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Impact of additive DBDS on Leakage Current and DC Resistance of Paper-Oil Insulation in Power Transformers

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***Abstract*—2-6-Di-tertiary-Butyl-Para-Cresol generally called DBPC and Dibenzyl Disulfide called DBDS are oxidation inhibitors used in transformer oil by the manufacturers. The transformer accidents caused by corrosive sulphur have occurred repeatedly, and caused great loss to the power grid. The source of corrosive sulphur is the transformer oil. It is formed by the reaction of both DBDS and DBPC, resulting in copper-sulfide deposition on the insulation paper. It degrades the insulation strength of paper and leads to reduced dc resistance and increased leakage current. The increase in the concentration of DBDS and DBPC increases the formation of copper sulfide leading to insulation failure. In present work, the effect of DBDS and DBPC on leakage currents and dc resistance and hence on dielectric characteristics have been studied.**

***Index Terms*— Transformer oil, Copper sulfide, DBDS, DBPC, Leakage current and dc resistance.**

I. INTRODUCTION

Over the past decade there has been increased interest in the effects of corrosive sulfur in mineral insulating oils, which has been determined to be the main culprit for the recent failures recorded in power transformers. A number of failures of transformers and reactors have occurred due to the resultant formation of copper sulfide (Cu_2S) in the windings. The deposits vary within the windings and usually there are more deposits on the upper part of the windings. Copper sulfide covered on the metal surface leads to overheating, arcing and then leads to failure of power transformers [7-9].There can be tens to hundreds of different sulfur compounds present in the oil. Of these, only small fractions are corrosive or are compounds that can degrade from stable species into ones that are reactive. This is usually based on time and temperature [10, 11, 13, 15]. Dibenzyl disulfide (DBDS) has been found to be the most corrosive sulphur compound in the insulating oil. DBDS easily breakdowns to the corresponding mercaptans (thiols) and other single-ring products which are highly reactive to copper and attacks the copper forming copper sulfide films. Benzyl mercaptan, a

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degrading compound of DBDS is the most reactive and corrosive. The chemical reaction of DBDS with copper is as follows:

$$4Cu + (C_6H_5CH_2)_2S_2 \rightarrow 2Cu_2S + C_6H_5CH_2CH_2C_6H_5$$

Experimental work has been carried out to investigate the role of DBDS in decreasing the DC Resistance of transformer oil insulation when different voltages are applied for various durations. Fig.1 below shows the chemical structure of DBDS. Its chemical formula is $C_{14}H_{14}S_2$.

II. Experimental Setup

The method involves an experimental setup having transformer tank in which two electrodes are placed horizontally having a gap of 2 mm between them. An Experimental setup is as shown in the Fig.1. An electrical grade paper is placed between these electrodes which are immersed in transformer oil. Three different cases are taken into consideration. Firstly the electrodes are immersed in clean oil and then clean oil with DBDS and lastly clean oil with DBPC. Each of these oils are analyzed under the different concentrations of DBDS and DBPC viz., 50ppm, 100ppm, 150ppm, 200ppm and 250ppm. And each of these samples are observed for different durations viz., 24h, 48h, 72h, 96h, 120h, 144h , and 168h.The voltage is applied across the electrodes in steps and the corresponding leakage current is measured. At a certain point a spark over takes place which gives the breakdown voltage of the oil.

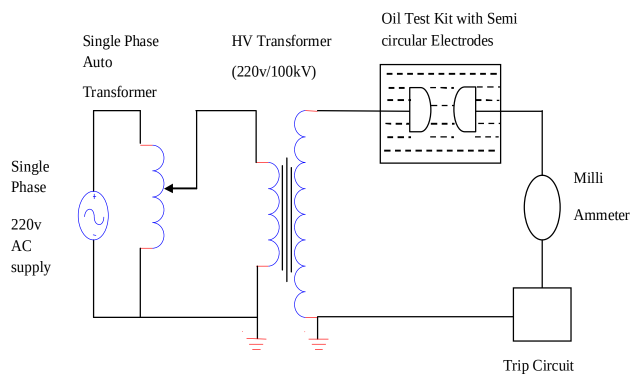

Fig.1: Experimental set up of placement of electrodes

Fig. 2 shows the plane-plane electrodes between which different insulation papers are added so as to find the leakage current for different applied voltages. Fig. 3 shows pig-tail sample used to find the dc resistance at different time intervals and different applied voltages.

