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A study on copper corrosion and its effect on dielectric properties of paper oil insulation of transformers using simulation and laboratory experiments

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This study investigates the impact of copper sulphide which is formed due to corrosive sulphur in mineral oil on dielectric properties of paper oil insulation of model transformer windings. The effect of copper sulphide on electric stress distribution is explained using FEM based electric field computations. frequency domain spectroscopy and insulation resistance measurements were carried out on the prototype transformer windings under conditions of copper corrosion at different temperatures and the variations in tan δ, real and imaginary part of complex permittivity (ε', ε''), insulation resistance, and polarization index are discussed.

Keywords: *Copper sulphide, DBDS, paper oil insulation, transformer, tan δ, permittivity, insulation resitance, polarization index.*

1.0 INTRODUCTION

Paper-oil insulation plays an important role in determining the performance and life span of the power transformers, reactors, etc,. In recent years, quality of mineral oil insulation and the major changes it undergoes during its service life have been carefully monitored to understand the health of the transformer and to prevent failures that are triggered by degradation of mineral oil. In recent past, many cases of transformer failures due to formation of semiconducting copper sulphide in paper insulation are reported [1-3]. The corrosive sulphur compounds in mineral oil react on copper conductors under certain conditions and this results in the formation and migration of copper sulphide (Cu_2S) towards inner paper layers.

2.0 CHEMISTRY OF COPPER CORROSION

Dibenzyl Disulphide (DBDS) is an anti-oxidant and anti-wear additive which is used in transformer oil to improve its performance. In presence of DBDS, mineral oil becomes corrosive at higher temperatures and this leads to Cu_2S formation and it is followed by its migration into the paper layers [4-5]. DBDS reacts with copper ions forming a copper-organic compound. This DBDS-Copper complex decomposes and results in the formation of copper sulphide and other by-products [5]. Thus building up of Cu_2S on paper starts and it is forced into inner layers of paper.

3.0 EFFECT OF CU_2S ON DIELECTRIC PARAMETERS

It is reported that Cu_2S is a semi-conductor which is widely used in photovoltaic applications [6]. The semi-conductive nature of Cu_2S is observed in the temperature range of 300 K to 383 K and it becomes conductive above 383 K [6]. When Cu_2S gets deposited on kraft paper, it tends to change the dielectric properties of paper insulation. It is also documented that the resistivity of Cu_2S

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contaminated paper decreases with temperature and moisture [7].

Cu_2S has the tendency to distort the electric stress in the paper insulation and it enhances the electric stress at certain locations. When Cu_2S migrates into inner paper layers, it will lead to significant increase in leakage current, tan δ and it also alters the electric stress distribution resulting in inception of electrical discharges around Cu_2S sites [7]. This can also trigger turn to turn flashovers in the windings and finally end up in the breakdown of insulation system.

In the larger perspective of preventive maintenance of in-service power transformers, it is necessary to understand the dielectric performance of paper oil insulation when formation and progressive migration of Cu_2S into the paper insulation takes place. This study attempts to understand the dielectric parameters of paper oil insulation in presence of Cu_2S. The distribution of electric stress in Cu_2S contaminated paper insulation of model transformer winding is studied using Finite Element Method (FEM) and the results are presented in this paper. This paper also presents results of Frequency Domain Spectroscopy (FDS) and Insulation Resistance (IR) on laboratory model of transformer windings contaminated by Cu_2S. The measurements were carried out at temperatures of 25º C, 90º C and 140º C. The effect of both temperature and extent of copper sulphide contamination on the dielectric performance of paper oil insulation is explained.

4.0 SIMULATION STUDY ON EFFECTS OF CU_2S

In this study, electric filed simulations were carried out on a pigtail sample configuration as shown in Figure 1. It consists of two paper covered copper conductors which are tightly held together by PTFE tape. Each copper conductor has four layers of paper each of 55 μm thickness. FEM simulation is confined to the straight portion of pigtail sample. The boundary conditions are V=1 at HV conductor and V=0 at LV conductor.

FEM simulations are carried out by representing the clean impregnated paper layer by its relative permittivity of 3.75. With the complete deposition of Cu_2S on the first layer, it is assigned a permittivity of 40 and different conductivity values of 1×10^{-15} S/m and 1×10^{-4} S/m are assigned in order to represent its semiconducting and metallic nature and these values are based on published data [7] .

