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Quality Assurance after Transformer Refurbishment by means of Polarisation Depolarisation Currents Analysis

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***Abstract*— This paper presents the result of Polarisation Depolarisation Currents (PDC) Analysis on two identical 10 MVA, 132/66-33/11 kV, 3ϕ separate-winding transformers after on-site refurbishment. It intends to show the achievement of the process in the form of dielectric properties evaluated by this new diagnostic tool. The paper demonstrates how the quality of oil and paper between each pair of windings can be assured by the technique.**

***Index Terms*--Complex capacitance, diagnostics, dissipation factor, insulation resistance, moisture in pressboard, oil conductivity, polarisation depolarisation current analysis, polarisation index, recovery voltage, refurbishment.**

I. Introduction

POWER transformers more than 30 years old in Australia and New Zealand are targeted for insulation refurbishment. At this age the process includes not only oil reclamation or oil replacement but in many cases paper dry out as well. Services in the market can be chosen from on-site or workshop process to on-line or off-line system. While the decision of what to be done on the transformer is based on its insulation condition and network requirement, the consideration of the process or the service depends on cost, quality and timeliness. It is the quality of refurbishment that maintains or increases the value of this asset, the transformer, which leads to the network reliability and availability.

The two identical 10 MVA, 132/66-33/11 kV 3ϕ separate-winding, free-breathing type transformers presented in this paper were manufactured in 1966 and were in service at the same substation. The moisture in oil of both units during the period of 1985-1997 had an average value of 16 ppm. Other oil test results were acceptable. In 1998 these two units were made redundant due to substation uprating and were kept in outdoor storage more than 3 years before being allocated to another substation. The oil tests prior to the installation revealed high water ingress during the storage. The moisture in oil was 66 ppm for Transformer No. 1 (T1) and 34 ppm for Transformer No. 2 (T2). On-site refurbishment including hot air and vacuum dehydration was applied which could remove about 200 litres of water from T1 and about 50 litres of water from T2. In order to verify insulation quality after the refurbishment, the new on-site off-line non-destructive technique called **P**olarisation **D**epolarisation **C**urrent (PDC) Analysis [1]-[6] was applied for thorough insulation analysis.

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II. PDC Analysis and The Measured Results

The purpose of PDC analysis, the measurement and the measured results are as follows:

A. Purpose of PDC Analysis

- PDC Analysis measures the actual currents during and after a dc step voltage application (Fig. 1) through the selected insulation system such as the insulation between windings. It gives the condition of oil in the main duct between the windings as well as the condition of the oil-impregnated pressboard and paper. The result of insulation properties can be easily obtained, at the end of PDC measurement when the data is evaluated.
- PDC Analysis gives the result of moisture in transformer pressboard in % by weight. Reference [3] reports that the moisture in solid insulation evaluated by PDC Analysis has a good correlation with the results of Karl-Fischer Titration and Dew Points measurements. The information of moisture in the insulating paper is useful in determining network reliability. If moisture in pressboard is higher than 3%, there is a risk of bubble formation due to sudden increases in load or when the transformer is supplying fault current.
- PDC Analysis can easily identify whether the cause of insulation trouble is due to conduction (such as free water) or polarisation (polar aging molecules dissolved in the oil).
- PDC Analysis Results include oil conductivity, complex capacitance and dissipation factor in frequency domain, insulation resistance together with polarisation index and the evaluation of recovery voltage polarisation spectrum.

B. PDC Measurement

For each transformer, the arrangement of windings starting from the core are: the 11 kV or low voltage winding (LV), the 33 kV or medium voltage winding (MV) and the 132 kV or high voltage winding (HV). For PDC measurement, two test arrangements were carried out for each transformer:

- HV-MV: The insulation between HV and MV.
- MV-LV: The insulation between MV and LV.

Figure 1 shows the principle of the measuring technique [5]. In this test, the insulation between windings (HV-MV or MV-LV) was charged by the dc voltage step of 500 V. A long charging time is required in order to assess the solid insulation. For each test, the polarisation current (or charging current) was measured continuously for 10,000 s. The tank was directly earthed and excluded from the current measuring circuit. In this connection, the polarisation current was the combination of the absorption current (due to polar aging molecules dissolved in the oil) and the conduction current (mostly caused by free water).

