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Understanding impulse surface flashover phenomenon on thermally aged oil impregnated pressboard material

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Surface flashover phenomena under lightening impulse voltage of positive and negative polarity on thermally aged Oil Impregnated Pressboard (OIP) material used in transformer is studied. OIP material with surface deposited Cu at different concentrations are also used for comparison. Total energy deposited on the OIP material and the magnitude of discharge current increased with ageing duration. The decay characteristics concerning optical emission from the surface flashover matched with the temporal decay of discharge current. The study also revealed some of the pre-breakdown phenomena before the main flashover breakdown. Optical Emission Spectroscopy (OES) revealed signature of diffused Cu and S in aged OIP material. Higher emission intensity for Cu was observed for higher aged OIP material, indicating larger possibility of degradation. OIP material collected from a failed transformer also showed optical emission lines matching with Cu emission, indicating possibility of employing the OES technique in contaminant detection. The temperature of the plasma during the surface flashover was also estimated.

Keywords : *Surface flashover, lightening impulse, oil impregnated pressboard, discharge current, pre-breakdown, optical emission spectroscopy*

1.0 INTRODUCTION

During the service, transformers undergo various types of over-voltages. Studies have also been carried out to understand the electrical strength of the oil-paper insulator under a combination of Alternating Current (AC) and lightening impulse voltages [1] Flashover is initiated by electrons generated by field electron emission and secondary electron emission [2] Electrons drift in the applied electric field. In addition to this electron current, ambient gas molecules ionize and contribute to the current. When this current in the insulating gap between negative and positive electrode becomes continuous, the potential barrier across the gap disappear. This causes breakdown of the material, which is the key process in flashover.

The mechanism of surface flashover mainly involves three processes. The first step is initiation of electron emission from the triple point ie. junction of insulator, electrode and the ambient medium. The second process is the development of streamer discharge which also includes emission of photons. In the final step, the ionization channel from negative to positive electrode is completed and the breakdown occurs. Relatively more studies are reported about surface flashover in vacuum ambience [3] The primary difference between vacuum ambience and air ambience is the contribution of ions to the discharge process. In vacuum ambience the ions are supplied by the desorbed gases, forming a thin layer on the surface of the insulator [4] while this is not significant in air medium due to the abundance of various molecules. Thus the arcing can happen in a broader region including

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air and the insulator surface. The Oxygen content in air causes ultra-violet photoemission [5] This photons causes release of electrons causing a net positive charge on the surface of the insulator. The strong electronegativity of oxygen holds the released electrons, increasing the net positivity of the surface. Further electron channel is attracted near the surface causing discharge to develop near the surface.

In transformer oil, presence of corrosive sulphur has been identified [6] It is reported that this corrosive sulphur reacts with current carrying conductors and form copper sulphide which diffuses into the pressboard insulating material, affecting its insulating properties [7] In this work, surface flashover phenonmena under lightening impulse voltage of positive and negative polarity on Oil Impregnated Pressboard (OIP) insulation material used in transformer is studied. Accelerated thermal ageing is performed on the OIP material in the presence of corrosive sulphur. Influence of copper sulphide diffusion on surface flashover is investigated by adopting electrical and optical emission measurement techniques.

2.0 EXPERIMENTAL SET UP

The setup for impulse surface flashover measurement is shown in Figure 1. A lightening impulse (1.2/50 μs) voltage of positive and negative polarity are applied on the oil impregnated pressboard material adopting IEC 60112 electrode configuration [9] The voltage waveform was recorded during flashover using a 1000:1 voltage probe. A current sensor was used to observe the current variations during the process of flashover. The optical emission during the surface flashover was detected using a optical lens – fiber – coupled spectrometer with operating in UV-Visible region. A Photo Multiplier tube (PMT) was used to detect the temporal evolution of the optical signal from the surface flashover process. Pressboard material prepared using accelerated ageing (denoted as aged OIP) and surface deposition of Cu particles (denoted as Cu OIP) were used for the study. The method of preparation was described in [10

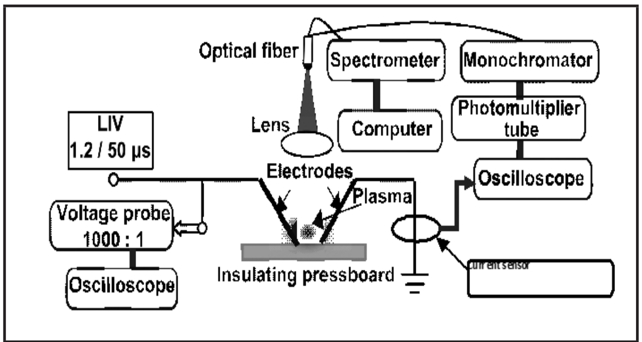

FIG. 1. SCHEMATIC OF SURFACE POTENTIAL MEASUREMENT AFTER CORONA CHARGING USING ELECTROSTATIC VOLTMETER PROBE.

