A STUDY ON THE APPLICATION OF LOW FREQUENCY TECHNIQUE FOR ASSESSMENT OF STATOR WINDING INSULATION

B. NAGESHWAR RAO[1]*, J. SUNDARA RAJAN[1], A SUDHINDRA[1] and B. RAMACHANDRA[2]
[1]Central Power Research Institute, Bangalore, India
[2]P.E.S. College of Engineering, Mandya, India
*Email: <nagesh@cpri.in>

Abstract: Ageing of stator winding insulation involves physical and or chemical changes of the insulation which in turn leads to changes in the dielectric response. The dielectric diagnostic methods like Capacitance and tan δ measurements at different frequencies, and Recovery voltage, which is time domain method have been adopted to study the dielectric response of epoxy mica insulation. Two different types of insulation systems are evaluated, resin poor and resin rich mica laminate and coils. Low voltage measurements at 140 volts peak were made in the frequency range of 1 mHz to 1 kHz using Dielectric spectroscopy. The Recovery voltage measurement technique was used to investigate the polarization processes in the dielectric to assess the insulation ageing. This paper presents and discusses the data on dielectric response of thermally degraded epoxy mica laminates and motor stator winding coils. Generator case study is discussed.

1 INTRODUCTION

The stator winding insulation deteriorates under thermal, electrical, mechanical (vibration) and thermo-mechanical stresses during service. The ageing processes are complicated and take place under stresses simultaneously or sequentially. Thermal aging is a chemical process leading to molecular decomposition and oxidation of organic materials resulting in changes in dielectric response. The dielectric response at low frequency involves phenomena like direct conduction, quasi dc conduction (low frequency dispersion), alpha dipolar relaxation mechanisms. Based on the related relaxation mechanisms which depend on the contaminants, the materials will polarize to a varying extent at different frequency electric fields. Studies based on the application of Dielectric spectroscopy technique (which is essentially a dissipation factor measurement performed at multiple frequencies ranging from few mHz to kHz) and Recovery or return voltage measurements (RVM) for evaluating the polarization and discharge characteristics of an epoxy mica insulation are limited [1,2].

Laboratory studies were undertaken to understand the low frequency response of thermally degraded stator winding insulation. The model bars of stator winding manufactured under resin poor process were subjected to accelerated thermal ageing. Low frequency dielectric spectroscopy measurement has been performed on number of unaged and thermally aged epoxy-mica laminates and on motor coils. Dielectric loss angle, Power Factor, capacitance were measured at frequencies ranging from 1 mHz to 1 kHz.

This paper presents and discusses the data on low frequency dielectric response of thermally degraded epoxy mica composites and motor stator winding coils. Generator case study is presented.

1.1 Dielectric Spectroscopy

Dielectric spectroscopy measurement is essentially an impedance measurement at different frequencies based on Impedance models like (a) Complex capacitance, (b) Capacitance combined with Power factor & tan δ and (c) Dielectric (permittivity and complex permittivity) models [3]. In the present investigation Programma, IDA 200 instrument is used. It measures impedance at a specific frequency and amplitude based on the mentioned models. Parameters such as capacitance, tan δ and Power Factor, complex capacitance and permittivity.

1.2 Preparation of samples for dielectric response studies

Samples were made using B grade, pre polymer tapes consisting of mica paper thoroughly impregnated with electrical grade modified epoxy resin. The muscovite calcined mica paper is about 0.18 mm thick. The composition of tapes is glass fabric 35± 3 gm/m^2, resin content 70±12 gm/m^2, volatile content ≤ 0.8%. The uncured tapes were layered to get the required thickness by machine hot pressing with tension of 40 to 60 N and cured at 433 K for 2 hours. Samples of dimension 150 mm x 150 mm and thicknesses of 1 mm, 2 mm and 3 mm were cut from the bigger sheet.

2 RESULTS AND DISCUSSION

The low frequency dielectric response studies has been performed on aged and unstressed samples made from both resin rich and resin poor epoxy mica insulation system.