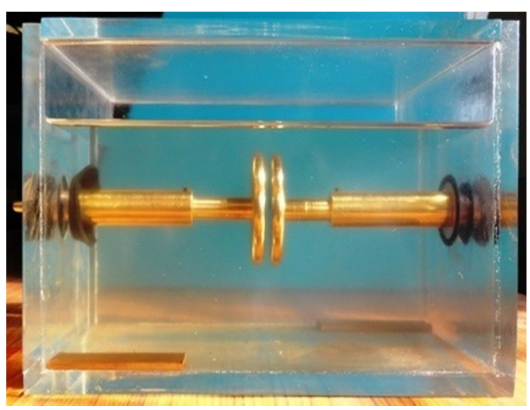

Fig. 2: Placement of plane-plane electrodes

The voltage is applied to the electrodes at the opposite ends (bolts are shown in Fig. 3)

Fig. 3: Pig tail sample used for measurement of dc

III. Results & Discussion

The immersion of Kraft paper in the presence of DBDS and DBPC results in the formation of copper sulfide which deposits on the outer surface forming a layer. Different concentrations of DBDS and DBPC and different gap distances are the parameters. The formation and deposition of copper sulphide is proportional to the concentration of DBDS or DBPC and durations of ageing. Later, there occurs a saturation and then the deposition is constant. Experiments were carried out on fresh and corroded oil to find out the V-I characteristics of the paper oil insulation of the transformer and then the effect on dc resistance. DC resistance was measured at applied voltages of 500 volts and 1000 volts for the durations of 1 minute, 5 minutes and 10 minutes

The results and corresponding graphs are tabulated below.

Table I: Current at different applied voltages for different distances between the electrodes of pure oil

Voltage Applied (kV)	Current (mA)			Voltage Applied (kV	Current (mA)		
	2 mm	4 mm	6 mm		2 mm	4 mm	6 mm
1	0.060	0.030	0.025	9	0.120	0.060	0.050
2	0.065	0.031	0.026	10	0.130	0.070	0.055
3	0.070	0.033	0.028	11	0.140	0.080	0.060
4	0.075	0.035	0.030	12	0.150	0.090	0.065
5	0.085	0.040	0.032	13	BD	0.100	0.075
6	0.095	0.045	0.035	14		0.110	0.085
7	0.100	0.050	0.038	15		BD	0.09
8	0.110	0.055	0.042	16			BD

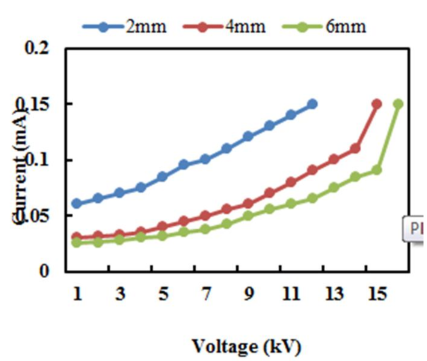

Fig. 4: Variation of voltage and current for pure oil at different distance between the electrodes

The leakage current measured for different applied voltages for different distance say, 2 mm, 4 mm and 6 mm distance between the electrodes are shown in Table 1. It is seen that with the increase in the distance between the electrodes the current decreases. The variation of current and voltages are plotted as shown in the Fig. 4. It is seen that the leakage current rises linearly for all gap distances. For, 2 mm electrode gap the breakdown strength was found to be 13kV while they were found to be 15 kV and 16 kV for 4 mm and 6 mm gap distances respectively.