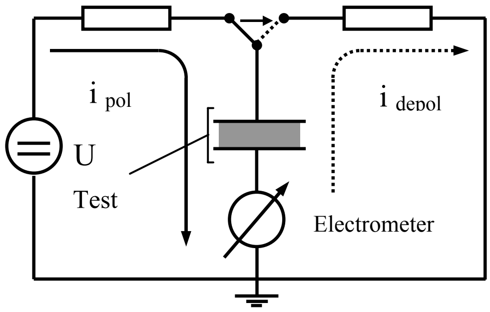

Fig. 1. Principle of test arrangement for PDC measuring technique [5]

At the end of the preset charging time, the circuit was automatically switched over to disconnect the insulation from the dc supply and replaced with a short-circuit for another 10,000 s. The discharging current measured during this duration consists only of the absorption current as conduction current exists only when there is power supply. The absorption current during the first part of the discharging (or depolarisation) period has the same magnitude as the absorption current during the polarisation, but with reverse polarity. If the insulation system is dry, the conduction current will be very small. The polarisation current and the depolarisation current will then be nearly equal within about 1/10 of the charging period.

C. PDC Measurement Results

The measured polarisation and depolarisation currents (sometimes called relaxation currents) of T1 and T2 are shown in fig. 2. The initial time dependence of these relaxation currents (<100 s) is very sensitive to the conductivity of the oil while the moisture content of pressboard influences mainly the shape of the current at much longer time [5]. The currents at the longer time e.g. >1,000 s (during which strong interfacial polarisation at the interface between oil gaps and pressboard barriers is built up) are always lower than the currents at the initial time. This is due to the fact that the insulation resistance of the paper, in spite of very high moisture, is always higher than the insulation resistance of the oil.

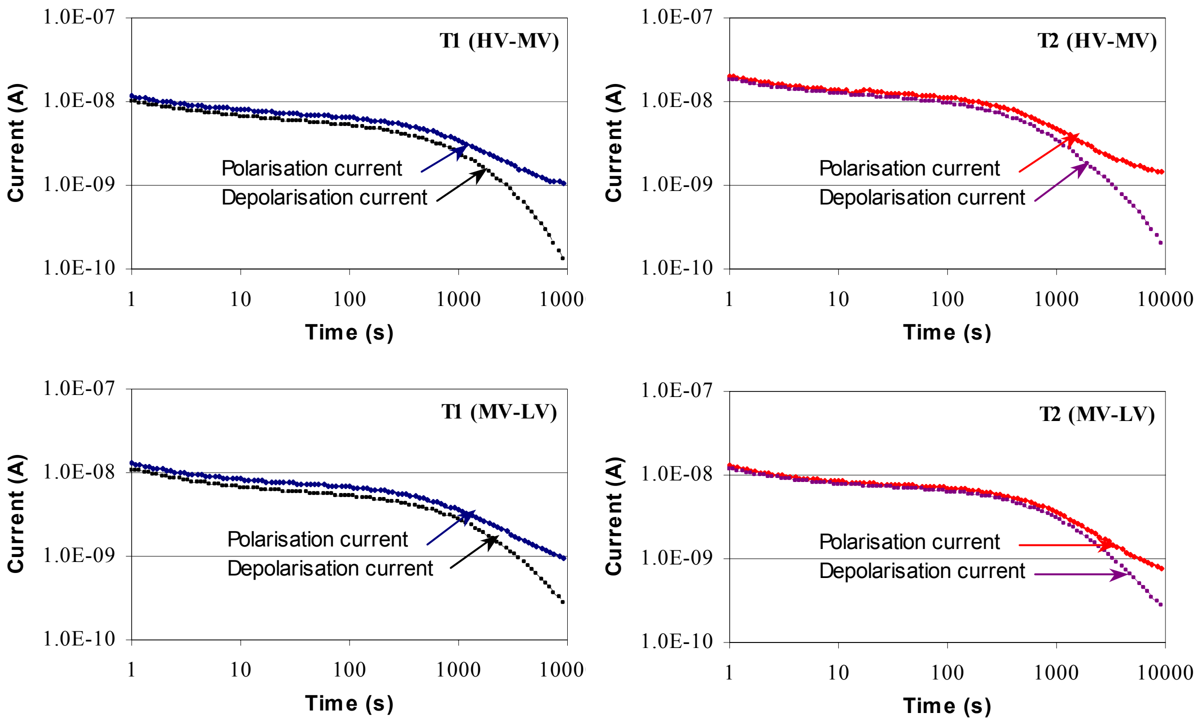

Fig. 2. The Measured Polarisation Depolarisation Currents of Transformer No.1 (left) and No.2 (right) after Refurbishment.