3.0 RESULTS

Typical voltage and current waveforms observed during the flashover is shown in figure 2.

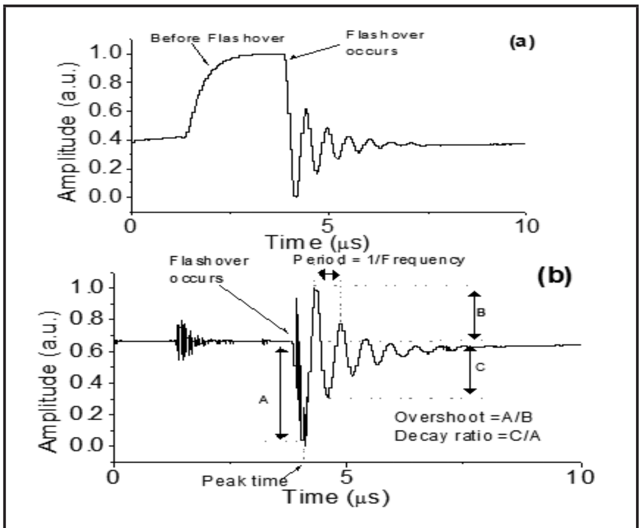

FIG. 2. TYPICAL TEMPORAL PROFILES OF (A) VOLTAGE (B) CURRENT DURING SURFACE FLASHOVER

During the surface flashover, the applied voltage collapsed and the magnitude of current increased. The discharge current had a ringing pattern irrespective of the polarity of the applied impulse voltage.

3.1 Characteristics of The Discharge

Characteristics of discharge current such as peak time, overshoot, decay ratio and frequency of oscillation were estimated from the discharge current profile. Peak time was the amount of time it takes to reach the maximum overshoot. Overshoot was defined as the ratio of the magnitude of first peak to second peak of the ringing current pattern. Decay ratio was the ratio of the heights of successive same polarity peaks in the response. Frequency of oscillation is the dominant frequency content in the current signal. The summary of estimated parameters are shown in Table 1.

TABLE 1

CHARACTERISTICS OF DISCHARGE CURRENT PROFILE

Parameter	+LIV (aged OIP)	-LIV (aged OIP)	+LIV (Cu OIP)	-LIV (Cu OIP)	+LIV (Virgin)	-LIV (Virg-in)
Peak time (µs)	1.8 – 4.0	0.20-0.21	0.4-2.0	1.7-3.7	0.4-1.7	0.21-0.22
Overshoot	0.9-2	2.10-5.0	0.13-0.9	0.96-2.12	0.2-0.9	1.9-2.1
Decay time	0.3-6.4	0.49-0.53	0.34 -5.4	0.31-1.03	0.7-7.5	0.5-0.6
Frequency (MHz)	1.89-2.4	1.89-1.90	1.90-2.44	1.88-1.89	1.89-2.44	1.90-1.91

The total energy deposited on the insulating pressboard material during the surface flashover was calculated by time integrating the instantaneous power delivered to the material surface. The results for both type of samples under +/-LIV voltages are shown in Figure 3.

An increasing trend of energy deposited with increase in ageing duration was observed in the case of aged OIP material. However, the Cu deposited samples had a deposited energy of 25-30 J irrespective of the surface concentration. This indicated that flashover is affected by bulk properties, even though the process happens on the surface. A high voltage stress on the surface on the OIP material can cause flashover breakdown due to the presence of diffused Cu contaminant.The magnitude of discharge current during the flashover was also important to look at. Figure 4 shows the room mean squared magnitude of discharge current for aged and Cu deposited OIP material under flashover by +/-LIV. Similar to the trend observed in the case of deposited energy, the magnitude of discharge current during surface flashover increases for increase in ageing duration of oil impregnated pressboard. The magnitude of current is in the range 18-20 A for Cu deposited OIP material.