2.1 Dielectric spectra of Resin rich unstressed specimens

The dielectric response of Resin rich epoxy mica unstressed specimens was measured at room temperature and in the frequency range 1 mHz to 1 MHz. Figures 1 and 2 show the variation of tan δ and Complex capacitance, C" respectively as a function of frequency. It is seen from these figures that the trend in variation of tan δ and complex capacitance with frequency are similar, as dielectric losses are represented either by tan δ or complex capacitance based on impedance models. The variation of loss factor from sample to sample in the frequency range 10 Hz to l kHz is marginal but below 10 Hz there is a strong dispersion and is maximum at 0.001 Hz. The larger dispersion at lower frequency range is probably due to the presence of polar species which vary in size and density contributing to the losses in the insulation.

The variation of Capacitance and power factor with frequency was also measured. Capacitance changes either due to change in permittivity or due to dimensional changes. Changes in permittivity in the frequency domain also reflect charge polarization or partial discharges that can occur in internal voids or de-laminations at higher stresses. It was observed that there was not much variation in measured capacitance up to a 0.001 Hz, but a small increase below 0.01 Hz. Partial discharge measurements were also conducted on these samples.

Table 1 shows tan delta and capacitance and partial discharge magnitude values at 50 HZ using conventional bridges. The tan δ and capacitance

Table 1: tan δ, Capacitance and PD data.

Measured properties	Sample designation				
	A	B	C	D	E
Tan δ (%) @ 2 kV (Schering bridge)	1.43	0.95	0.86	0.93	0.93
Capacitance (pF) (Schering bridge)	66.5	72.3	67.5	68.7	67.3
PD magnitude (pC) @ 2 kV	18.1	16.0	15.0	10.0	17.4

values measured at 50 Hz, 2 kV using Schering bridge method is in agreement with the values measured by dielectric spectroscopy. The partial discharge magnitudes are well within the limits and no intense discharge activity was observed.

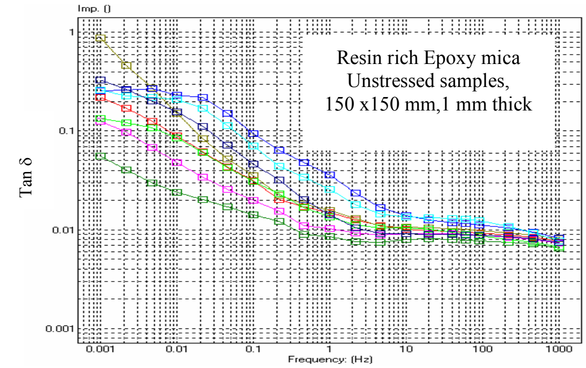

Figure 1: Measured tan δ over the frequency range 1 mHz to 1 KHz

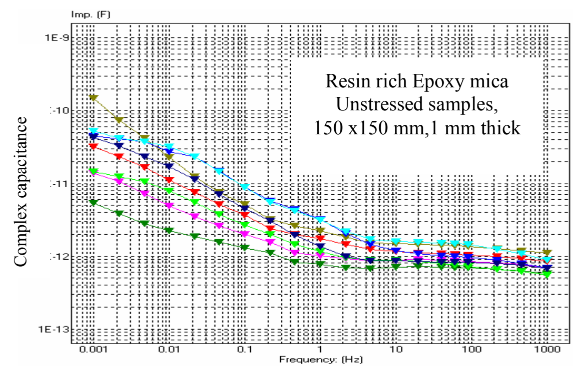

Figure 2: Measured Complex Capacitance C" over the frequency range 1 mHz to 1 KHz

2.2 Dielectric spectra of Resin poor unstressed specimens

Studies were made on epoxy-mica resin poor laminates. The samples were impregnated under vacuum and cured. Figures 3 and 4 show the variation of tan δ, Change in permittivity, (Δε) as a function of frequency respectively,