In Fig. 2, the polarisation current and the depolarisation current up to 100 s of T1 have more differences in magnitude while the polarisation current and the depolarisation current within 100 s of T2 are nearly equal. This means the oil in T1 was more influenced by conduction (water content) rather than polarisation processes (polar molecules) but for T2, the dominant cause of oil aging was polarisation rather than conduction.

In addition, the relaxation currents at initial time of T1 are slightly lower than the currents at initial time of T2 in spite of higher temperature during the measurement (data in Table I). This reflects the better quality of oil in T1 than the oil in T2.

D. Evaluation of the Measured Results

From the measured relaxation currents; oil conductivity, moisture in pressboard and various dielectric responses were evaluated by means of the standard software and special software for transformer insulation systems available with the PDC Analyser. The details are as follows:

1) Evaluation of Moisture Content in pressboard and Oil Conductivity

In the evaluation of moisture content in pressboard by PDC Analysis technique, the oil conductivity and the insulation geometry are taken into account. For insulation geometry, a parameter, X, is defined as the ratio of the sum of all the thickness of all the barriers in the oil duct, lumped together, and divided by the duct width. The spacer coverage, Y, is defined as the total width of all the spacers divided by the total length of the periphery of the duct [1].

The evaluation is done by fitting the measured current curve with simulating currents of different values of oil conductivity, moisture in pressboard and insulation geometry. Regarding the influence of geometry, it has an influence on the response but not as significant as the effect of the oil conductivity [1].

When two identical transformers (same manufacturer, same type and same rating) are measured such as in this case, the availability of the insulation dimension is not important. The evaluation can be carried out by applying the same values of X and Y for each current curve measured from similar test arrangement.

From the simulation of these 2 units, it appeared that the barriers fill 36% of the main duct (X=36%) between HV and MV and 30% between MV and LV (X=30%). The spacers fill 22% of the circumference for the insulation between HV and MV (Y=22%) and 27% for the insulation between MV and LV (Y=27%).

Regarding to the oil conductivity, the test results in Table I show that both units have very good oil condition and T1 has better oil quality than T2. For T1, the oil in the main duct between HV and MV has lower conductivity than the oil in the main duct between MV and LV. For T2 the result is opposite.

2) Frequency Scan of Dielectric Dissipation Factor (DDF) and Capacitance

When the current measurement is carried out for 10,000 s polarisation and 10,000 s depolarisation, the DDF and capacitance can be determined from the measured values in the frequency range from 10^{-4} Hz to 1 Hz. Fig. 3 shows the frequency scans of capacitance for each test arrangement and Fig. 4 shows the frequency scan of DDF. It is clearly seen from the capacitance chart in Fig. 3 that the capacitance values of T2 (HV-MV) at very low frequencies are higher than the others. This reflects the inferior quality of insulation system between HV and MV windings of T2 compared to the others.

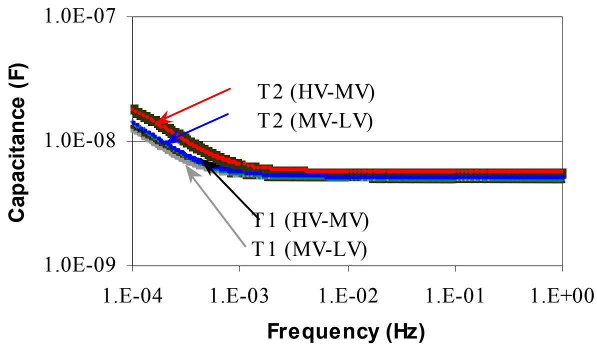

Fig. 3. Capacitance of insulation between windings for T1 and T2 in the frequency range from 10^{-4} Hz to 1 Hz.