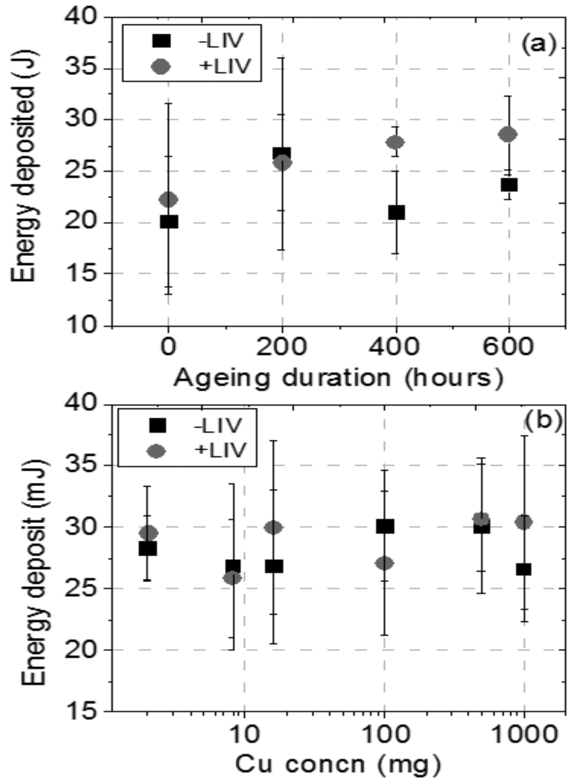

FIG. 3. THE TOTAL ENERGY DEPOSITED ON THE SURFACE FOR (A) AGED OIP (B) CU DEPOSITED OIP

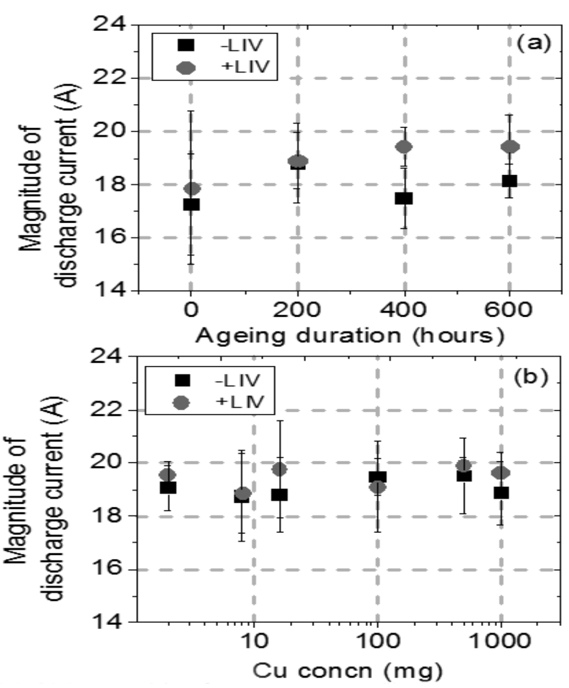

FIG. 4. MAGNITUDE OF DISCHARGE CURRENT DURING SURFACE FLASHOVER FOR (A) AGED OIP (B) CU OIP

The optical emission during flashover, detected using PMT showed an exponentially decaying envelope pattern. The persistence time of the optical emission was estimated by calculating the time at which PMT signal decayed to 1/e of the initial amplitude. The persistence time of optical emission is shown in Figure 5. The aged OIP material showed an increase of optical emission persistence time with increase in the duration of ageing. The Cu deposited samples also showed a marginal increase in persistence with concentration.

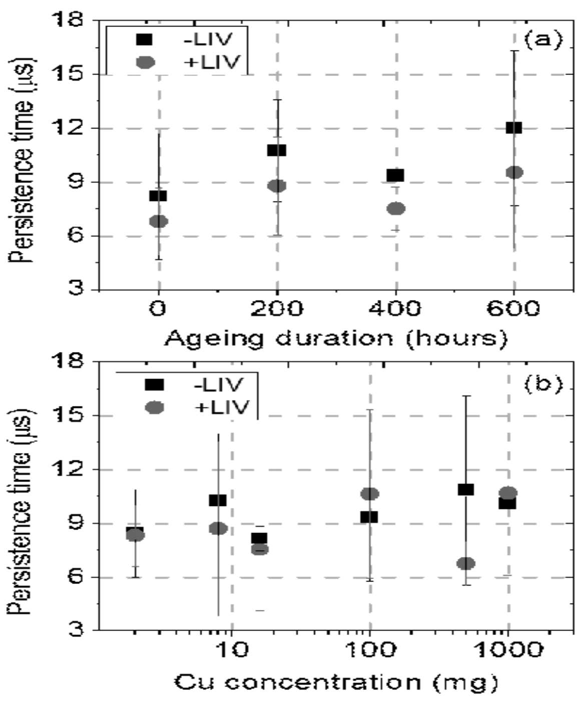

FIG. 5. OPTICAL EMISSION PERSISTENCE TIME FOR (A) AGED OIP (B) CU OIP

3.2 Time Probing of Surface Flashover

During surface flashover, the discharge current generated and the optical signal detected by PMT do develop instantaneously and decay exponentially.