TABLE II: CURRENT AT DIFFERENT APPLIED VOLTAGES FOR DIFFERENT DISTANCES BETWEEN THE ELECTRODES FOR OIL WITH DBDS

Voltage Applied (kV)	Current (mA)			Voltage Applied (kV	Current (mA)		
	2 mm	4 mm	6 mm		2 mm	4 mm	6 mm
1	0.066	0.0327	0.0270	9	0.1320	0.0654	0.0562
2	0.0715	0.0337	0.0280	10	0.1495	0.0763	0.0623
3	0.0770	0.0359	0.0302	11	0.1610	0.0911	0.0675
4	0.0825	0.0380	0.0324	12	BD	0.1026	0.0734
5	0.0936	0.0436	0.0345	13		0.1141	0.0842
6	0.1045	0.0490	0.0378	14		0.1254	0.0960
7	0.1100	0.0545	0.0410	15		BD	0.1073
8	0.1211	0.0599	0.0453	16			BD

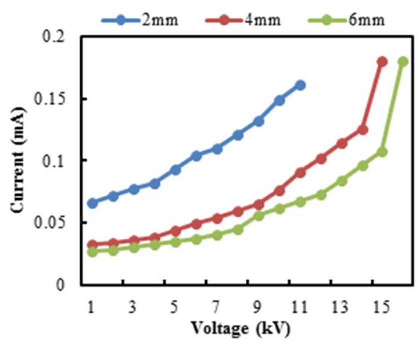

Fig. 5: Variation of voltage and current for oil with DBDS at different distance between the electrodes

The values of voltage and current of oil with DBDS at different distance between the electrodes are as shown in the Table 2. The values of leakage current are more than that of the pure oil for different values of applied voltages which shows that the DBDS enhances the vulnerability of transformer oil. The variation of voltage and leakage current is shown in Fig. 5. The values of voltage and leakage current of oil with DBPC at different gap distances between the electrodes are as shown in the Table 3.

In next method of analysis on effects of DBDS on insulation characteristics, Experiments were carried out on fresh and corroded oil to find out the DC resistance of the paper oil insulation of the transformer.

The DC resistance for an applied voltage of 500 Volts and 1000 Volts are calculated for various combinations of the paper layers on both electrodes (HV and LV).

TABLE III: CURRENT AT DIFFERENT APPLIED VOLTAGES FOR DIFFERENT DISTANCES BETWEEN THE ELECTRODES FOR OIL WITH DBPC

Voltage Applied (kV)	Current (mA)			Voltage Applied (kV)	Current (mA)		
	2 mm	4 mm	6 mm		2 mm	4 mm	6mm
1	0.0668	0.0330	0.0272	9	0.1332	0.0660	0.0545
2	0.0721	0.0314	0.0283	10	0.1508	0.0805	0.0557
3	0.0777	0.0363	0.0305	11	0.1624	0.0920	0.0684
4	0.0832	0.0386	0.0327	12	BD	0.1036	0.0708
5	0.0943	0.0440	0.0348	13		0.1150	0.0855
6	0.1054	0.0495	0.0381	14		0.1265	0.0969
7	0.1110	0.0550	0.0414	15		BD	0.1083
8	0.1220	0.0605	0.0457	16			BD

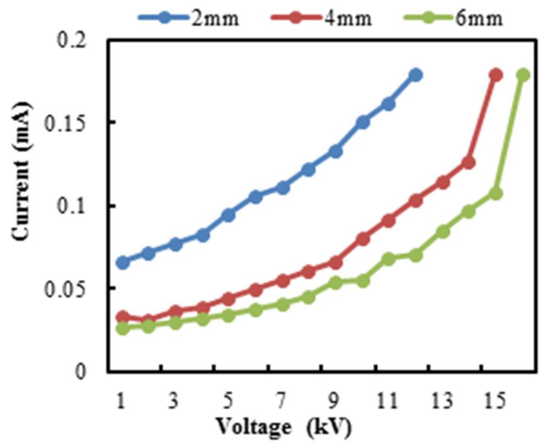

Fig. 6: Variation of voltage and current for oil with DBPC at different distance between the electrodes