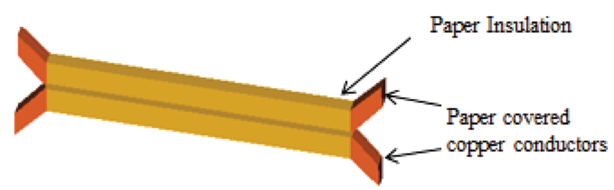

FIG. 1 PIGTAIL SAMPLE CONSISTING OF PAPER COVERED COPPER CONDUCTORS

It is assumed that Cu_2S is initially formed on the conductor surface and then it migrates to the first paper layer and sequentially to inner paper layers on High Voltage (HV) conductor and then sequentially onto the Low Voltage (LV) conductor of the pigtail sample. Under these assumptions, electric field simulation has been performed for the following cases:

a) Cu_2S with conductivity of 1×10^{-15} S/m and $\varepsilon_r = 40$ (Lower conductivity, temperature < 383 K).

b) Cu_2S with conductivity of 1×10^{-4} S/m and $\varepsilon_r = 40$ (Higher conductivity, temperature > 383 K).

The electric stress (E) in clean paper is observed to be 2.28 V/mm for an input voltage of 1V. The electric stress is also computed for progressive migration of Cu_2S and the values of electric stress in the clean and Cu_2S contaminated paper layers for different values of conductivity of Cu_2S are furnished under Table 1 and 2.

From Table 1 and 2 it is observed that the increase in electric stress is not significant during the initial stages of Cu_2S migration. But, when migration of Cu_2S takes place into second, third and subsequent layers, there is a considerable increase in electric stress across clean paper layers. This is much severe in case of Cu_2S having conductivity of $\sigma = 10^{-4}$ S/m.

TABLE 1 ELECTRIC STRESS IN CU_2S CONTAMINATED AND CLEAN PAPER LAYERS ($\Sigma = 10^{-15}$ S/M)			
No. of Cu_2S contaminated paper layers from HV conductor	**Maximum Electric Stress (V/mm)**		
	E_{Cu2S}	**E_{Clean}**	**% increase in stress compared to clean case**
1	0.24	2.56	12
2	0.27	2.94	29
3	0.32	3.45	51
4	0.39	4.16	82
5	0.50	5.24	130
6	0.67	7.10	211
7	1.03	11.00	382
8	2.28	----	----

TABLE 2 ELECTRIC STRESS IN CU_2S CONTAMINATED AND CLEAN PAPER LAYERS ($\Sigma = 10^{-4}$ S/M)			
No. of Cu_2S contaminated paper layers from HV conductor	**Maximum Electric Stress(V/mm)**		
	E_{Cu2S}	**E_{Clean}**	**% increase in stress compared to clean case**
1	0.003	2.60	14
2	0.004	3.03	32
3	0.007	3.64	60
4	0.008	4.54	99
5	0.009	6.05	165
6	0.010	9.05	297
7	0.030	18.00	690
8	2.280	----	----

It is also evident that the electric stress is reduced across Cu_2S contaminated papers and there is enhancement of electric stress across clean areas of paper. Thus it is expected that higher electric stress appears across clean paper leading to its breakdown and this is followed by breakdown of Cu_2S contaminated paper layers. The variation of maximum electric stress (E_{max}) across clean paper layers for progressive migration of Cu_2S for different conductivity values is shown in Figure 2.

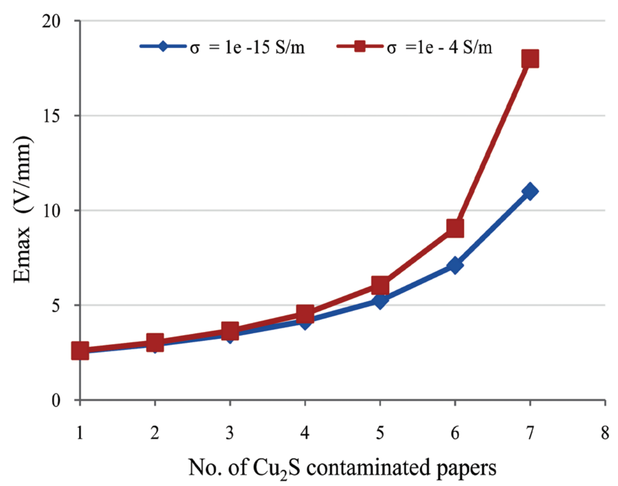

FIG. 2 VARIATION OF MAXIMUM ELECTRIC STRESS ON CLEAN PAPER LAYERS WITH NUMBER OF CU2S CONTAMINATED LAYERS

It is interesting to note that migration of Cu_2S into third and subsequent paper layers results in significant increase of electric stress. In such cases it can exceed dielectric strength of paper insulation and may lead to the complete breakdown of insulation system.