Figure 6 shows the correlation between the discharge current and the PMT signal of a typical impulse surface flashover. Since PMT is negative biased, on application of both +LIV (Figure (a)) and –LIV (Figure (b)) the decay is negative exponential. It can be seen that the temporal decay of optical signal is well correlated with the decay of discharge current during surface flashover. The correlation existed in the case of both virgin and aged OIP material.

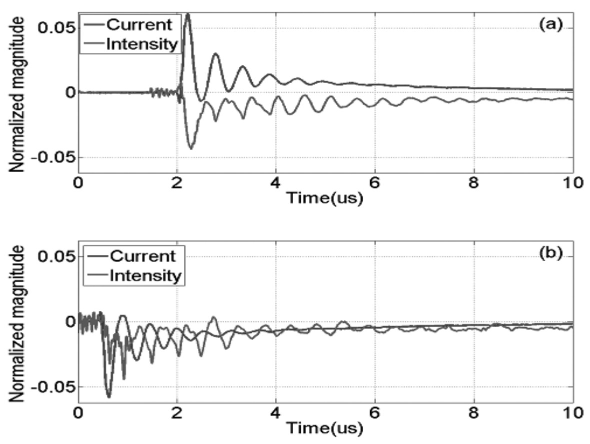

FIG. 6. DISCHARGE CURRENT AND PMT SIGNAL DURING SURFACE FLASHOVER UNDER (A) +LIV (B) -LIV

3.2.1 Pre-breakdown phenomenon

Various stages of small breakdowns prior to the main breakdown event occur during surface flashover. These can be probed by monitoring the discharge current as shown in Figure 7. Figure 7 (a) shows the very early pre-breakdown process producing a discharge current in the order of 100 mA.

The very early pre-breakdown occurs approximately 2.5 µs prior to the main breakdown event. Figure 7 (b) shows the early pre-breakdown process producing a discharge current of the order of 0.5-1 A, 5-10 times higher than the magnitude of very early pre-breakdown discharge current. The early pre-breakdown initiated around 800-900 ns prior to the main breakdown event. Figure 7 (c) shows the largest pre-breakdown event producing ~ 3A discharge current which occurred at ~ 100 ns prior to the main breakdown event. During the main breakdown, a huge discharge current of the order of 20 A is produced. The graphs shown are for +LIV, however –LIV also produced similar observations.