TABLE IV: DC RESISTANCE MEASURED IN MΩ FOR THE CASE WHERE NO LAYER ON HV (ALL CLEAN) AND DIFFERENT NUMBER OF LAYERS ON LV ARE CONTAMINATED FOR AN APPLIED VOLTAGE OF 1000 VOLTS FOR THE CASE OF PURE OIL.

Actual contamination	Layers contaminated on LV	Dc resistance measured in MΩ for an applied voltage of 1000 volts		
		1 min	5 min	10 min
0Ct+0Ct	0	340	335	325
0Ct+1Ct	1	334	330	322
0Ct+2Ct	2	332	328	316
0Ct+3Ct	3	327	324	312
0Ct+4Ct	4	324	322	299

TABLE V: DC RESISTANCE MEASURED IN MΩ FOR THE CASE WHERE ONE LAYER ON HV AND DIFFERENT NUMBER OF LAYERS ON LV ARE CONTAMINATED FOR AN APPLIED VOLTAGE OF 1000 VOLTS FOR THE CASE OF PURE OIL.

Actual contamination	Layers contaminated on LV	Dc resistance measured in MΩ for an applied voltage of 1000 volts		
		1 min	5 min	10 min
1Ct+0Ct	0	326	325	320
1Ct+1Ct	1	322	320	316
1Ct+2Ct	2	319	318	314
1Ct+3Ct	3	315	312	309
1Ct+4Ct	4	312	308	304

TABLE VI: DC RESISTANCE MEASURED IN MΩ FOR THE CASE WHERE TWO LAYER ON HV AND DIFFERENT NUMBER OF LAYERS ON LV ARE CONTAMINATED FOR AN APPLIED VOLTAGE OF 1000 VOLTS FOR THE CASE OF PURE OIL.

Actual contamination	Layers contaminated on LV	Dc resistance measured in MΩ for an applied voltage of 1000 volts		
		1 min	5 min	10 min
2Ct+0Ct	0	330	320	318
2Ct+1Ct	1	328	316	315
2Ct+2Ct	2	326	316	312
2Ct+3Ct	3	323	311	300
2Ct+4Ct	4	316	308	297

TABLE VII: DC RESISTANCE MEASURED IN MΩ FOR THE CASE WHERE NO LAYER ON HV AND DIFFERENT NUMBER OF LAYERS ON LV ARE CONTAMINATED FOR AN APPLIED VOLTAGE OF 1000 VOLTS FOR THE CASE OF OIL WITH 50 PPM OF DBDS.

Actual contamination	Layers contaminated on LV	Dc resistance measured in MΩ for an applied voltage of 1000 volts		
		1 min	5 min	10 min
0Ct+0Ct	0	272	268	260
0Ct+1Ct	1	267	264	257
0Ct+2Ct	2	266	262	252
0Ct+3Ct	3	262	259	248
0Ct+4Ct	4	259	257	240

TABLE VIII: DC RESISTANCE MEASURED IN MΩ FOR THE CASE WHERE ONE LAYER ON HV AND DIFFERENT NUMBER OF LAYERS ON LV ARE CONTAMINATED FOR AN APPLIED VOLTAGE OF 1000 VOLTS FOR THE CASE OF OIL WITH 50 PPM OF DBDS.