5.0 EXPERIMENTAL STUDY

The experimental studies under this investigation were carried out on pigtail samples. The paper layers on the High Voltage (HV) conductor are initially contaminated by Cu_2S and Low Voltage (LV) conductor is clean. All the samples were initially dried and impregnated with dried and degassed mineral oil by conventional method and each sample was immersed in 500 ml of mineral oil in a sealed container and kept in a temperature controlled oven. The temperature of the oven was preset to 25º C, 90º C and 140º C respectively.

5.1 Results of FDS Measurements

FDS measurements were carried out on pigtail samples at 200 V AC over a frequency range of 0.1 mHz to 1 kHz using dielectric response analyser of M/s. Omicron Electronics.

5.1.1 Effect of Cu_2S and temperature on tan δ

The variations of tan δ with frequency in clean and Cu_2S contaminated paper at 25º C, 90º C and 140º C are shown in Figure 3, 4 and 5.

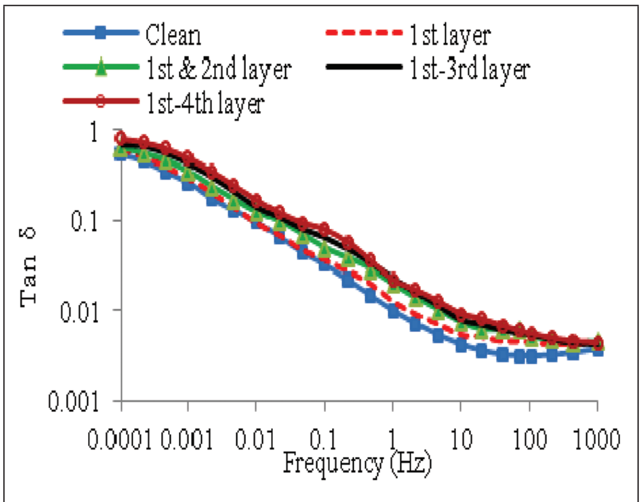

FIG. 3 VARIATION OF TAN Δ WITH FREQUENCY IN CLEAN AND CU2S CONTAMINATED PAPER AT 25º C.

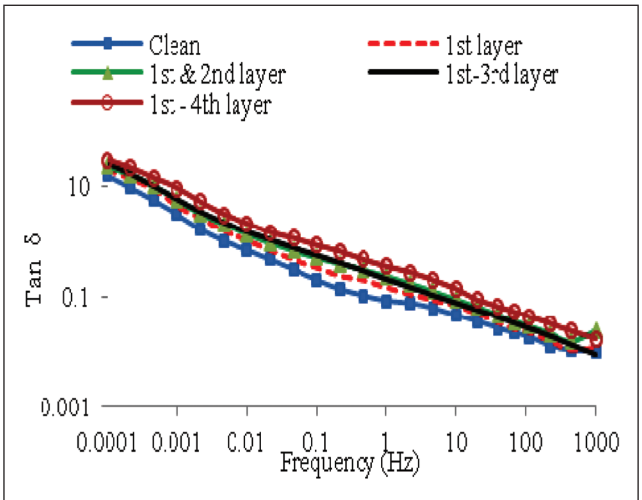

FIG. 4 VARIATION OF TAN Δ WITH FREQUENCY IN CLEAN AND CU2S CONTAMINATED PAPER AT 90º C

It is observed that there is a upward shift in tan δ values with increase in the number of Cu_2S affected paper layers and this is mainly attributed to Cu_2S deposits on paper. The minimum of tan δ is observed at 100 Hz for clean paper layer and at higher frequencies for Cu_2S contaminated layers respectively. It is also seen that there is a logarithmic shift of magnitude of tan δ which is caused by increase in activation energy at higher temperatures [8]. An increasing contribution of conduction mechanisms is indicated by the slope of the tan δ curve at lower frequencies. Hence, temperature appears to be very crucial to the observed results. This becomes more prominent with Cu_2S deposits.