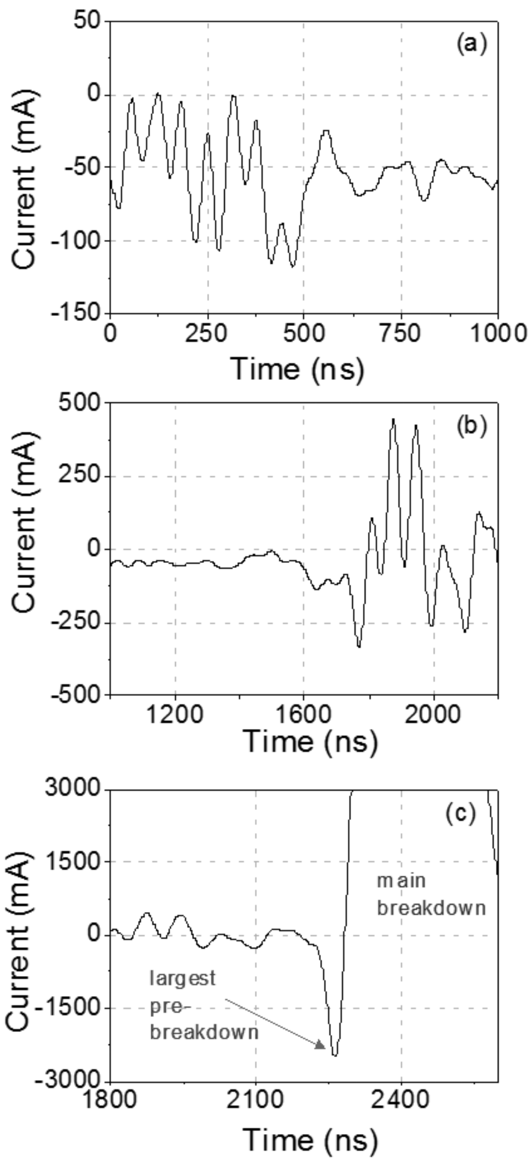

FIG. 7. DISCHARGE CURRENT DURING (A) VERY EARLY PRE-BREAKDOWN (B) EARLY PRE-BREAKDOWN (C) LARGEST PRE-BREAKDOWN

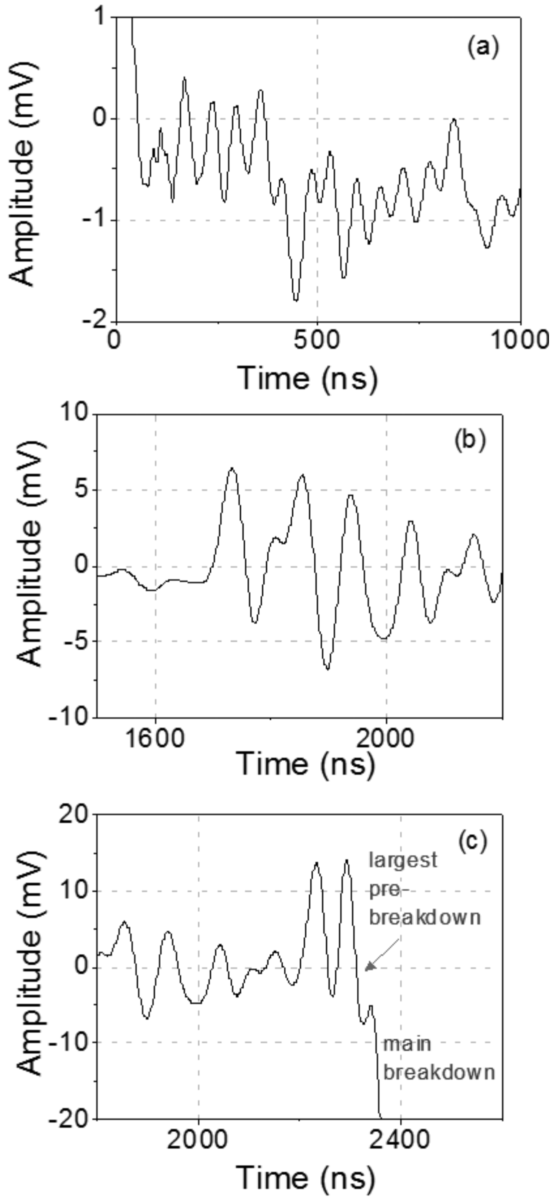

FIG. 8. PMT SIGNAL DURING (A) VERY EARLY PRE-BREAKDOWN (B) EARLY PRE-BREAKDOWN (C) LARGEST PRE-BREAKDOWN

The different stages of breakdown can be probed by the PMT signal as shown in Figure 8. Similar to Figure 7 (a), a very early pre-breakdown can be observed in the PMT signal of Figure 8 (a), the values being very less since the optical emission is too small. Figure 8 (b) shows increased optical emission amplitude and the largest pre-breakdown can be seen in Figure 8 (c). Although the pre-breakdown patterns were similar for virgin and aged OIP material, a time lag of 120 ns was observed for the largest pre-breakdown event to occur in the case of aged OIP material.

3.3 OES measurements

Optical Emission Spectroscopy (OES) of surface flashover is useful for analysing the element specific information of the discharge. OES analysis of aged and Cu deposited OIP are discussed below.

3.3.1 Spectral analysis of aged OIP material

In the OES emission spectrum of aged OIP material is shown in Figure 9.