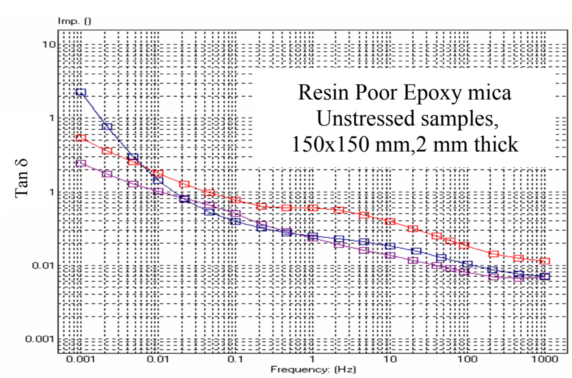

Figure 3: Measured tan δ over the frequency range 1 mHz to 1 KHz

On comparison with resin rich samples of identical dimensions, the trend is observed to be similar as seen from figures 1 and 2. However the loss values are lower than the resin rich samples. This could be due to variation in processing technology and less number of voids, de-laminations, defects in resin poor samples. The complex permittivity is both frequency and temperature dependent. In the lower frequency range <1 kHz, the ionic and molecular polarization processes are expected to dominate. Most of the degraded products are polar or ionic, and hence measurement of complex permittivity reflects all possible degradation mechanisms. Figure 4 shows the incremental change in complex permittivity,($\Delta\varepsilon$) which decreases with frequency. The dispersion is observed to be more at lower frequencies.

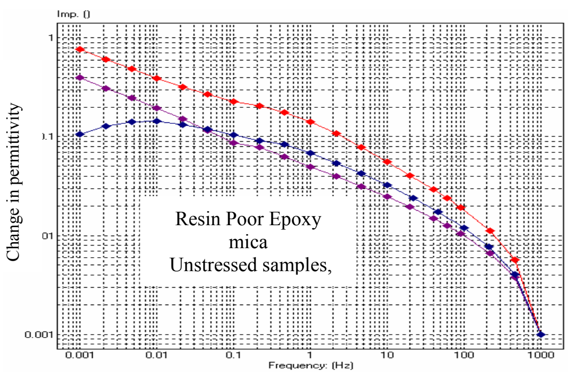

Figure 4: Measured Change in permittivity, ($\Delta\varepsilon$) as a function of frequency

2.3 Dielectric spectroscopy spectra of thermally aged samples

The resin rich epoxy–mica laminate samples of 2 mm thick in two groups 'A' and 'B' were thermally stressed at 473 K for 1000 hours and 5000 hours respectively. Figures 5 and 6 show a comparative plot of the variation of loss factor (tan δ) and complex capacitance, C" (loss) as a function of frequency for samples thermally aged at 473 K for 1000 hours and 5000 hours respectively. The curves at the upper band show the variation for group "B" samples (thermally aged specimens for 5000 hours) while lower band of curves are for group "A" samples (aged for 1000 hours). The degradation as indicated by higher values of tan δ can be distinctly seen with over aged specimens. Dielectric losses are more and steeply increase between frequency of 1 kHz to 1 mHz. The dispersion is much wider at lower of frequencies. Thermal ageing of epoxy insulation promotes irreversible chemical reactions, such as decomposition and oxidation. These changes may create internal voids and or increase in density of polar molecules, resulting in increased dipole polarization and hence higher losses. The shape of frequency dependence of the loss factor can be explained as follows. The dipole processes is increasingly overlapped by the effect of conduction in the resin. At still lower frequencies the barrier effect of the lower conductivity of the organic component manifests itself. Charge is accumulated at the interface and this causes redistribution of the field strength in the composite dielectric and decrease in the resulting conduction.

The dissipation factor measured at 1 kV, 50 Hz using Tan δ and Capacitance bridge instrument was in agreement with the dielectric spectroscopy results. However the values measured at power frequency at higher voltages were much larger due to effects like partial discharge activity etc. From these studies it is concluded that the thermal degradation in epoxy mica samples can be distinctly seen by measuring the loss factor at lower frequencies.

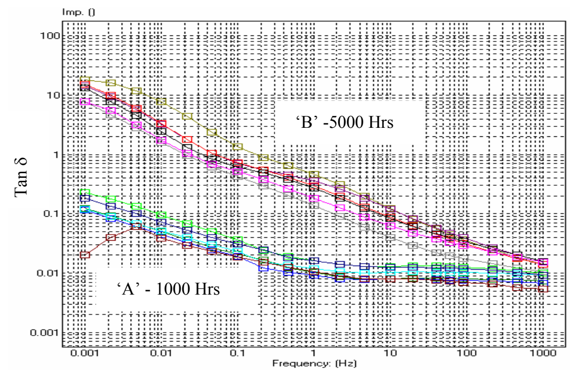

Figure 5: Comparative plot of measured tan δ over the frequency range 1 mHz to 1 KHz, Thermally aged samples (473 K for, 1000 hours and 5000 hours)

