Experience With Return Voltage Measurements for Assessing Insulation Conditions in Service-Aged Transformers

Tapan Kumar Saha, *Senior Member, IEEE*, and Zheng Tong Yao, *Member, IEEE*

***Abstract*—This paper describes the investigation of the insulation condition of a number of power and distribution type transformers of different manufacturing dates and with different operating histories. Return voltage measurements were conducted for these transformers. Effects of moisture and aging on the oilpaper insulation of these transformers were investigated and results are presented in this paper. Moisture in oil samples at known temperature was measured for these transformers. Previously accelerated aging experiments were performed on paper wrapped insulated conductors in different environments over a temperature range of 115 to 145 °C. Results from the measurements on transformers are compared with those of the accelerated aged samples and are described in this paper.**

***Index Terms*—Condition monitoring, dielectric measurement, insulation aging, insulation life, molecular weight, polarization, power transformer, transformer insulation.**

I. Introduction

IN RECENT years, there has been a growing interest in the condition assessment of transformer insulation. Primarily this is due to the increasingly aged population of transformers in utilities around the world. A large proportion of existing power transformers within electric utilities are approaching the end of their design life. Many, perhaps most, seem to be operating satisfactorily. However, insulation degradation continues to be a major concern for these aged transformers. Insulation materials degrade at higher temperatures in the presence of oxygen and moisture. The degradation from thermal stress affects electrical, chemical, and mechanical properties [9].

In our previous research projects, two comparatively new diagnostic techniques were investigated for analyzing the condition of accelerated aged cellulose insulation. These are: interfacial polarization spectra (IPS) measurement by the return voltage (RV) method and measurement of molecular weight distribution by gel permeation chromatography (GPC). The results from these experiments have been presented elsewhere [3], [4], [6]. In our recent research project, accelerated aging experiments were completed under air and nitrogen environments over the temperature range 115–145 °C.

The objectives of these experiments were to study the nature of cellulose and oil degradation, the deterioration of chemical, electrical and mechanical properties and the effect of oxidation on the degradation process. The results have been described in a number of papers [5], [8]. In this research we have also investigated a number of power and distribution transformers of different manufacturing dates with the return voltage measurement technique. Results obtained from these measurements on full transformers will be presented in this paper. A comparison of results with those obtained form the accelerated aging experiments will be also be investigated.

These transformers were owned by local transmission/distribution and generation companies, and hence, we had limited access. For obvious reasons, we did not have any opportunity to open the tanks of these transformers for collecting paper/pressboard samples. Hence, molecular weight measurements by either traditional viscosity measurements (for DP calculation) or by gel permeation chromatography measurements (for molecular weight distribution) were not investigated on any paper/pressboard samples from these transformers. The correlation between RV parameters and the molecular weight measurements based on accelerated aged samples also will be analyzed in this paper to further explain the results obtained from the full-size transformers.

The oil samples were collected from transformer tanks at ambient temperatures and moisture contents of oil samples were measured by the Karl Fischer titration technique. The moisture contents of solid insulation can be estimated by standard equilibrium curves [2]. Some insight into the aging and moisture impacts on RV parameters will be described in this paper.

II. Return Voltage Measurements Theory

When a direct voltage is applied to a dielectric for a long period of time, and is then short circuited for a short period, after opening the short circuit, the charge bounded by the polarization will turn into free charges i.e., a voltage will build up between the electrodes on the dielectric. This phenomenon is called the return voltage. Now, the process of polarization and the equations to describe this process will be described in detail [12], [13].

When a dielectric material is charged with an electric field the material become polarized. The total current density $j(t)$ is the summation of the displacement current density and the conduction current density, which is given by

$$j(t) = \sigma E(t) + \frac{dD}{dt} \tag{1}$$

Manuscript received May 16, 2001; revised April 18, 2002.

The authors are with the School of Information Technology and Electrical Engineering, The University of Queensland, Brisbane, Australia (e-mail: saha@itee.uq.edu.au; zheng@itee.uq.edu.au).

Digital Object Identifier 10.1109/TPRWD.2002.803722

where σ is the dc conductivity, and $D(t)$ is the electric displacement given by (2)

$$D(t) = \varepsilon E(t) + \Delta P(t) = \varepsilon_o \varepsilon_r E(t) + \Delta P(t) \quad (2)$$

where ε_o is the vacuum permittivity, and ε_r is the relative permittivity at power frequency (typically 4.5 for cellulose paper/pressboard and 2.2 for transformer hydrocarbon oil). The term $\Delta P(t)$ is related to the response function $f(t)$ by the convolution integral shown in

$$\Delta P(t) = \varepsilon_o \int_0^t f(t-\tau) E(\tau) d\tau. \quad (3)$$

If we expose the insulation to a step voltage at time $t = 0$ the charging current density is given by

$$j_{\text{polarization}} = E(\sigma + \varepsilon_o f(t)). \quad (4)$$

If we consider the case where an insulation system with geometrical capacitance C_o is exposed to a step voltage, U_a, the charging/polarization current can be given by

$$i_{\text{polarization}} = C_o U_a \left\{ \frac{\sigma}{\varepsilon_o} + f(t) \right\}. \quad (5)$$