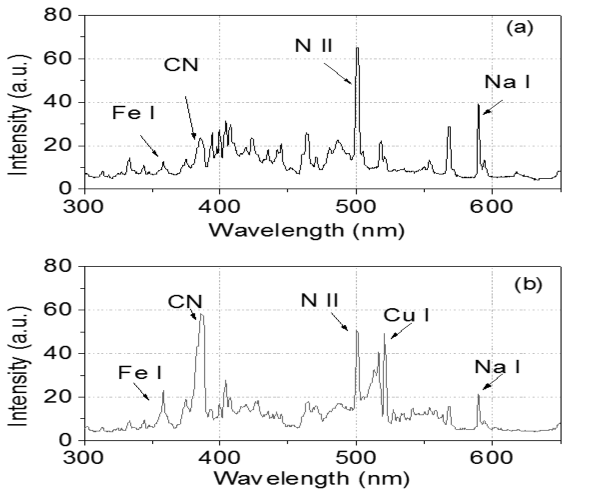

FIG. 9. OES EMISSION SPECTRA FOR (A) VIRGIN OIP (B) AGED OIP

Cu I emission line was detected in the case of aged OIP material (Figure 9 (b)) which was not observed in OES emission spectrum of virgin OIP material (Figure 9 (a)). This confirmed the diffusion of copper contaminant into the OIP material due to thermal ageing.

Presence of S II emission lines in trace intensities were also found in OES emission spectrum of aged OIP material as shown in Figure 10 (b). The corresponding OES spectrum of virgin OIP material (Figure 10 (a)) does not show the presence of S II emission lines. This indicated that sulphur contaminant has diffused into the aged OIP material due to ageing. Both Cu I and S II emission lines were in agreement with NIST database [11]

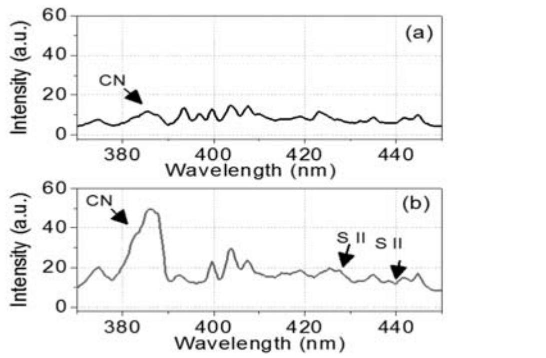

FIG. 10. SELECTED PORTION OF OES EMISSION SPECTRUM FOR (A) VIRGIN OIP (B) AGED OIP

The intensity of Cu I emission line was estimated for aged OIP material of different ageing durations as shown in Figure 11. A marginal increase in Cu I intensity was observed with increase in ageing duration of OIP material. Surface flashover was found to occur at a lower voltage in the case of aged OIP material [10]. This indicated that a longer aged OIP material has a larger chance of surface flashover.

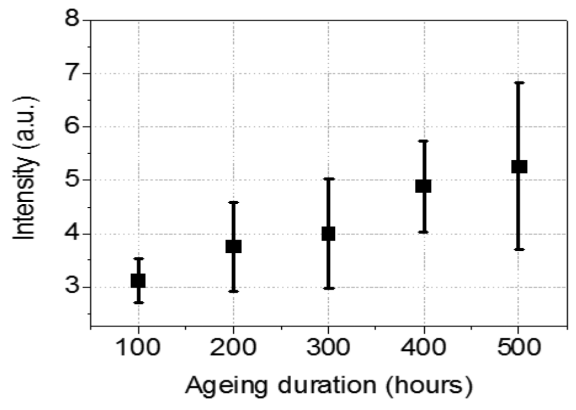

FIG. 11. CU I EMISSION LINE INTENSITY OF AGED OIP MATERIAL

Surface flashover studies were also carried out on OIP material collected from a failed transformer (16 MVA, 110/33-11 kV). The OES emissions were captured as shown in Figure 12.

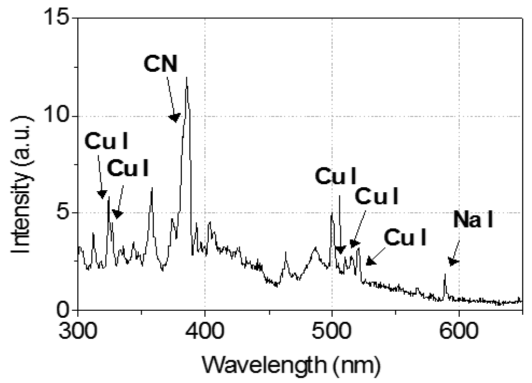

FIG. 12. OES EMISSION SPECTRUM FOR OIP MATERIAL COLLECTED FROM FAILED TRANSFORMER

Five Cu I emission lines were visible in the OES emission spectrum indicating clearly the presence of diffused Cu contaminant in the insulating OIP material of the failed transformer. OES study was carried out on various positions on the OIP material from failed transformer. The intensity of Cu I emission lines were varying with position. Largest intensity was observed in the positions with darker colour on the surface. The image of the surface of the OIP material from field transformer is shown in Figure 13. Figure 13 (a) shows virgin OIP material and Figure 13 (b) shows OIP material from the failed transformer.