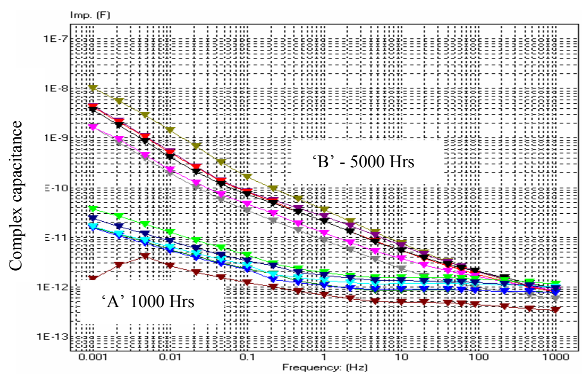

Figure 6: Comparative plot of measured complex Capacitance over the frequency range 1 mHz to 1 KHz Thermally aged samples (473 K for, 1000 hours and 5000 hours)

2.4 Stator winding coils of 6.6 kV Motor

Stator winding of 6.6 kV motor shown in figure 7 were subjected to accelerated electrical and thermal stresses at 5 kV/mm and 473 K for a duration of 1000 hours. Dissipation factor, Power factor and capacitance measurements were conducted in the frequency range 1 mHz to 1 kHz. Figures 8 and 9 show the variation of dissipation factor and capacitance as a function of frequency. The trend observed is similar to the trend observed in case of laminates. One of the coil which failed during power frequency tan δ measurement at 3 kV, has shown a different trend when measured at very low voltage 140 V_{rms} and variable frequency as seen from figure 8. In case of a failed coil, the maxima in tan δ are observed at 10 Hz and decreases below 10 Hz.

Figure 7: A view of motor stator coils under test

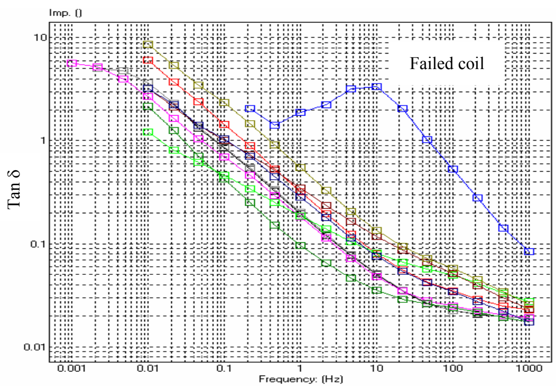

Figure 8: Measured tan δ over the frequency range 1 mHz to 1 KHz, Thermally aged samples (473 K , for 1000 hours)

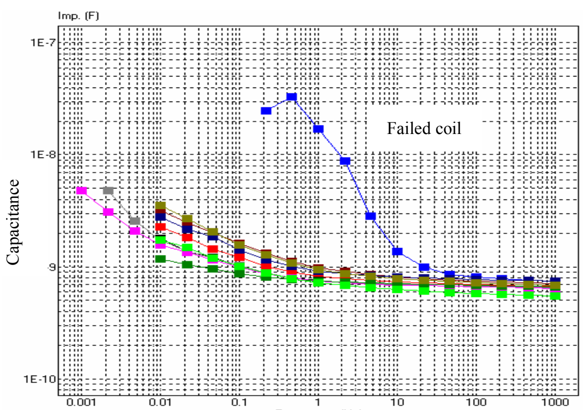

Figure 9: Measured Capacitance . over the frequency range 1 mHz to 1 KHz, Thermally aged Coils (473 K for, 1000 hours)

2.5 Stator winding of 17 MW Generator

Table 2 presents the condition monitoring tests data obtained 17 MW Generator operating in Hydro Power plant. From the table it is seen that the IR & PI values lie in the acceptable range for a 50 years old machine indicating that the stator winding is clean and dry. The DC leakage current characteristics obtained on the stator winding showed the magnitude of the leakage current was

Table 2: Test data on 17 MW Generator

Phase	IR	PI	Tan δ (%) @ 2.2 kV	ΔT (%)	ΔC (%)	PD age (pC)
R	387	3.59	3.083	0.130	0.22	No PD
Y	388	3.80	3.721	0.125	0.20	No PD

small and its variation with the test voltage does not exhibit steep rise as shown in the figure 10. These results further confirm that surface conditions of the stator winding are dry and show moderate ageing of the insulation. Figure 11 shows the measured tan δ as a function of frequency obtained on two phases of the generator winding. The characteristic curve indicates no abnormality.

