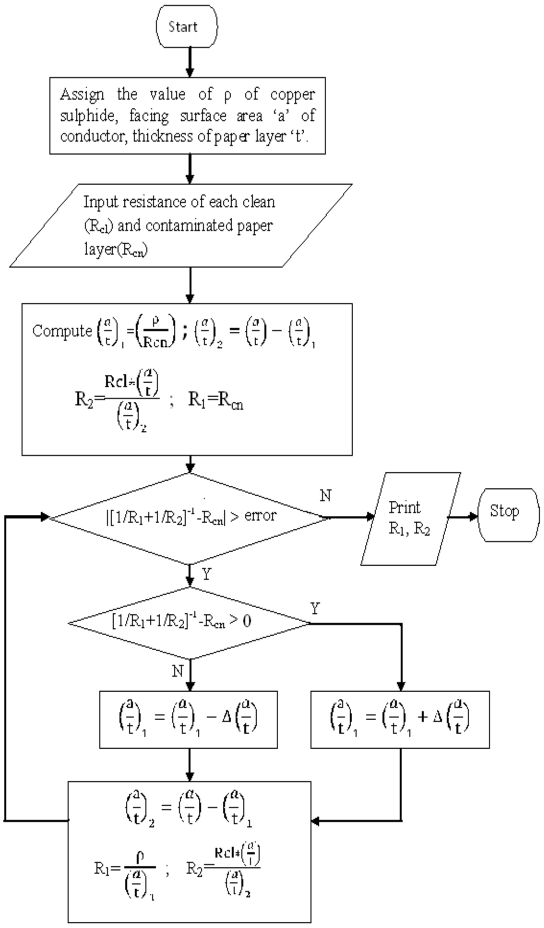

Figure 5: Flow chart for the evaluation of components of resistive model

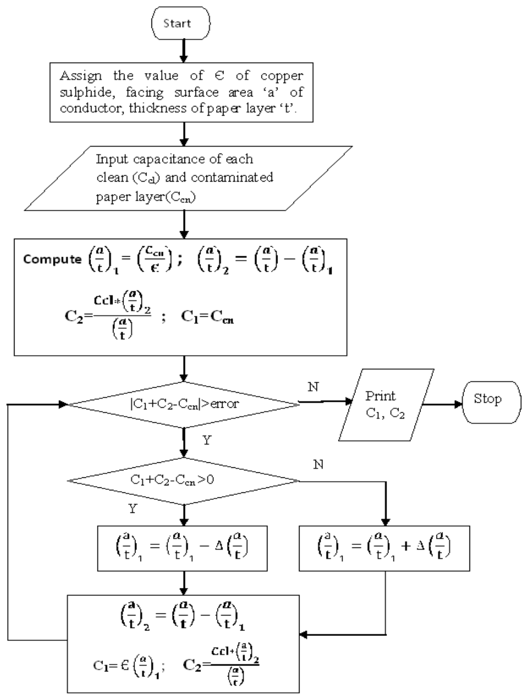

Figure.6: Flow chart for the evaluation of components of capacitive model

In this study the variation of the parameter a/t, where “a” is the area of the capacitor and “t” is the thickness of copper-sulphide affected or is clean paper sample as the case may be. This ratio for capacitance of clean paper and copper sulphide affected paper and similarly for resistance are computed based on the experimental data and the same is shown in table 4 and table 5 for capacitance and resistance models.

Table 4: Computed values of capacitance each layer of contaminated paper-oil insulation.

Layer wise	Capacitance				
	C_{12} (pF)	C_1 (pF)	C_2 (pF)	$(a/t)_1$ (mm)	$(a/t)_2$ (mm)
1	652.35	393.64	258.7	1778	14585
2	605.35	362.13	243.22	1636	14727.6
3	530.23	298.6	231.62	1349	15014.6
4	348.23	130.64	217.59	590.2	15773.4
5	328.31	132	196.3	596.4	15767.2

C_{12}=Total capacitance of the contaminated paper-oil insulation layer. This is the parallel combination of C_1 and C_2.
(a/t)=Ratio of surface area of copper conductor to thickness of paper-oil insulation layer of respective form

Table 5: Computed values of resistance of each layer of contaminated paper-oil insulation

Layer wise	Resistance				
	R_{12} (GΩ)	R_1 (GΩ)	R_2 (GΩ)	$(a/t)_1$ (mm)	$(a/t)_2$ (mm)
1	453	586	2241	1761	14603
2	488	613	2388	1630	14733.6
3	558	757	2121	1320.4	15043.2
4	1000	1789	2267	558.83	15804.8
5	1000	1728	2374	578.8	15785

The decreasing values of (a/t) from layer number 1, the layer next to the hv electrode to layer number 5 indicates that copper sulphide is migrating from the hv electrode. This has demonstrated that migration takes place from the HV electrode side towards inner layers. This result is also true in case of resistance model. The ratios (a/t) of respective components in resistive form and capacitive form show close agreement.