If the step voltage is now disconnected from the insulation

$$i_{\text{depolarization}} = -C_o U_a \left\{ f(t) - f(t + t_{\text{charging}}) \right\} \quad (6)$$

gives the discharging/depolarization current. The charging time normally should be at least ten times larger than the time for which the response function is calculated then the second term in (6) can be neglected. Therefore, the response function $f(t)$ becomes proportional to the depolarization current. Hence, the response function and conductivity can be calculated simultaneously by using polarization and depolarization currents. Very often, the response function needs to be expressed in a parameterized form. The response function can be written in the general form

$$f(t) = \frac{A}{(\frac{t}{t_o})^n + (\frac{t}{t_o})^m}. \quad (7)$$

The response function describes the fundamental memory property of any dielectric system and can provide significant information about the insulation material. After opening the short circuit, the charge bounded by the polarization will turn into free charges i.e., a voltage will build up between the electrodes on the dielectric. This phenomenon is the return voltage. The return voltage arises from the relaxation processes inside the dielectric material. The current density during the return voltage measurement is zero and

$$j(t) = \sigma E(t) + \frac{dD}{dt} = \sigma E(t) + \frac{d}{dt}(\varepsilon_o \varepsilon_r E(t) + \Delta P(t))$$
$$j(t) = \sigma E(t) + \varepsilon_o \varepsilon_r \frac{d}{dt} E(t) + \varepsilon_o \frac{d}{dt} \left\{ \int_0^t f(t-\tau) E(\tau) d\tau \right\} \quad (8)$$

gives the expression of current density, where $E(t)$ is the electric field resulting from the return voltage build up across the open circuited dielectric. Equation (8) shows that the return voltage depends on the conductivity σ, relative permittivity ε_r and dielectric response function $f(t)$. These parameters are all affected by aging and moisture in the insulation. The response function can be obtained from the polarization and depolarization currents. These currents depend on the geometric capacitance and on the applied step excitation. The response function and conductivity can be calculated from equations (5) and (6) if the geometric capacitance of the transformer composite insulation C_o is known. If the proper geometry of the transformer oilpaper insulation is known then by solving (8), return voltage for a transformer can be estimated. The return voltage also depends on the applied electric field and if the dielectric material is assumed to be linear this problem is resolved easily for the interpretation of results [7]. A modeling tool can be very useful to investigate the impact of geometry on RV results.

TABLE I
SET OF CHARGING/DISCHARGING TIMES USED FOR RV MEASUREMENT

Charging time (s)	Discharging time (s)
1	0.5
2	1
4	2
8	4
Continued until peak value of the max. RV is obtained	

III. RETURN VOLTAGE MEASUREMENTS TECHNIQUE

An automatic experimental set up was developed and implemented to measure the return voltage of a two terminal dielectric system [8]. The charging voltage was 1000 V dc. Adsorbed moisture and temperature of the oilpaper insulation affect the return voltage measurement. Therefore, the return voltage measurement was always conducted at ambient environmental conditions (20–30°), and after each measurement, the moisture content of the oil was measured with known oil sampling temperature. Our experience suggests that RV measurement result is not very reproducible at relative humidity above 70%. To eliminate this problem, all measurements were conducted at ambient condition of lower than 70% relative humidity. One thousand volt dc was applied for a preselected charging time between shorted primary terminals and shorted secondary terminals. Then, the dc supply was turned off and the shorted primary–secondary terminals were short circuited together to discharge through ground for a preselected time. After this discharge time, the short circuit was removed and the open-circuit voltage between the shorted primary and secondary side was measured. This voltage is the return voltage.

As interfacial polarization is predominant at longer time constants, the spectrum of the return voltage was investigated by changing the charging and discharging times over a range of times greater than 0.5 s until the peak value of the maximum return voltage was obtained. The ratio of charging and discharging time was two [11]. Table I shows a set of charging and discharging times used for RV measurement.

A typical return voltage wave shape from a retired 25-MVA transformer is shown in Fig. 1. The relevant parameters (maximum return voltage, initial slope and central time constant—the

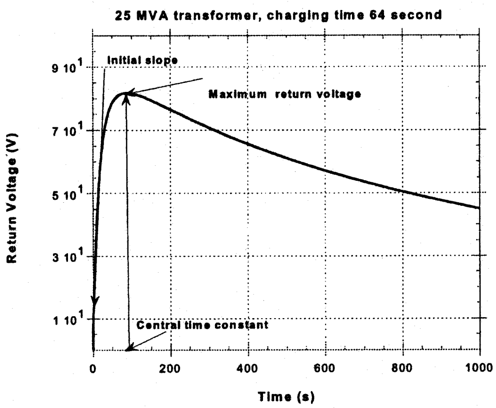

Fig. 1. Typical return voltage wave shape from a retired transformer.

