Modern ART

(Accuracy in Resistance Testing)

Presented by Alan Purton on behalf of Megger Limited

EuroTechCon 2014 - Warwick, UK

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Date 11/2014

Keywords Temperature; insulation; resistance; dielectric frequency response (DFR); frequency domain spectroscopy (FDS); independent temperature compensation (ITC); Megger; Arrhenius equation

Abstract Temperature has a large influence on the value of insulation resistance being measured at any instance. As is often the case the object temperature is greater than the ambient. This will give errors in values being obtained at that time (compared to any specific 20ºC condition for example). This paper will demonstrate the advantages of applying a variable low frequency AC waveform and, using temperature-to-frequency conversion techniques developed, and also the ability to correct any resistance value automatically to a to a known temperature corrected result.

Modern Art (Accuracy in Resistance Testing)

New approach to Accuracy in Insulation Resistance Testing (ART) by employing Dielectric Frequency Response (DFR) and Independent Temperature Compensation (ITC) techniques.

I. INTRODUCTION

DC has been used for over a century to give a pass or fail result of the insulation property. Early instruments date back to the late 19th century as shown in (Fig. 1). However with the steady evolution of more accurate and repeatable AC waveforms generated by digital electronic supplies, developed in recent times. These can now be applied to a great advantage, obtaining truer resistance properties of complex materials in use today. In addition a more detailed diagnostics of the device under test can be obtained over DC alone.

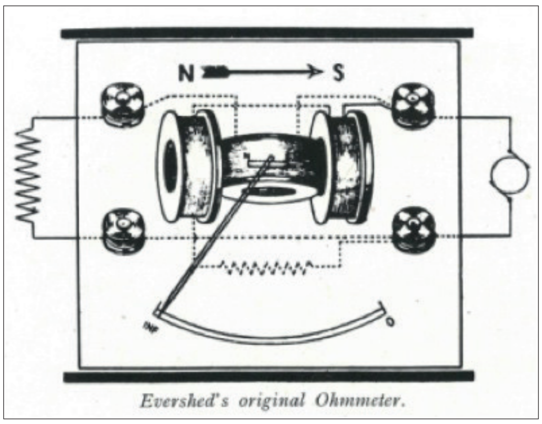


Fig. 1: The Evershed original cross coil ohmmeter

With the introduction of this wide-bandwidth stable generating source, the means has become available to accurately compute many measurable variables in, for example, a transformer. Measuring the basic 'Dissipation Factor' (Tan Delta or Power Factor are other terms) is a well established test method. However, many more useful results can be interpolated if the new measuring techniques developed recently are made available to the user of this D.F test equipment.

The value of readings (if they can be accurately made and repeated) can give us the means to identify changes that would be otherwise unobservable. We will in this paper show how these tests can now be made. .

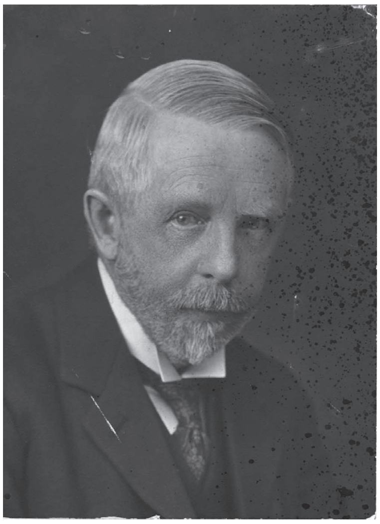


Fig. 2: The inventor of the Megger

The inventor Sydney Evershed who was appointed General Manager of Goolden & Trotter in 1886. In conjunction with Ernest B Vignoles, assisted by Prof W.E Ayrton and A Vines, they established the Evershed & Vignoles Instrument Company in Acton Lane Chiswick, with the brand name of Megger.

The Megger name was derived from the two words MEG(G) Ohm & testER. With 'multiple millions' of Meggers in use worldwide, the name has become synonymous with the world of insulation testing.

II. THE LIMITS OF DC TESTING

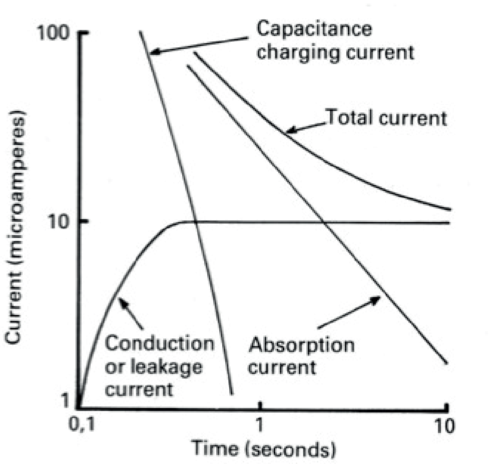


Fig. 3: Typical time constants for low capacitance test object.