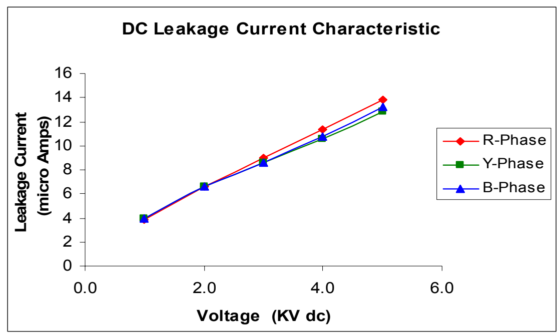

Figure 10: DC leakage current characteristic

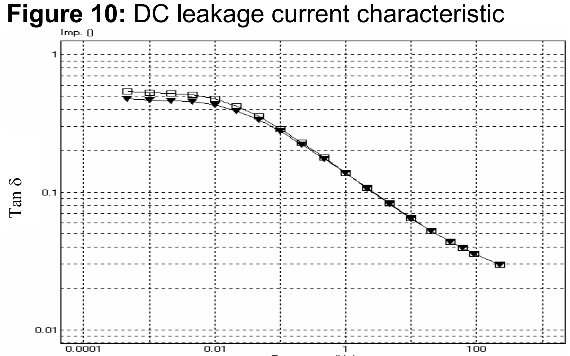

Figure 11: Measured tan δ over the frequency, 17 MW Generator

3 RECOVERY VOLTAGE MEASUREMENTS

Recovery voltage measurement (RVM) technique is another technique which is used to investigate the slow polarization processes, and it is sensitive to larger polar species, associated with thermal ageing while 50 Hz dissipation factor responds to smaller species. RVM method consists of four phases: charging, discharging, measurement and relaxation and analyzing the curve of maximum recovery voltage versus charging time, the so called polarization spectrum. The interpretation of an RVM measurement relies strongly on the identification of maxima in the polarization spectrum. Identifying the insulation problem is based on the analysis of polarization spectrum.

The basic parameters measured during the RVM cycle are V_{max} – the recovery voltage, the maximum of the voltage after open-circuiting the object; t_{peak} – the peak time, the time after open-circuiting the object at which V_{max} occurs; and S_r the initial slope, the slope of the voltage immediately after starting of phase 3. The maximum recovered voltage is used as identifier for insulation ageing. However often such maxima are small, making it difficult to determine the "maximum" is real or must be attributed to disturbances / errors in measurement. In the present investigation apart from polarization spectrum (Plots of V_r vs charging time), Slope spectrum (Sr Vs charging time), time spectrum (t_{peak} vs charging time) and combined spectrum (Max. recovery voltage vs Slope) are used for interpretation of the data.

4 RVM TEST RESULTS

The data discussed below was obtained on Epoxy-mica Resin poor and resin rich samples. The test voltage was 2 kV DC and charging times were 0.02 s, 0.05 s, 0.1s, 0.2 s, 0.5 s …. up to a maximum of 2000 seconds for each RVM cycle.

4.1 RVM spectra of Resin poor unstressed specimens

The RVM data obtained on Resin poor epoxy mica unstressed sample is shown in figures 10 and 11. The polarization spectrum which is a plot of all values in log scale Recovered voltage (Vr) for every charging time is shown in figure 10. Theoretically the spectrum in log scale should clearly depict the dominant peaks. However it is difficult to identify the actual peaks as they are either small or they result due to system disturbances. In order to interpret the RVM data beyond polarization spectrum, additional spectra slope spectrum and peak time spectrum are used. From the slope spectrum shown in figure 11 a peak could be observed at charging times 0.05 seconds. However the time spectrum does not give much information (Figure is not shown). Combining all the three, a plot of initial slope (V/s) against Max. Recovered voltage, Vr (V) is made which is shown in figure 14. From these plots a clear peak in the form of "bun" and "nose" can be distinctly seen which probably could give more information on the bigger polar species and the polarization phenomena.