TABLE II
DETAILS OF THE TRANSFORMERS INVESTIGATED

Identity No	Capacity MVA	HV KV	LV KV	Year of Manufacture
T1	1	10.5	0.415	1952
T2	1.5	33	11	1955
T3	1.5	33	11	1955
T4	1.5	33	11	1966
T5	2	11	3.3	1953
T6	3.15	11	3.3	1993
T7	5	33	11	1960
T8	5	33	11	1965
T9	5	33	11	1966
T10	10	33	11	1983
T11	25	33	11	1997
T12	145	295	13.8	1971 (new*)

time at which the return voltage is maximum) are identified in Fig. 1. Initial slope is the slope of the return voltage graph (with linear approximation) for first few seconds.

Then the spectra of maximum return voltage and the initial slope were plotted versus the central time constant (the time at which the return voltage is maximum). The peak value of the maximum return voltage (from the return voltage spectrum) and the corresponding initial slope (from the initial slope spectrum), along with central time constant (from either of the spectrum), are the parameters used to assess the insulation condition from the return voltage measurements [6], [7], [11]. Details of the transformers tested are shown in Table II.

IV. RESULTS

A. Transformers of Ratings 1–1.5 MVA

Return voltage measurements were carried out on four transformers of ratings up to 1.5 MVA. They are identified as T1, T2, T3, and T4 in Table II. The spectra of maximum return voltage and initial slopes for transformers T1–T4 are presented in Figs. 2 and 3, respectively. Summary results from the RV spectra measurements (from Figs. 2 and 3) are presented in Table III.

It can be observed from Table III that there was a considerable variation in peak maximum return voltage for different transformers. Two transformers (T2 and T3) of the same rating

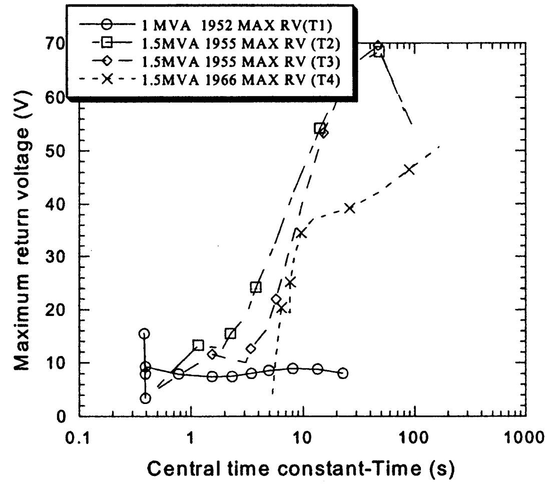

Fig. 2. Spectra of maximum return voltage for transformers T1–T4.

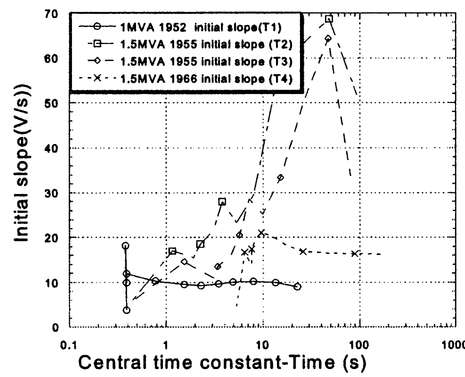

Fig. 3. Spectra of initial slopes for transformers T1–T4.

TABLE III
SUMMARY RESULTS OF RV MEASUREMENTS FROM TRANSFORMERS T1–T4

Transfor mer	Peak max. Return voltage (Volt)	Central Time Constant (s)	Initial Slope (Volt/s)	Oil Water Content (PPM)	Temp. Oil Sample (°C)
T1	15.5	0.4	18	40	30
T2	69	48	69	27	31
T3	70	47	64	28	34
T4	51	164	16	24	30

and age (based on the manufacturing year of 1955) produced almost identical return voltages.

Fig. 2 and Table III show that the variation of the central time constant for different transformers is very significant. For transformer T4, the central time constant is 164 s (still rising), and for transformers T2 and T3, it is only 48 and 47 s, respectively, whereas for transformer T1, it is only 0.4 s. In general, the central time constant decreases sharply with aging and moisture content [5]–[7]. However, the individual impact of moisture and aging on RV result cannot be predicted from this result. T1 has higher moisture content compared to the other three transformers. In particular, for the oldest transformer T1 (based on manufacturing date), the central time constant dropped sharply.

Table III shows that the variation of the initial slopes for different transformers is also very significant. From the results, it is also clear that peak maximum return voltage and initial slope have some dependency on the rating of the transformer (for different geometric capacitance and insulation resistance).