FIG. 13. (A) VIRGIN OIP MATERIAL (B) OIP MATERIAL FROM FAILED TRANSFORMER

3.3.2 Plasma temperature analysis

The surface flashover generates discharge plasma during the cooling of which, optical emission is generated. The collective temperature of the discharge plasma can be calculated under an assumption of local thermal equilibrium.

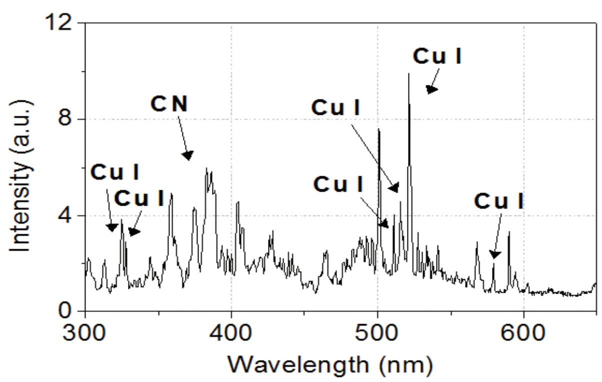

FIG. 14. OES EMISSION SPECTRUM CU DEPOSITED OIP

In the Cu deposited OIP material, optical emission during surface flashover was captured as shown in Figure 14. Several Cu I emission lines were observed in the OES spectrum. This is due to the discharge during surface flashover passing through the deposited Cu layer. Presence of several Cu I lines in the spectrum allows us to estimate plasma temperature at different concentrations of Cu on the pressboard surface. Boltzmann-Saha equations are used for calculating the plasma temperature. The parameters used are shown in Table 2.

TABLE 2

PARAMETERS FOR CU PLASMA TEMPERATURE CALCULATION

line	λ (nm)	E_k (eV)	E_i (eV)	g_k	A_{ki} (s^{-1})
Cu I	510.55	3.817	1.389	4	2e6
Cu I	515.32	6.191	3.786	4	6e7
Cu I	521.82	6.192	3.817	6	7.5e7
Cu I	578.21	3.786	1.642	2	1.65e7

For the temperature estimation, a linear fit was performed between E_k and for suitable Cu I lines as shown in Figure 15 where I is the intensity of a particular emission line, λ is the wavelength, E_k is the upper energy level, E_i is the lower energy level, g_k is the upper level degeneracy and A_{ki} is the transition probability of a particular transition. In the case of field OIP material, 3 available Cu I lines were used for the calculations while for Cu OIP, 4 lines were used. Negation of the inverse of slope of the linear fit gives plasma temperature.

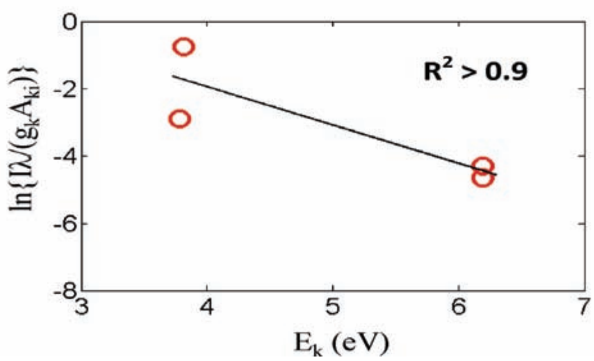

FIG. 15. PLASMA TEMPERATURE ESTIMATION METHOD USING CU I EMISSION LINES AS DESCRIBED IN TABLE 2.

Estimated plasma temperature of Cu plasma for Cu OIP material and field OIP material from failed transformer are shown in Figure 16. For low deposition concentrations of Cu OIP material, plasma temperature is about 16 $\times 10^3$ K while for larger concentrations, plasma temperature raises upto 19 $\times 10^3$ K. For field OIP material, plasma temperature is much larger, it is in the order of 28 $\times 10^3$ K. This indicates that during surface flashover, field OIP is heated up much more than Cu OIP. This can be attributed to the increased degradation for field OIP material. Plasma temperature during surface flashover can be taken as an indication of severity of degradation. Further study is essential to use the proposed OES technique for field measurements.