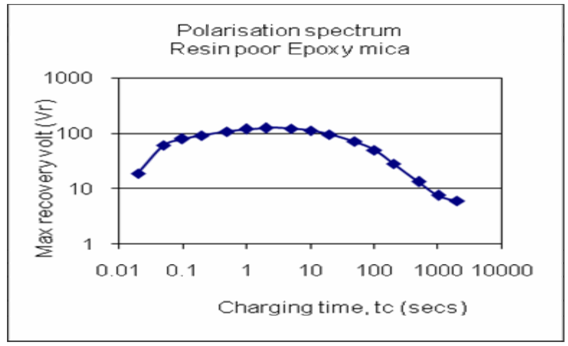

Figure 12: Polarization spectrum in log scale, Resin poor epoxy mica

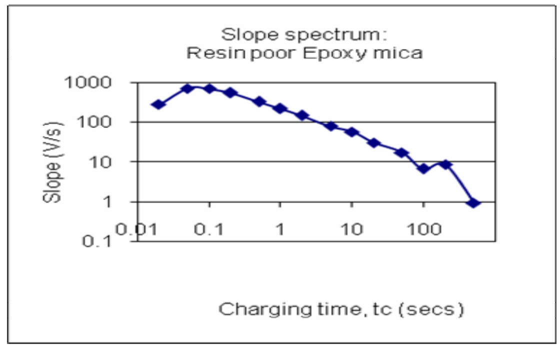

Figure 13: Slope spectrum in log scale Resin poor epoxy mica

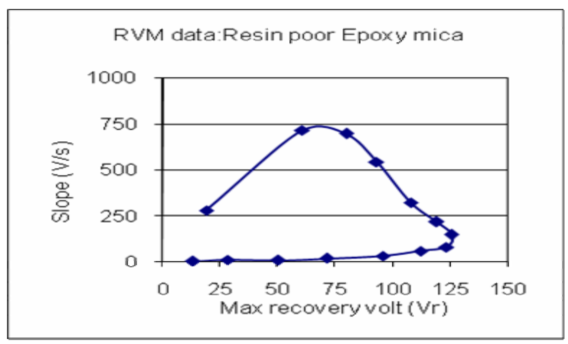

Figure 14: Combined spectrum (Slope Vs Max. recovery voltage), Resin poor epoxy mica

4.2 RVM spectra of Resin rich unstressed specimens

Studies were also made on resin rich epoxy mica system. The plots of polarization spectrum and combined spectrum (plot Vr vs. Sr) are shown in figures 15 and 16 respectively. The dominant peaks could not be identified distinctly from the polarization spectra shown in figures 15. However a sharp peak is seen at 0.05 secs charging time corresponding to a recovery voltage of 10 volts from the combined spectrum (figure 16).

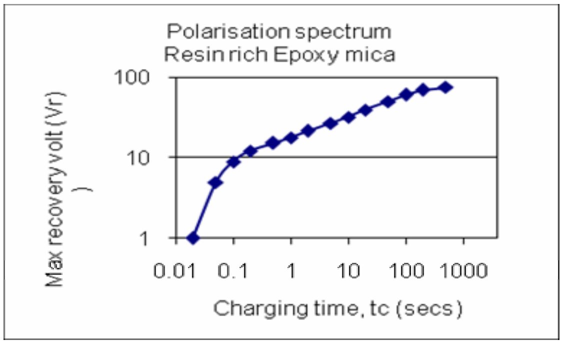

Figure 15: Polarization spectrum in log scale, Resin rich epoxy mica

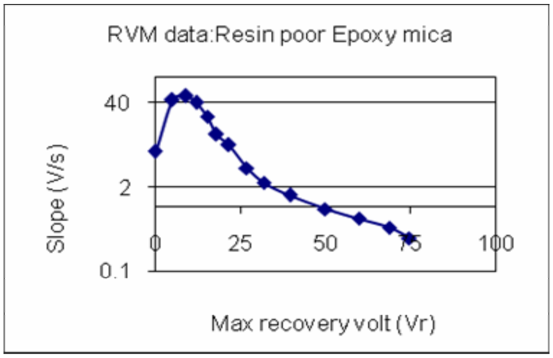

Figure 16: Combined spectrum (Slope Vs Max. Recovery voltage), Resin rich epoxy mica