It has been reported by Gafvert *et al.* [12] that the geometric capacitance of a core type transformer can be estimated by the cylindrical capacitance as given in (9), shown below, where h is the average winding height and r_a and r_b are, respectively, the inner and outer radius of the insulation between windings. If the design of the transformers insulation is available, the geometric capacitance can be calculated. Otherwise, geometric capacitance can be estimated by measuring the capacitance between the measured electrodes (same as during RV measurements) and dividing by the effective permittivity of the combination of materials. From (9)

$$C_o = \frac{\varepsilon_o 2\pi h}{\log(r_b/r_a)} \tag{9}$$

it is observed that the geometric capacitance varies with the insulation structure, which is dependent on the MVA rating. We did not measure capacitance during RV measurement and the design of these transformers was not available. Therefore, we find it hard to compare the initial slope result of a 1-MVA transformer to those of 1.5-MVA transformers without any normalization. A modeling tool can help to explain this problem and we are investigating this in our current research project. T2 and T3 showed almost identical results in all respects, including the oil moisture content. However, T4 shows lower peak maximum return voltage, lower initial slope and longer central time constant compared with those of T2 and T3. T4 has slightly lower moisture content compared to T2 and T3. Their oil sampling temperatures were also in a similar range (30–34 °C). Finally, it can be concluded that transformer T1 shows a combined high level of insulation degradation and high moisture level. Similarly T2 and T3 in the 1.5 MVA group have shown relatively higher insulation degradation and slightly higher moisture level compared to T4. As mentioned previously, the RV parameters change due to moisture and aging. The moisture content of oil samples shows this dependency. However, the direct impact of aging on RV parameters cannot be quantified based on this measurement results. For this reason a number of authors suggested some form of equivalent moisture content due to the combined effect of moisture and aging [11]. We are currently conducting a group of experiments to separate the impact of aging and moisture on RV parameters. Hopefully, some preliminary findings will be reported in the CIGRE 2002 Paris Session.

B. Transformers of Ratings 2–5 MVA

Return voltage measurements were carried out on five transformers of ratings between 2–5 MVA and are identified as T5, T6, T7, T8, and T9. The spectra of maximum return voltages and initial slopes for transformers T5 and T6 are presented in Figs. 4 and 5, respectively. The spectra of maximum return voltages and initial slopes for transformers T7–T9 are presented in Figs. 6 and 7, respectively. Summary results from the RV spectra measurements (from Figs. 4–7) are presented in Table IV.

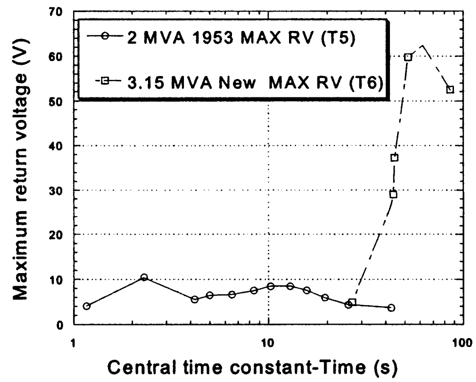

Fig. 4. Spectra of maximum return voltage for transformers T5 and T6.

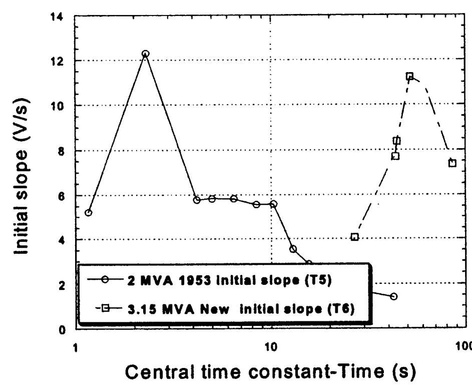

Fig. 5. Spectra of initial slopes for transformers T5 and T6.

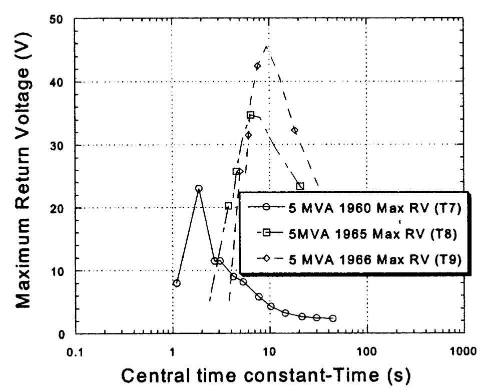

Fig. 6. Spectra of maximum return voltage for transformers T7–T9.

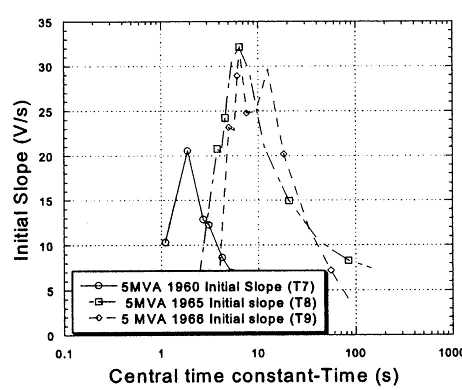

Fig. 7. Spectra of initial slopes for transformers T7–T9.