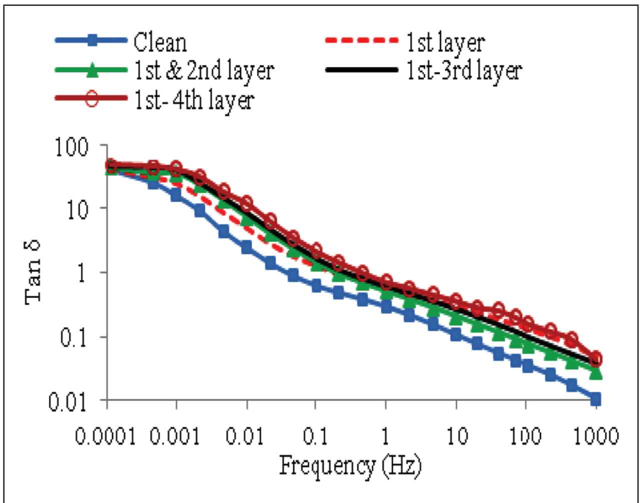

FIG. 5 VARIATION OF TAN Δ WITH FREQUENCY IN CLEAN AND CU2S CONTAMINATED PAPER AT 140º C

5.1.2 Effect of Cu_2S and temperature on ε'

The variations of real part of complex permittivity (ε') with frequency in clean and Cu_2S contaminated paper at 25º C, 90º C and 140º C are shown in Figure 6, 7 and 8. The results show that there is an increasing trend in ε' with increase in number of Cu_2S affected paper layers at the low frequency region and variations are very much reduced at middle and higher frequencies at 25º C. On the other hand, at 90º C and 140º C , the variations in ε' are least, at the higher frequencies. There is also significant increase in ε' values at temperatures of 90º C and 140º C.

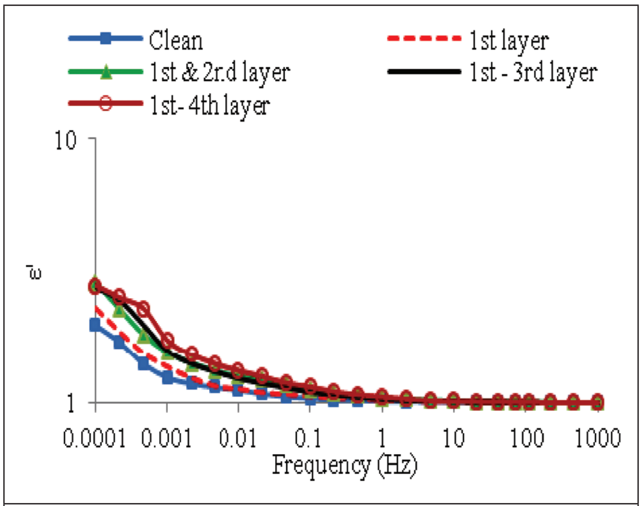

FIG. 6 VARIATION OF Ɛ' WITH FREQUENCY IN CLEAN AND CU2S CONTAMINATED PAPER AT 25º C.

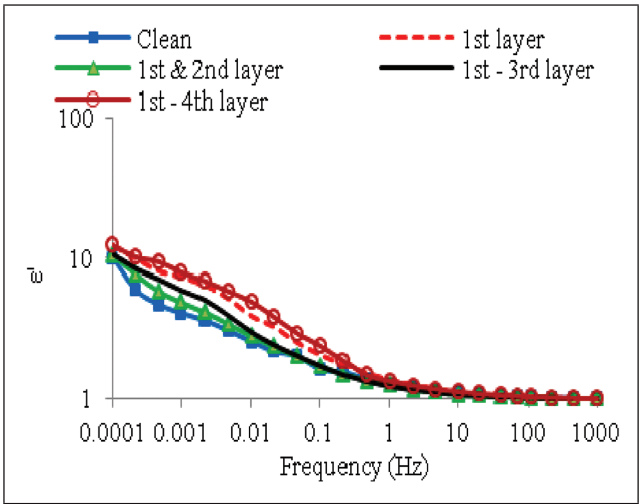

FIG. 7 VARIATION OF Ɛ'WITH FREQUENCY IN CLEAN AND CU2S CONTAMINATED PAPER AT 90º C.