The use of Direct Current test equipment is the universal method adopted to prove insulation properties. Why? It offers low size and weight, as it has power requirements to drive the DUT only with enough energy to overcome three components. These are i) charging or capacitive current, ii) absorption current, iii) leakage currents.

These then sum to the 'total current' (Fig.3) when the test voltage source is present.

As long as the insulation tester has a sufficiently low source impedance to drive these required currents into the load, and at the same time maintaining the test voltage, then the time it takes to reach a steady-state reading is often immaterial.

The manufacturing limit of portable hand-held DC Insulation Testers (over and above size constraints governing portability) is based mainly on the following constraints:-

- The maximum test voltage required
- Efficiency of the step up voltage converter, and
- The maximum short-circuit current the insulation tester is required to output.

Age of equipment	Core insulation resistance	Condition of insulation and actions required
New	>1000 MΩ	Manufacturer to be consulted for values less than 1000 MΩ for recomended course of action
Service-aged	>100 MΩ	Normal
	>10 - <100 MΩ	Indicative of insulation deterioration
	<10 MΩ	Needs to be investigated

Fig 4. Accepted pass and fails according to: IEEE C57.152, "Guide for Diagnostic Field 2 Testing of Fluid-Filled Power Transformers, Regulators, and Reactors". Test voltage < 1000V

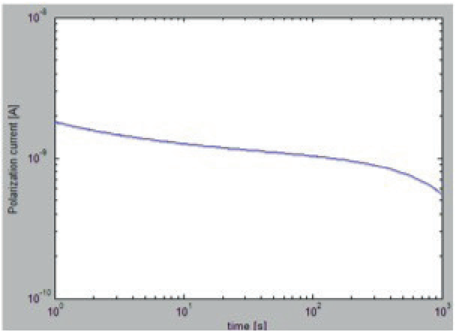


Fig 5a: Polarization current for a transformer with low moisture (1%) BUT NEW oil (0.1 pS/m)

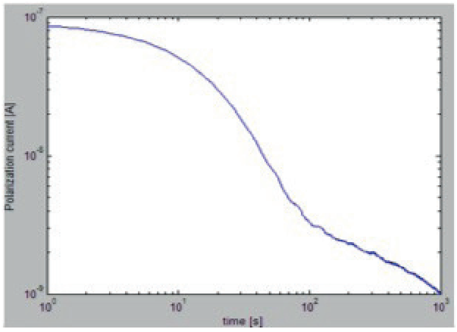


Fig 5b: Polarization current for a transformer with low moisture (1%) BUT AGED oil (10 pS/m)

DC Resistance limiting values, are still the tcommon way, insulation mediums are specified when periodic testing is required. Figure 5 shows the expected results from a relatively low test voltage; these are typical of the values specified for transformer testing by IEEE C57.152

Oil conductivity (pS/m)	0.1 pS/m – NEW ?	10pS/m – AGED?
Polarisation Index (PI)	1.5 – QUESTIONABLE?	4.5 – GOOD?
Previous slide P.I values indicate:-		
PI 2-4 = GOOD		
PI 1-2 = QUESTIONABLE		
PI <1 = UNSATISFACTORY		

Fig 5c: Results of Conductivity in pS/m shown as good (green) & bad (red), HOWEVER the P.I. values contradict the conductivity values?

Typical methods used in present I.R measurements:–

Developments are continually taking place in electrical industries which help compliment the standard direct current (DC) I.R tests. These include measurements such as PDC, DD, DAR and PI (Fig 6a - 6d) and these are currently used in testing applications daily. However, to gain more information into resistance changes in transformers, we need to employ more advanced measuring techniques. Transformer insulation typically suffers from two types of degradation, either a steady decline due to contaminant build up, or a sudden change due to electrically induced stresses. The use of AC testing brings several added advantages. By having a sweep of many decades of frequency, and measuring both voltage and currents simultaneously (as is presently encompassed in the Tan Delta (D.F) testers much more information can be gained from test results previously undertaken.

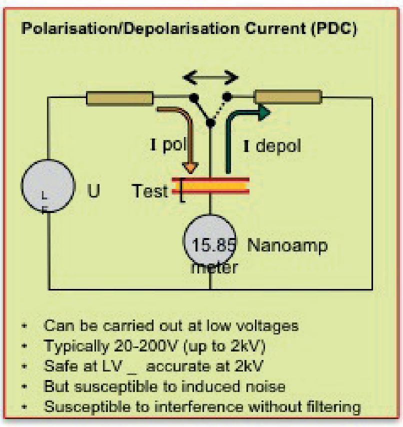


Fig 6a: Pol/Depolarisation Current (PDC)

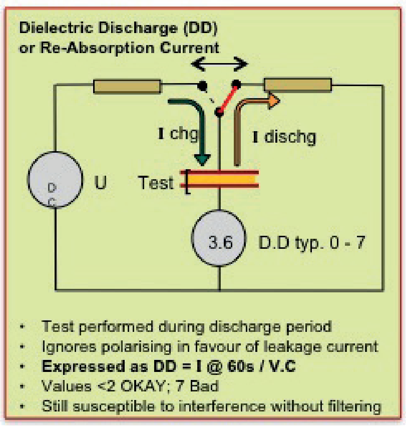


Fig 6b: D.D or / R.A (DD)