TABLE IV
SUMMARY RESULTS OF RV MEASUREMENTS FROM TRANSFORMERS T5–T9

Transformer	Peak max. Return voltage (Volt)	Central Time Constant (s)	Initial Slope (Volt/s)	Oil Water Content (PPM)	Temp. Oil Sample (°C)
T5	10.5	2.3	12.3	18	32
T6	62.3	62	11	28	30
T7	23	1.9	20.5	23	28
T8	34.7	6.4	32	13	28
T9	45	9.4	25	13	28

It would appear from Table IV that the 45-yr-old 2-MVA transformer (T5) shows a significant degradation with a very small central time constant compared to a 5-yr-old transformer of 3.15 MVA (T6). The spectra of the two transformers (T5 and T6) are altogether different. As mentioned previously, the maximum value of return voltage is dependent on the rating of the transformer as well as the insulation resistance of the transformer. With these limited measurements, it is difficult to comment on the variation of peak maximum return voltage magnitude. The initial slope is also dependent on the corresponding maximum voltage and we find it difficult to compare initial slope of one transformer with other transformers of different ratings.

Moisture content of oil from transformer T5 was lower than that of T6. The temperature of oil sampling was not very different. Hence, the moisture in paper insulation in T6 was higher than that of T5. RV results provide information about the status of aging of the insulation as well. Although it is commonly believed that RV results are predominantly influenced by moisture content, our findings suggest that moisture definitely has a strong impact on RV results. At the same time, the influence of aging products on RV results cannot be ignored. Higher aging in T5 shows the lower central time constant compared to T6. Here the aging impact might be more pronounced than the moisture impact.

The three transformers of 5-MVA rating (T7, T8, and T9) were all in service for more than 30 yr. They all showed very small central time constants and large initial slopes. Inter-comparison between the three 5-MVA transformers showed that the 1960 made transformer (T7) had the lowest central time constant followed by the T8 and T9 transformers.

However, the initial slopes are all very high compared to the five year old transformer T6 and do not show any trend. The peak values of the maximum return voltage also do not show any trend. Overall, transformers T5, T7, T8, and T9 have very degraded insulation condition and need refurbishment to improve the status of insulation. Once again, the moisture in oil for T8 and T9 were much smaller than T7. However, the RV results were not much different than T7. This again suggests that aging also has a strong impact on RV results.

C. Transformers of Ratings 10 and 25 MVA, 33/11 kV

Two transformers of 10 and 25 MVA were tested with RV measurements, they are identified as T10 and T11. T10 was a 15-year-old transformer, while T11 was a new transformer. The

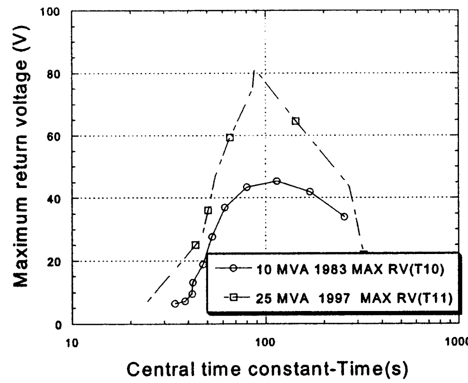

Fig. 8. Spectra of maximum return voltage for transformers T10 and T11.

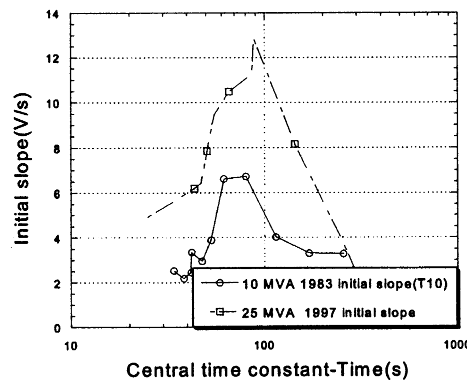

Fig. 9. Spectra of initial slopes for transformers T10 and T11.

TABLE V
SUMMARY RESULTS OF RV MEASUREMENTS FROM TRANSFORMERS T10 AND T11

Transformer	Peak max. Return voltage (Volt)	Central Time Constant (s)	Initial Slope (Volt/s)	Oil Water Content (PPM)	Temp. Oil Sample (°C)
T10	45.3	114.6	4.0	8	33
T11	82	88	13	22	30

spectra of maximum return voltage and initial slopes for transformers T10 and T11 are presented in Figs. 8 and 9 respectively. Both the transformers were 33/11 kV. Summary results from the RV spectra measurements (from Figs. 8 and 9) are presented in Table V. Results from Figs. 8 and 9 and from Table V suggest that the 25-MVA new transformer (T11) has a large maximum return voltage compared to the 10-MVA 15-year old transformer (T10), but their central time constants are in a similar range. However, as the initial slopes are dependent on their peak maximum return voltages, they do not show any specific trend.

Although T10 was 15 yr old, the moisture content of oil was also found to be very low. Usually, we expect to have several hundred seconds of central time constant for a new transformer with low moisture content.