For the DDF charts in Fig. 4, the maximum values (DDF_{MAX}) of each curve appears at the frequency lower than 10^{-3} Hz but the DDF_{MAX} of T2 (HV-MV) appears at slightly higher frequency than the others. This means the insulation system of these two units is in good condition but the insulation between HV and MV windings of T2 is inferior to the others which is also manifested by the larger capacitance below 10^{-3} Hz (Fig.3), obviously caused by the larger humidity content of the pressboard.. For the insulation system that has similar geometry, higher frequencies the DDF_{MAX} appears, the worse the insulation condition is.

The DDF at 1 Hz represents the quality of oil in the main duct while the DDF at 10^{-4} Hz represents the quality of solid insulation between windings. The lower the DDF, the better the insulation quality. Good oil normally has DDF at 1 Hz less than 0.01 or 1%. From Table I the DDF at 1 Hz for each unit and each arrangement is in the range of 0.10 - 0.18 %, which reflects the very good oil quality.

3) D.C. Resistance and Polarisation Index (P.I.)

The apparent insulation resistance is calculated from the polarisation current and the constant applied voltage. The polarisation current is dependent on the insulation structure or geometry in addition to the characteristics and

TABLE I
PDC ANALYSIS RESULTS OF TRANSFORMER NO. 1 AND NO. 2

Description	Transformer T1		Transformer T2	
	HV-MV	MV-LV	HV-MV	MV-LV
Test Temperature (^{o}C)	17	16	12	10
Moisture Content of Pressboard (% weight)	1.5	1.5	2.0 +	1.5 - 2.0
Oil conductivity at 20^{o}C (pS/m)	0.098	0.138	0.270	0.221
Capacitance (C) at 50 Hz (nF)	5.459	4.915	5.570	5.076
C at 10^{-4} Hz / C at 50 Hz (Polarisation)	2.39	2.6	3.27	2.78
C at 10^{-4} Hz / C at 50 Hz (Depolarisation)	2.31	2.47	3.17	2.75
DDF or tan δ at 1 Hz ...Polarisation (%)	0.10	0.14	0.15	0.14
DDF or tan δ at 1 Hz...Depolarisation (%)	0.10	0.11	0.18	0.13
Insulation Resistance at 60s (GΩ)	74.1	70.9	42.4	68.2
Insulation Resistance at 600s (GΩ)	116	111	77.4	108
Polarisation Index (between 60s and 600s)	1.56	1.57	1.82	1,59
Charging time at 1st peak of Polarisation Spectrum (s)	1400	1900	850	1600
Maximum Recovery Voltage at 1st peak (V)	95.0	98.2	102.8	108.2
Time to peak at the Maximum Recovery Voltage (s)	1261	1763	728	1583
Initial slope at the Maximum Recovery Voltage (V/s)	0.34	0.35	0.64	0.41