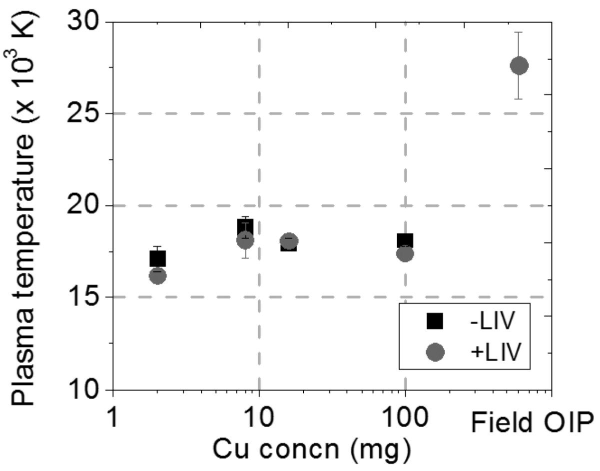

FIG. 16. ESTIMATED PLASMA TEMPERATURE FOR CU OIP MATERIAL AND FIELD OIP MATERIAL

4.0 CONCLUSION

Surface flashover phenomenon on oil impregnated pressboard material under impulse voltage was studied. The magnitude of deposited energy during flashover was found to increase with increase in the duration of ageing of OIP material. The increase was from 20-30 J. The magnitude of discharge current was increasing from 17-20 A with increase in duration of ageing. This was in agreement with energy deposited and indicated a higher damage possible at a higher ageing level of OIP material. The optical emission persistence time also increased with increase in duration of ageing. OES measurements indicated diffusion of Cu contaminant in aged OIP material. Trace indication of S contaminants was also indicated in OES spectrum. This supported the diffusion of copper sulphide contaminants in thermal ageing of OIP material. Higher aged OIP material showed a larger intensity of Cu emission line which suggested a larger chance of degradation. OIP material collected from failed transformer from the field also showed prominent Cu emissions during surface flashover. This indicates the feasibility of OES for detecting Cu contaminants in the insulating pressboard of a transformer. In addition, plasma temperature during surface flashover was found to be 19 $\times 10^3$ K for Cu OIP and 28 $\times 10^3$ K for field OIP material.

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REFERENCES

[1] F. Mosinski, J. Wodzinski, L. Sikorski, and J. Ziencikiewicz, "Electrical strength of paper-oil insulation subjected to composite voltages," IEEE Trans. Dielectr. Electr. Insu., Vol. 1, pp. 615-623, 1994.

[2] J. Krile, "Physics of dielectric surface flashover at atmospheric pressures," Master of Science, Electrical engineering, Texas Tech University, 2003.

[3] A. Neuber, M. Butcher, L. Hatfield, and H. Krompholz, "Electric current in dc surface flashover in vacuum," Journal of applied physics, Vol. 85, pp. 3084-3091, 1999.

[4] H. C. Miller, "Surface flashover of insulators," IEEE Trans. Dielectr. Electr. Insu., Vol. 24, pp. 765-786, 1989.

[5] Y. P. Raizer and J. E. Allen, Gas discharge physics Vol. 2: Springer Berlin, 1997.

[6] T. Amimoto, N. Hosokawa, E. Nagao, J. Tanimura, and S. Toyama, "Concentration Dependence of Corrosive Sulfur on Copper-Sulfide Deposition on Insulating Paper Used for Power Transformer Insulation," IEEE Trans. Dielectr. Electr. Insu., Vol. 16, pp. 1489-1495, 2009.

[7] K. Mizuno, R. Nishiura, F. Kato, and M. Hikita, "Elucidation of Formation Mechanism of By-products of Copper Sulfide Deposition on Insulating Paper in Oil-immersed Transformer," IEEE Trans. Dielectr. Electr. Insu., Vol. 21, pp. 1376-1383, 2014.

[8] A. Kalantar and M. Levin, "Factors affecting the dissolution of copper in transformer oils," Lubrication Science, Vol. 20, pp. 223-240, 2008.

[9] IEC-60112-Method for the determination of the proof and the comparative tracking indices of solid insulating material, Vol. BS EN 60112: 2003, 2003.

[10] N. Aparna, N. J. Vasa, R. Sarathi, and J. S. Rajan, "Feasibility study for detecting copper contaminants in transformer insulation using laser-induced breakdown spectroscopy," Appl. Phy. A mater. sci. process, Vol. 117, pp. 281-288, 2014.

[11] J. E. Sansonetti and W. C. Martin, "Handbook of basic atomic spectroscopic data," Journal of Physical and Chemical Reference Data, Vol. 34, pp. 1559-2259, 2005.