This suggests some aging products may have affected the time constant of T10. Transformer T11 was never placed in service and the insulation system was expected to be in very good

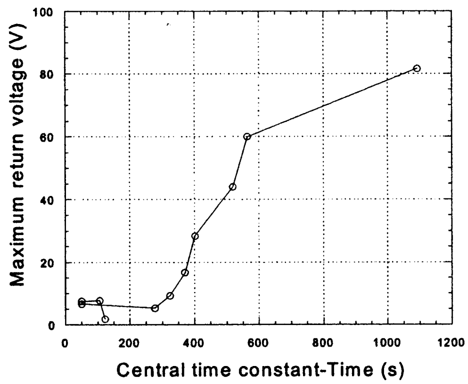

Fig. 10. Spectra of maximum return voltage of 145-MVA transformer (T12).

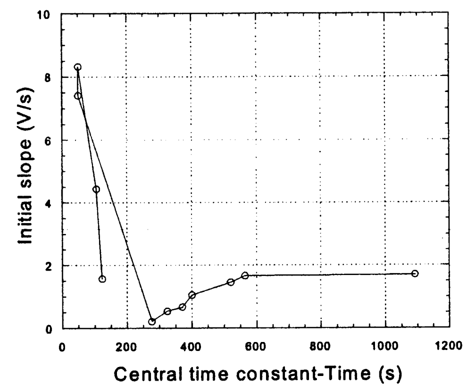

Fig. 11. Spectra of initial slope of 145-MVA transformer (T12).

TABLE VI
SUMMARY RESULTS OF RV MEASUREMENTS FROM TRANSFORMER T12

Transformer	Peak max. Return voltage (Volt)	Central Time Constant (s)	Initial Slope (Volt/s)	Oil Water Content (PPM)	Temp. Oil Sample (°C)
T12	81.5	1093	1.7	8	25

condition. The central time constant of this transformer might have been affected by improper drying of the insulation.

D. Return Voltage Measurement on a 145-MVA Transformer

The rating of the transformer (T12) is 145 MVA and voltage rating is 13.8/295 kV. The year of manufacture was 1971. The transformer was in operation for more than 25 yr. After a failure, the windings of the transformer were replaced by new ones and the old oil has been replaced with new oil. The RV measurement was carried out for the bulk insulation between the primary and the secondary windings.

The spectra of maximum return voltage and initial slopes for transformer T12 are presented in Figs. 10 and 11. Summary results from the RV spectra measurements (from Figs. 10 and 11) are presented in Table VI.

In the graph of maximum return voltage versus central time constant spectra shown in Fig. 10, it can be seen that there is a small step at around 105 s. This can also be observed in the graph of initial slope versus central time constant spectra in Fig. 11. After this initial step (as shown in Fig. 10), the return voltage maximum value continues to rise. In fact, the return voltage was still rising after 1000 s charging.

As the trend was clearly defined, after 1000 s charging the measurement was finally stopped. This transformer has not been in operation after rewinding. Previously we have experienced similar unstable results when the oil and paper equilibrium has not been properly achieved. This initial step presumably was from insufficient oil and paper equilibrium. This does not show any evidence of degradation within the transformer.

Among the RVM parameters, the initial slope at peak maximum return voltage is 1.7 V/s. This is much smaller than the normal initial slope (as measured from a number of new and old transformers). From the RV parameters and spectra in Figs. 10 and 11, the insulation paper has shown no degree of degradation. The oil moisture content is measured and is only 8 PPM. Since the initial slope is very low and the central time constant is high (comparable with the usual several hundred seconds for a new insulation), the general paper insulation conditions in these windings show no evidence of degradation.

From the RVM spectra, it is observed that the insulation between the winding is not associated with any degradation (as expected). This result would be of great interest to compare with other similar size and aged transformers as well as with measurements of this transformer after several years in service.

From the analyses in this section, central time constant has been consistently found to vary with moisture and aging. As mentioned previously, RV peak maximum voltage and initial slope depends on the rating of the transformer and hence need further investigation. Similarly the separate impact of aging and moisture on RV parameters needs to be investigated.

V. COMPARISON WITH ACCELERATED AGING RESULTS

In our present research project, accelerated aging experiments were conducted under air and nitrogen environments over the temperature range 115–145 °C [8]. In these experiments, two insulated conductors were placed side by side to form the test specimen, the thickness of paper insulation between the conductors was 1.0 mm. The insulation structure was different from a full size transformer. This means the capacitance of the sample would be different than that of the full size transformer. Therefore, we will not compare peak maximum return voltage and initial slope. The central time constant has been the most significant parameter, which showed most consistency in explaining the conditions of different transformers insulation. Therefore, an attempt will be made to compare the RV results (particularly central time constants) from full size transformers with those of accelerated aging experiments.

It was observed that the variation of the central time constant for different aging times was very significant for air aging. Initially up to 14 days at 145 °C aging, the central time constant was many hundreds of seconds, while it became only a few seconds after 21 days of aging in the presence of air. In general, the central time constant decreased sharply with respect to aging time. In particular, after 21 days, the central time constant dropped sharply. At 135 °C up to 12 days aging, the central time constant was several hundred seconds, while it became only a few seconds after 37 days of aging in the presence of air. In contrast, it was found that the central time constant was unaffected by aging in nitrogen. The most degraded samples (similar two conductors side by side forming the specimen) from a 25-yr-old transformer showed central time constants in the range of 20 to 35 s [7]. A good replication of the insulation condition in the aged transformer was observed for high temperature aged samples of the insulated conductor for 21 days of aging at 145 °C, for 37 days of aging at 135 °C, for 67 days of aging at 125 °C and for 125 days of aging at 115 °C in the presence of air.