Actual contamination	Layers contaminated on LV	Dc resistance measured in MΩ for an applied voltage of 1000 volts		
		1 min	5 min	10 min
1Ct+0Ct	0	261	260	256
1Ct+1Ct	1	258	256	252
1Ct+2Ct	2	255	254	250
1Ct+3Ct	3	252	250	248
1Ct+4Ct	4	250	246	244

TABLE IX: DC RESISTANCE MEASURED IN MΩ FOR THE CASE WHERE TWO LAYER ON HV AND DIFFERENT NUMBER OF LAYERS ON LV ARE CONTAMINATED FOR AN APPLIED VOLTAGE OF 1000 VOLTS FOR THE CASE OF OIL WITH 50 PPM OF DBDS.

Actual contamination	Layers contaminated on LV	Dc resistance measured in MΩ for an applied voltage of 1000 volts		
		1 min	5 min	10 min
2Ct+0Ct	0	264	256	254
2Ct+1Ct	1	262	253	252
2Ct+2Ct	2	260	252	249
2Ct+3Ct	3	258	248	242
2Ct+4Ct	4	253	246	238

TABLE X: DC RESISTANCE MEASURED IN MΩ FOR THE CASE WHERE THREE LAYER ON HV AND DIFFERENT NUMBER OF LAYERS ON LV ARE CONTAMINATED FOR AN APPLIED VOLTAGE OF 1000 VOLTS FOR THE CASE OF OIL WITH 50 PPM OF DBDS.

Actual contamination	Layers contaminated on LV	Dc resistance measured in MΩ for an applied voltage of 1000 volts		
		1 min	5 min	10 min
3Ct+0Ct	0	256	249	246
3Ct+1Ct	1	254	246	244
3Ct+2Ct	2	251	244	241
3Ct+3Ct	3	248	240	238
3Ct+4Ct	4	246	237	234

TABLE XI: DC RESISTANCE MEASURED IN MΩ FOR THE CASE WHERE ALL FOUR LAYER ON HV AND DIFFERENT NUMBER OF LAYERS ON LV ARE CONTAMINATED FOR AN APPLIED VOLTAGE OF 1000 VOLTS FOR THE CASE OF OIL WITH 50 PPM OF DBDS.

Actual contamination	Layers contaminated on LV	Dc resistance measured in MΩ for an applied voltage of 1000 volts		
		1 min	5 min	10 min
4Ct+0Ct	0	252	245	243
4Ct+1Ct	1	250	241	239
4Ct+2Ct	2	248	238	232
4Ct+3Ct	3	233	227	210
4Ct+4Ct	4	196	178	154

IV. CONCLUSION

The presence of potentially corrosive sulfur species in insulating oil has caused a significant number of catastrophic failures. The primary effect of the presence of corrosive sulfur species in insulating oil is the formation of copper sulfide (Cu_2S) on the surface of copper conductors and its subsequent migration through the insulating paper layers, leading to electrical faults. The main compound known to cause copper corrosion leading to the formation of copper sulfide is dibenzyl disulfide (DBDS). The dissolved copper (DBDS-Cu complex) influences the copper sulfide generation on the insulating paper. Moreover, the weight of copper deposited on the insulating paper was increased with the existence of oxygen. The rate of copper sulfide contamination is a function of time and enhanced with temperature.

As the distance between the electrodes increases there is decrease in the magnetic coupling between the electrodes. The leakage current also decreases. Main conclusions of the present work are that

1. The leakage current for oil with DBDS is 9% more for 1-9kV and about 13% for 10-15kV compared to pure oil and increases with distance between the electrodes. Similarly the leakage current for oil with DBPC is 10% more for 1-9kV and about 14% for 10-15kV compared to pure oil and consequently increases as the distance between the electrodes increases.
2. The DC resistance falls gradually as the contamination penetrates into more and more layers of paper.
3. Contamination formed is directly proportional to the amount of DBDS in transformer oil. Approximately, the DC resistance is found to be 20% less in an average in case of oil with 20 ppm of DBDS compared to pure oil.
4. The magnetic field lines get equally distributed as the contamination penetrates into paper layers simultaneously on both LV and HV.

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