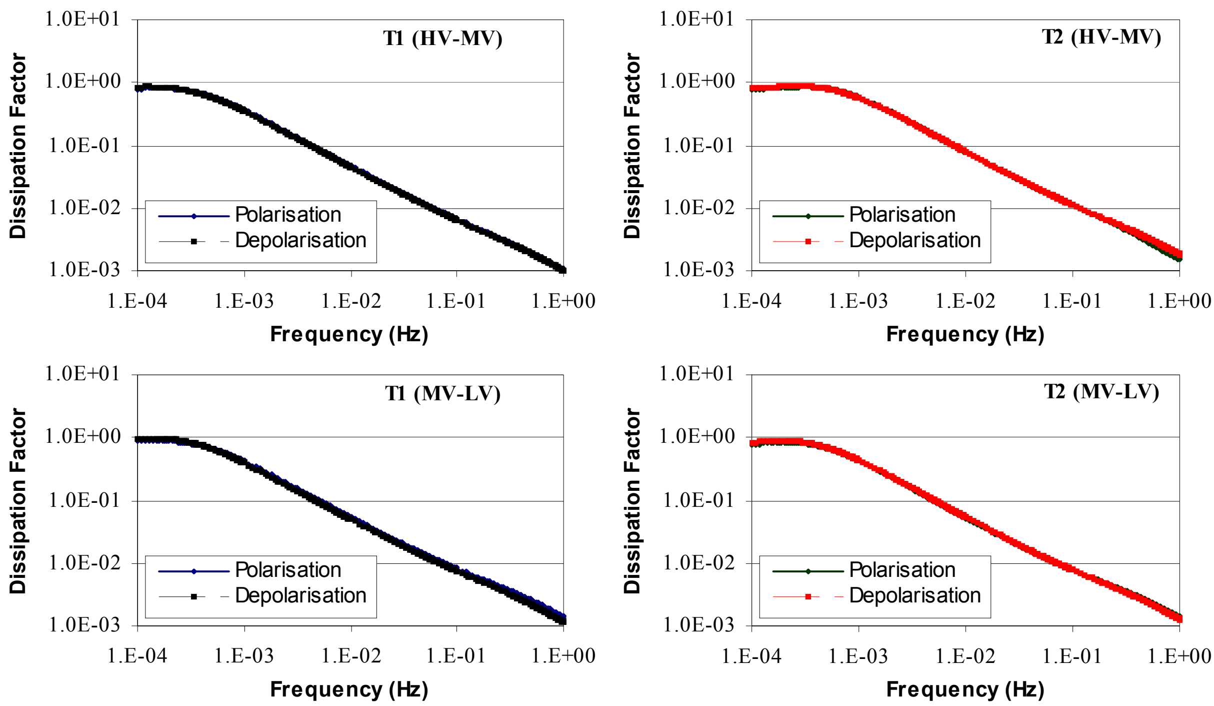

Fig. 4. Frequency scans of Dissipation factor and Capacitance for Transformer No. 1 and No. 2.
(For each test arrangement, the polarisation current and the depolarisation current are nearly equal in magnitude).

parameters of the insulating oil and insulating paper at the condition when the measurement is taken. As the polarisation current is measured continuously up to the end of the charging time, an insulation resistance curve for the entire test duration can be drawn (Fig. 5). Like the polarisation current, the initial part of the insulation resistance curve such as at 15 s or 60 s (1 min.) is influenced by the oil conductivity and the tail of the curve is influenced by the paper condition. At 600 s, the insulation resistance of many transformers is more influenced by paper than by oil but some others still have more influence of the oil than paper. In many cases, the resistance at 600 s is influenced by the interfacial polarisation processes at the oil/paper interface.

The insulation resistance at 60 s and 600 s as well as P.I., which is the ratio of insulation resistance at 600 s to the insulation resistance at 60 s, for each test arrangement are shown in Table I. The resistance and P.I. of the insulation between MV and LV windings for T1 and T2 are very close and the insulation condition is considered (from the resistance values) very good although the P.I. is less than 2.

For the HV-MV, the resistance values for T1 are higher than T2. This means T1 had better insulation condition than T2 in spite of a lower value of P.I. Therefore, P.I. is not an essential factor if the insulation resistance at 60 s and 600 s are high enough or acceptable.

Fig. 5 shows the insulation resistance of both transformers evaluated from the polarisation current and the depolarisation current. For the latter case, the resistance is derived from the difference between the polarisation current and the depolarisation current. When the difference of the two currents are high, which reflects the high conduction, the resistance curve evaluated from each method will appear closer.

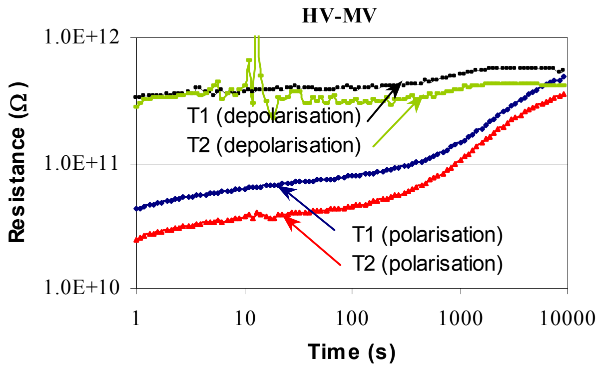

Fig. 5. D.C. Resistance of the insulation between HV and MV windings for transformer T1 and T2

4) Recovery Voltage Method (RVM) and Polarisation Spectrum

The maximum values of the relevant recovery voltages for different charging time and the polarisation spectrum can be evaluated from the measured relaxation currents. Fig. 6 presents the PDC Analysis results in the form of RVM Polarisation Spectrum Charts (T1: top, T2: middle) and the so-called "Guuinic representation" (bottom), in which the initial slope is plotted against the maximum recovery voltage. The data of maximum recovery voltage (magnitude, time-to-peak and the initial slope) at the first peak of polarisation spectrum are also shown in Table I.