Transformer T12 (145 MVA) had a central time constant of 1093 s. This is comparable to unaged samples. While transformers T1, T5, T7, T8 and T9 had central time constants in the range of 0.4 to 10 s. These time constants were even smaller than the corresponding times for 21 days of aging at 145 °C, for 37 days of aging at 135 °C, for 67 days of aging at 125 °C and for 125 days of aging at 115 °C in the presence of air. These transformers had significant degradation in their insulation systems. While transformers T2 and T3 have central time constants in the range 45–60 s. This group of transformers has shown some degree of degradation and still can be used after proper refurbishment. Transformer T4 has a central time constant of 164 s. The insulation conditions can be predicted as good, while some moisture trapping might have affected the central time constants to lower values than several hundred seconds, as would be expected for new insulation systems.

Our experience with the accelerated aging of paper wrapped insulated conductors has been reported previously [6], [7]. These findings were somewhat different than those found with the full size transformers due to the influence of size/ratings. In the case of paper wrapped insulated conductors, both the initial slopes and central time constants were found to be very sensitive to aging. The samples were identical in geometry. The samples geometry did not have any impact on the results. The geometric capacitance and the insulation resistance were the same for all samples during unaged state. The experiments were conducted under controlled conditions. However, the transformers were of different ratings and have different geometric insulation resistance and capacitance at the unaged state. As a result, the return voltages and corresponding initial slopes were all different for different ratings. We are currently investigating this by developing a modeling tool.

As mentioned previously, DP measurement has been commonly used by utility engineers for assessing insulation condition in aged transformers. DP provides intrinsic strength of the insulation paper. The major drawback with this measurement is that paper samples need to be taken from the transformer tank. As we have performed lots of molecular weight measurements on accelerated aged samples it would be worthwhile to examine the correlation between molecular weight measurements by gel permeation chromatography with the RV measurements on accelerated aged samples obtained from our experiments. As the paper sample degrades due to thermal and oxidative degradation, a number of polar by products are produced. These polar functionalities are expected to change the RV spectra parameters. As we have reported earlier, the significant changes were observed on central time constants (time to peak maximum return voltage) and initial slopes. The molecular weight was found to drop significantly due to cleavage of the chain between glucose rings in the paper polymer due to thermal and oxidative degradation. So it may be worthwhile to investigate the correlation between the results from RV and molecular weight measurements from the accelerated aged samples.

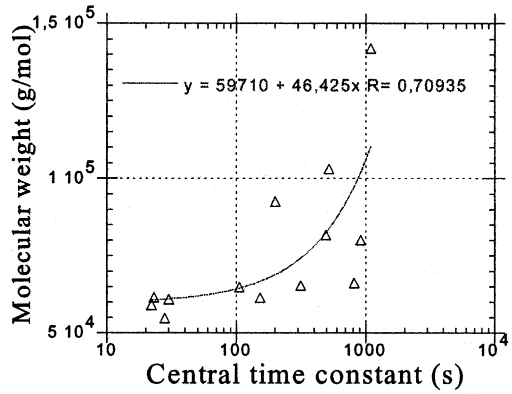

Fig. 12. Correlation between central time constants and molecular weights of samples aged under air.

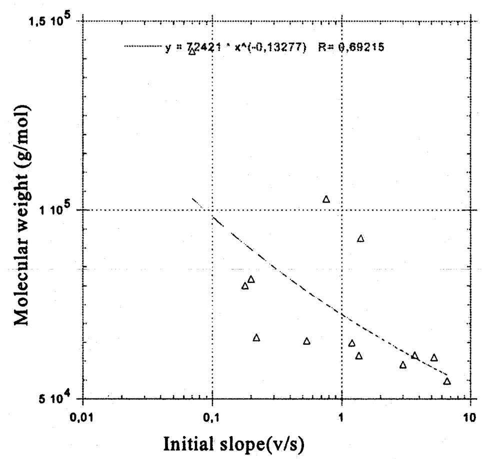

Fig. 13. Correlation between initial slopes and molecular weights of samples aged under air.

Fig. 12 shows the correlation between the molecular weight and central time constants for air-aged samples. Although there are few scatter points, which is a clear indication of some relationship exists between the two parameters. As the central time constant increases logarithmically, the molecular weight increases. Similarly, Fig. 13 shows the correlation between initial slopes and molecular weight. Once again, some relation exists between the parameters. As expected the initial slope is higher for degraded samples with lower molecular weight, and initial slope is smaller for unaged samples with higher molecular weight. Without much reservation, it can be said that some relationships exist between the RV parameters and molecular weights.