4.3 RVM spectra of Resin rich thermally degraded specimens

The resin rich epoxy–mica laminate samples of 2 mm thick were thermally stressed at 473 K for 1000 hours and 5000 hours. Figures 17 show the combined spectrum obtained on a sample aged for 1000 hours at 473 K. From the polarization spectrum (fig not shown) there are no dominant peaks which are an indicator of ageing, are seen. However from the combined spectrum shown in figure 17 multiple peaks are distinctly observed which clearly exhibit the degradation phenomena. Thermal ageing of epoxy insulation promotes irreversible chemical reactions, such as decomposition and oxidation. These changes may create internal voids and or increase in density of polar molecules, resulting in increased dipole polarization. Figures 18 present the data obtained on a sample aged for 5000 hours at 473 K. Here again from the combined spectrum distinct peaks are seen which again clearly exhibit the degrading phenomena.

5 CONCLUSIONS

The use of dielectric spectroscopic technique has resulted in a better knowledge of the electrical properties of thermally degraded epoxy – mica stator winding insulation. The dielectric response exhibited by thermally aged epoxy-mica insulation at lower frequencies shows the predominant influence on interfacial polarization on the total dielectric response of epoxy-mica layer. This method could possibly be used to evaluate the condition of the bulk of the insulation and its degree of aging.

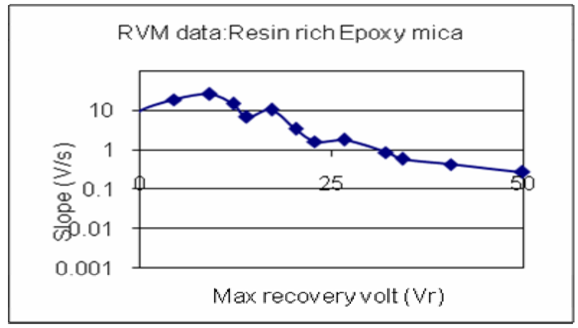

Figure 17: RVM data resin rich laminate, thermally aged 473 K, 1000 hours

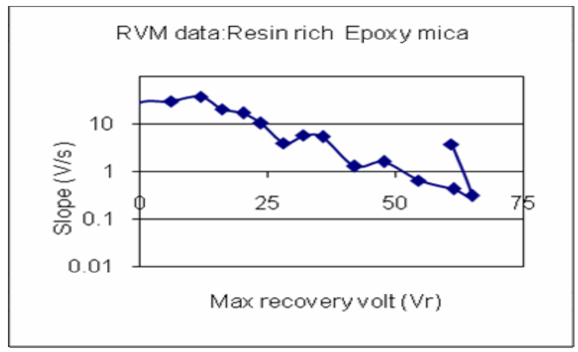

Figure 18: RVM data on resin rich laminate, Thermally aged 473 K, 5000 hours

The insulation ageing and interpretation of an RVM measurement relies strongly on the identification of maxima in the polarization spectrum. The RVM slope spectrum and the combined spectrum (Plot of Max. recovered voltage, Vr versus Initial Slope) are more useful in identifying the dominant peaks. Multiple peaks are seen in case of thermally aged samples, due to irreversible chemical reactions, such as decomposition and oxidation. These changes may create internal voids and or increase in density of polar molecules, resulting in increased dipole polarization.

6 ACKNOWLEDGMENTS

The authors acknowledge with thanks the management of CPRI for the permission given to publish the paper.

7 REFERENCES

[1] J. Ross McDonald, Impedance Spectroscopy Emphasizing Solid Materials and Systems, John Wiley and Sons, New York, 1987

[2] R. Gerhardt, "Dielectric and Impedance spectroscopy J. Phys. Chem. Solids 55, 1994, pp-1491-1506

[3] B. Nageshwar Rao, A. Sudhindra and B. Ramachandra, Low frequency dielectric response of thermally degraded epoxy-mica insulation, ICPDAM, 2009, Harbin, China.