The important implication of this study is that the source of copper sulphide is copper conductor and it is necessary to stop its formation by protecting the conductor by enamel coating or by adding metal passivator to oil.

In-service transformer oil data on mercaptan sulphur

Extensive field data was collected on the quality of transformer oil. For historical reasons, more than 30 year old power transformers were included for analysis of oil. It is interesting to observe that the mercaptan sulphur value was less than the permissible 1ppm level in majority of the transformers, irrespective of the transformer rating, its service conditions and design. The results of some of the transformers are shown in table 6 with the details of installation and Power rating and figure 7 shows the distribution of the values for 50 cases.

Table 6: Mercaptan sulphur values of oil drawn from different transformers with their year of commissioning

Sl. No	Year	Power rating	Mercaptan sulphur(mg/kg)
1	1964	67.5 MVA	0.08
2	1964	67.5MVA	0.09
3	1965	500kVA	1.16
4	1965	500kVA	1.02
5	1966	50MVA	0.08
6	1971	400kVA	0.05
7	1978	50MVA	0.09
8	1978	50MVA	0.09
9	1982	13.55 MVA	0.08
10	1984	150MVA	0.05
11	1984	150MVA	0.06
12	1988	1000kVA	0.07
13	1988	63 MVA	0.09
14	1993	16MVA	0.16
15	1993	16MVA	0.27
16	1993	16 MVA	0.26
17	1994	20MVA	0.06
18	1995	20MVA	0.15
19	1997	20MVA	0.14
20	1997	2.5MVA	0.19
21	1997	16 MVA	0.61
22	1998	1000kVA	0.08
23	1998	16MVA	0.1
24	1998	16MVA	0.1
25	1998	70 MVA	0.08
26	1998	12.5 MVA	0.08
27	1998	20MVA	0.13
28	1999	16MVA	0.11
29	2000	80 MVA	0.11
30	2004	31500	0.09
31	2005	1500KVA	0.05
32	2006	25MVA	0.05
33	2006	4000kVA	0.61

34	2007	31.5MVA	0.05
35	2008	30.7MVA	0.08
36	2008	30.7MVA	0.08
37	2008	30.7MVA	0.08
38	2009	30.7MVA	0.08
39	2009	30.7MVA	0.08
40	2009	30.7MVA	0.06
41	2010	80000KVA	0.42
42	2010	80000KVA	0.43
43	2010	20/25 MVA	0.05
44	2010	20/25 MVA	0.05
45	2011	200MVA	0.09
46	2011	200MVA	0.06

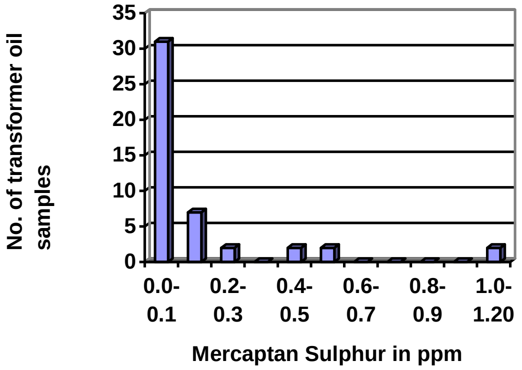

Figure 7: Measured mercaptan sulphur values in a sample survey of 50 power transformers

CONCLUSIONS

The following are some of the important conclusions of the study:

Partial discharge statistical parameters can be closely monitored and the point of onset of PDs of significant magnitude and increase in number of discharge events/sec gives indication of possible formation/migration of copper sulphide.

Results of PD under different depths of penetration of copper sulphide and copper sulphide in oil have shown some uniqueness in PD statistical parameters which are to be further exploited for development of improved transformer diagnostics.

The proposed simulation model based on experimental data has shown that migration of copper sulphide is from conductor to paper layers. The probability of migration from oil to paper was not observed in the ageing studies carried out.

Both Resistive and capacitive models clearly establish that the copper sulphide displacement is from the site of formation towards paper layers close to it. The a/t values in both the cases show good agreement.

Measurement of mercaptan sulphur of more than 100 transformers in service has shown that the values are much below the stipulated value of 1 ppm.

The field data based on chemical analysis did not show any alarming results and most of these transformers were of conventional design and were working under normal service conditions.

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