VI. Conclusions

Return voltage measurements have been applied to a number of power and distribution transformers. The RV parameters are found to vary significantly and consistently with the aging condition of insulation systems as well as with moisture levels.

Among RV parameters, a central time constant has been found to be the most sensitive to aging and moisture. While the peak maximum return voltage and initial slope are dependent on the geometry of the insulation, it was difficult to compare these for different ratings of transformers. For the same rating transformer the initial slope was found to be easy to compare.

Some fingerprints from RV measurements will definitely help to standardize the interpretation procedure. Our recommendation is in favor of "central time constant," which can be used for assessing the condition of aged insulation in power transformers. Moisture content of oilpaper insulation was found to have a strong impact on RV results. Based on accelerated aged samples, we have also established that RV parameters have strong correlation with molecular weight of cellulose insulation. The problem with full-size transformers remains the lack of paper samples and that was the only reason molecular weight measurement by viscosity (to find DP) or by GPC was not possible to investigate. The question of separation of moisture and aging impacts on RV results still remained unanswered. We are currently investigating this phenomenon and findings from this study will help to interpret RV results more accurately.

REFERENCES

[1] M. Darveniza, T. K. Saha, D. J. T. Hill, and T. T. Le, "Investigation into effective methods for assessing the condition of insulation in aged power transformers," *IEEE Trans. Power Delivery*, vol. 13, pp. 1214–1223, Oct. 1998.

[2] Y. Du, B. C. L. Zahn, A. V. Mamishev, and S. R. Lindgren, "Moisture equilibrium in transformer paper–oil systems," *IEEE Electr. Insul. Mag.*, vol. 15, no. 1, Jan./Feb. 1999.

[3] D. J. T. Hill, T. Le, M. Darveniza, and T. K. Saha, "A study of degradation of cellulosic insulation materials in a power transformer—Part 1: Molecular weight study of cellulose insulation paper," *Polymer Degradation Stability*, vol. 48, no. 1, pp. 79–87, 1995.

[4] ——, "A study of degradation of cellulosic insulation materials in a power transformer—Part 2: Tensile strength of cellulose insulation paper," *Polymer Degradation Stability*, vol. 49, no. 3, pp. 429–435, 1995.

[5] T. K. Saha, Z. T. Yao, T. Le, M. Darveniza, and D. Z. T. Hill, "Investigation of interfacial polarization parameters for accelerated aged oil–paper insulation samples and its correlation with molecular weights and furan compounds," in *Proc. CIGRE Session*, Paris, France, Aug. 27–Sept. 2, 2000, Paper 15-201.

[6] T. K. Saha, M. Darveniza, D. J. T. Hill, and T. T. Le, "Electrical & chemical diagnostics of transformers insulation, Part B: Accelerated aged insulation samples," *IEEE Trans. Power Delivery*, vol. 12, pp. 1555–1561, Oct. 1997.

[7] ——, "Electrical & chemical diagnostics of transformers insulation, Part A: Aged transformers samples," *IEEE Trans. Power Delivery*, vol. 12, pp. 1547–1554, Oct. 1997.

[8] T. K. Saha, M. Darveniza, D. J. T. Hill, Z. T. Yao, and G. Yeung, "Investigating the effects of oxidation and thermal degradation on electrical and chemical properties of power transformers insulation," *IEEE Trans. Power Delivery*, vol. 14, pp. 1359–1367, Oct. 1999.

[9] D. H. Shroff and A. W. Stannett, "A review of paper aging in power transformers," *Proc. Inst. Elect. Eng. C*, vol. 132, no. 6, pp. 312–319, Nov. 1985.

[10] J. Unsworth and F. Mitchell, "Degradation of electrical insulation paper monitored using high performance liquid chromatography," in *Proc. 2nd Int. Conf. Properties Applications Dielectric Mater.*, Beijing, China, Sept. 12–16, 1988, pp. 337–340.

[11] A. Bognar *et al.*, "Diagnostic tests of high voltage oil–paper insulating systems (in particular transformer insulation) using DC dielectrometrics," in *CIGRE Session*, Paper 15/33-08.

[12] U. Gafvert *et al.*, "Modeling of dielectric measurements on power transformers," in *Proc. CIGRE Session*, Paris, France, Aug. 30–Sept. 5, 1998, Paper 15-103.

[13] A. K. Jonscher, *Dielectric Relaxation in Solids*. New York: Chelsea Dielectrics, 1984.

Tapan Kumar Saha (SM'97) is a Senior Lecturer with the School of Information Technology and Electrical Engineering, University of Queensland, Brisbane, Australia. His research interests include power systems and condition monitoring of electrical equipment.

Dr. Saha is a Chartered Professional Engineer of the Institution of Engineers, Australia.

Zheng Tong Yao (M'96) received the B.E. degree in electrical engineering from the James Cook University of North Queensland, Townsville, Australia, and the M.S. degree from the University of Queensland, Brisbane, Australia. Presently, he is pursuing the Ph.D. degree with the School of Information Technology and Electrical Engineering, University of Queensland.