When the insulation system is in good condition, the first peak of polarisation spectrum appears at longer charging time and the curve so-called "Guuinic representation" appears at lower initial slope.

The charts in Fig. 6 confirms the very good insulation condition between each pair of windings in both transformers, but the insulation condition between HV and MV windings of T2 is inferior to the others.

III. Conclusion

PDC Analysis is like an X-ray that gave the whole picture of the internal insulation system of the two transformers after refurbishment. It informed that both the oil and the paper were much improved to a satisfactory level and T1 had better

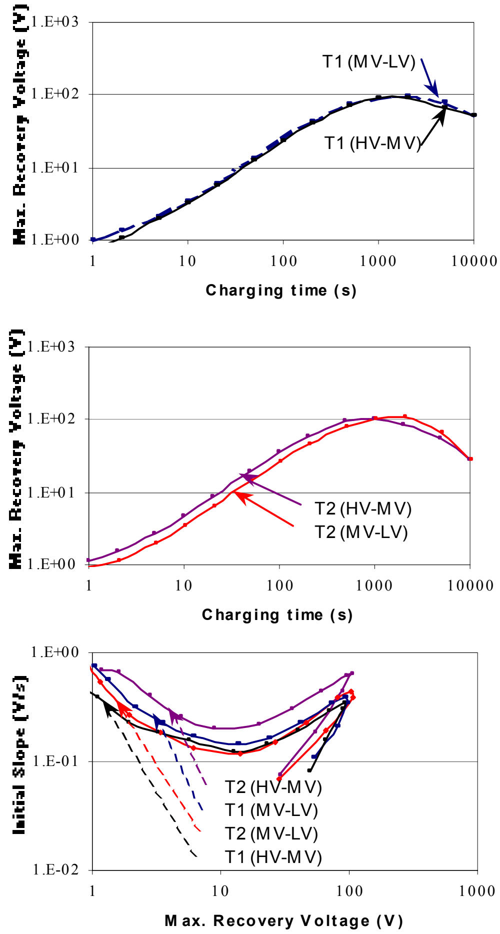

Fig. 6. RVM Polarisation Spectrum of Transformer T1 (top) and Transformer T2 (middle) and the so-called "Guuinic representation" of both units (bottom).

insulation quality than T2. It also analysed that the insulation between HV and MV windings of T2 was slightly inferior to the others. In addition, PDC analysis identified that the insulation system of T1 was more influenced by conduction rather than polarisation and T2 had the opposite result.

Finally, the remaining lives of the two transformers were extended. The quality after refurbishment was assured by PDC Analysis and the insulation between HV and MV windings of T1 was the best, with the following properties:

Moisture content in pressboard	1.5	% wt.
Oil Conductivity at 20°C	0.1	pS/m
DDF or tan δ at 1 Hz	0.1	%
D.C. Resistance at 60 s	74	GΩ
Charging time at 1st peak of polarisation spectrum	1,400	s
Maximum Recovery Voltage	95	V
Initial slope at Max. Recovery Voltage	0.34	V/s

IV. Acknowledgment

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VI. Biographies

Supatra A. Bhumiwat (M'81) was born in Bangkok, Thailand on June 17, 1955. She graduated B.Eng. degree from Chulalongkorn University, Bangkok in March 1977.

She worked for Electricity Generating Authority of Thailand in the Extra-High Voltage Laboratory up to February 1997. Her main field of interest was diagnostic tests especially in transformers. Her research works included aging insulation study of instrument transformers and power transformers. She was a member of CIGRE WG12.15 and CIGRE WG12.16.

In March 1997, she migrated to Auckland, New Zealand and has been an independent consultant for High Voltage Diagnostics. Her services at present include Transformer Oil Analysis and PDC Analysis.

Peter A. Stattmann was born in Adelaide, Australia on August 29, 1964. He graduated from the University of South Australia with a B.Eng.Elect. (Hons) in March 1997.

His employment experience included the Electricity Trust of South Australia and ElectraNet SA. His main field of interest has been high voltage plant maintenance within substation environments. He is a member of CIGREA3 (previously AP13). His services at present include maintenance and operations of high voltage transmission substations.