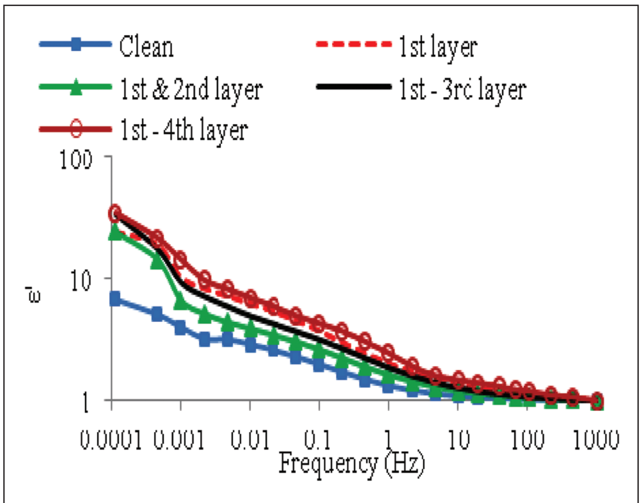

FIG. 8 VARIATION OF Ɛ'WITH FREQUENCY IN CLEAN AND CU2S CONTAMINATED PAPER AT 140º C.

5.1.3 Effect of Cu_2S and temperature on ε"

The variations of imaginary part of complex permittivity (ε") with frequency in clean and Cu_2S contaminated paper at 25º C, 90º C and 140º C are shown in Figure 9, 10 and 11. The variation in ε" is similar to the tan δ variations. The conductivity of Cu_2S is visible in terms of increase in ε" and the temperature dependent conductivity of Cu_2S is observed to be more significant at 90º C and 140º C respectively.

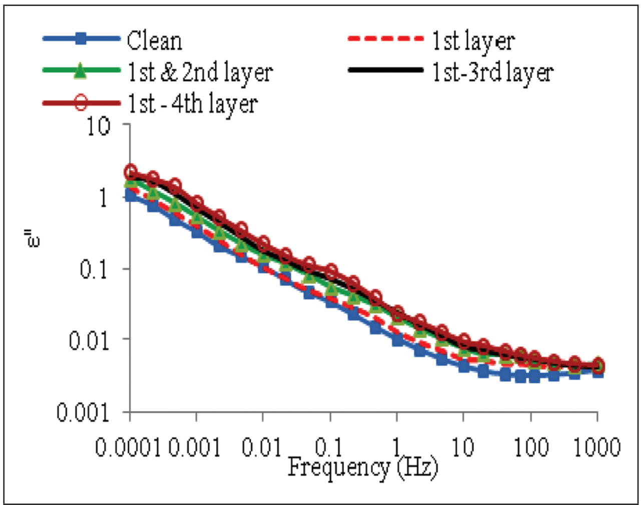

FIG. 9 VARIATION OF Ɛ" WITH FREQUENCY IN CLEAN AND CU2S CONTAMINATED PAPER AT 25º C.

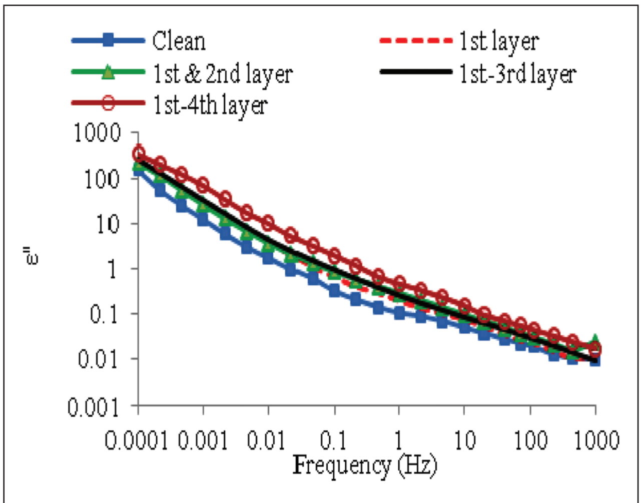

FIG. 10 VARIATION OF Ɛ" WITH FREQUENCY IN CLEAN AND CU2S CONTAMINATED PAPER AT 90º C.

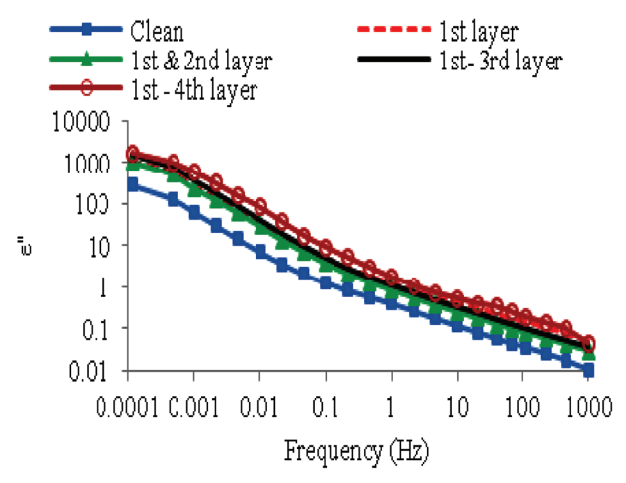

FIG. 11 VARIATION OF Ɛ" WITH FREQUENCY IN CLEAN AND CU2S CONTAMINATED PAPER AT 140º C.

5.2 Effect of Cu_2S and temperature on Insulation Resistance

The values of Insulation resistance (IR) are measured at 500 V for one minute for both clean case and Cu_2S contaminated samples. The measurements are carried out at 25º C, 90º C and 140º C respectively and the results are shown in Figure 12.

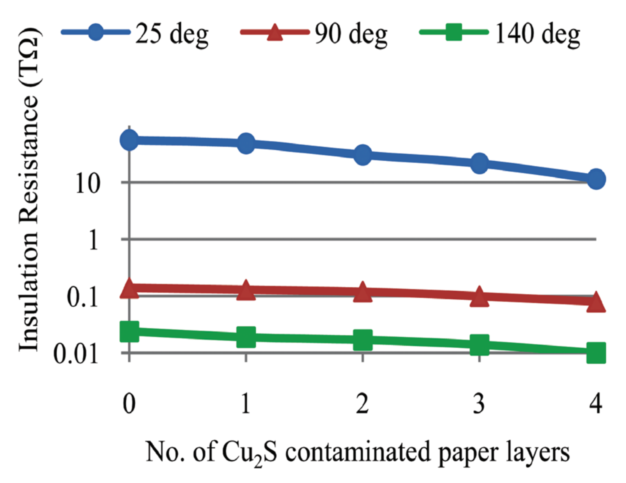

FIG.12 VARIATIONS OF INSULATION RESISTANCE FOR CLEAN AND CU_2S CONTAMINATED PAPER AT 25º C, 90º C AND 140º C

There is a reduction in the value of insulation resistance with increase in temperature and number of paper layers contaminated by Cu_2S.

5.3 Effect of Cu_2S and temperature on Polarization Index

The values of polarization index (PI) calculated from the ratio of 10 minutes IR to 1 minute IR values at 500 V for clean case and Cu_2S contaminated samples at 25º C, 90º C and 140º C are presented in Table 3. It is observed from Table 3 that the polarization index decreases with increase in temperature and number of paper layers contaminated by Cu_2S. The trend observed in the PI values are similar to IR values and the reduction in PI values are significant at 90º C and 140º C.

TABLE 3

VALUES OF PI FOR CLEAN AND CU_2S CONTAMINATED PAPER LAYERS AT 25º C, 90º C AND 140º C

NO. OF PAPER LAYERS WITH CU_2S ON HV SIDE	At 25º C	At 90º C	At 140º C
0	2.926	1.264	0.971
1	2.868	1.188	0.932
2	2.603	1.041	0.838
3	2.494	0.989	0.649
4	2.272	0.866	0.571

6.0 CONCLUSION

The important conclusions of this study are:

1. The effect of Cu_2S migration on paper layers has shown that there is a non uniform electric stress distribution across paper layers. The electric stress is more across the clean paper layers as compared to Cu_2S affected papers.

2. The values of tan δ, ε' and ε" increase in magnitude at higher temperature under Cu_2S contamination.

3. Polarization Index (PI) and Insulation resistance (IR) decrease with increase in temperature and progressive migration of Cu_2S.

Though there are characteristic changes in dielectric parameters under conditions of copper corrosion, it becomes challenging to use the conventional dielectric measurement in actual transformer windings where the insulation geometry is huge. Morever, dielectric response measurements such as FDS may give confusing or misleading information about the moisture content in the paper when the Cu_2S deposits are present together in paper-oil insulation.

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