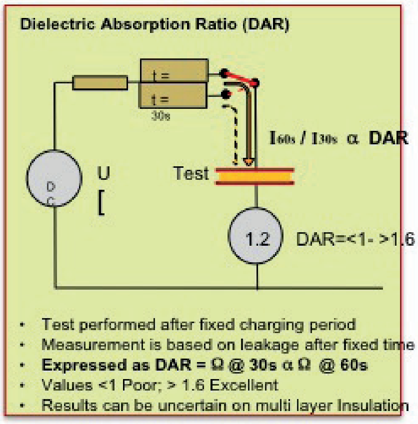


Fig 6c: Dielectric Absorption (DAR)

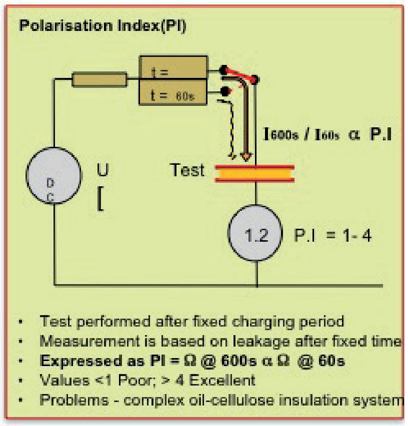


Fig 6d: Polarisation Index (PI)

Adding the variable frequency in the range of 0.1-500 Hz in place of the basic 50/60 Hz enables a far more detailed diagnosis. It is very simple with the technology available now to generate and change frequency with ease, and also provide very low frequencies, down in the order of a tenth of a milli-hertz (<0.0001 Hz).This range of measurements takes us into a new field of insulation material diagnostics, that can be applied in both field and laboratory surroundings.

III. TEMPERATURE EFFECT: ON INSULATION PROPERTIES

An increase in temperature causes a decrease of the insulation resistance. Resistance is inherently variable depending upon the temperature of the material under test. A typical graph of percentage change/degree is characterised in (Fig 7).

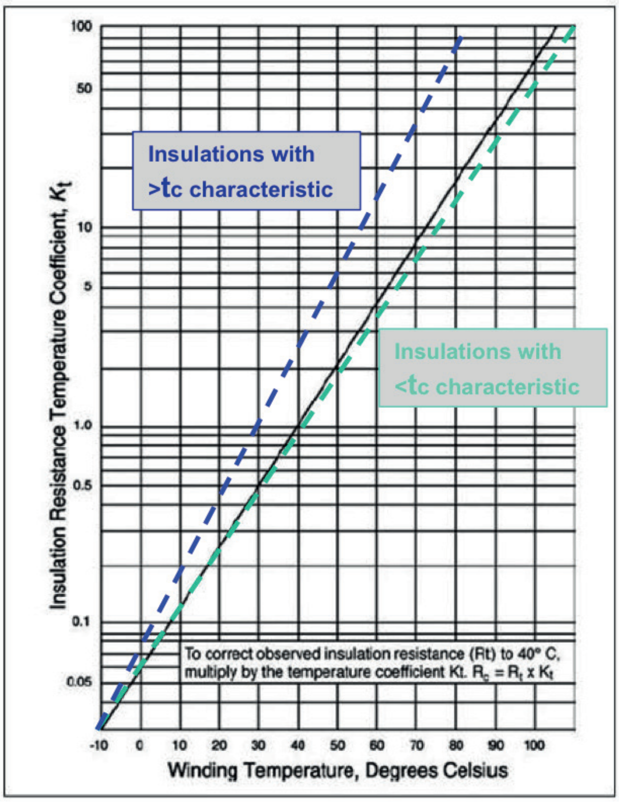


Fig 7. Typical Insulation/temperature correction table based on rotating machines standard at 40°C

The KT constant is derived from the difference of temperatures of insulation from that of a known insulation resistance at a known temperature

$K_T = (0.5)^{(40-T)/10} = (0.5)^{(40-35)/10} = (0.5)^{5/10} = (0.5)^{1/2}$

therefore $K_T = 0.707$

Each decade temperature increase causes a halving of the I.R. value. This is very significant when tests may be in any of the world's geographical regions. Take the example of a motor with insulation temperature of 40°C, but when measured insulation value of 10 MΩ at 20 °C = R40*k40 = 4.8*(10 MΩ) = 48 MΩ.

Using the proper correction factor is very beneficial when these values may vary between 0.5 and 8 times the t*ref* value per decade of temperature rise, depending on the individual insulation material in question. The method for performing Individual Temperature Compensation is (ITC). addressed by Megger patent US 2010/0106435 April 29, 2010

IV. WATER CONTENT - IS A HARD NUT TO CRACK!

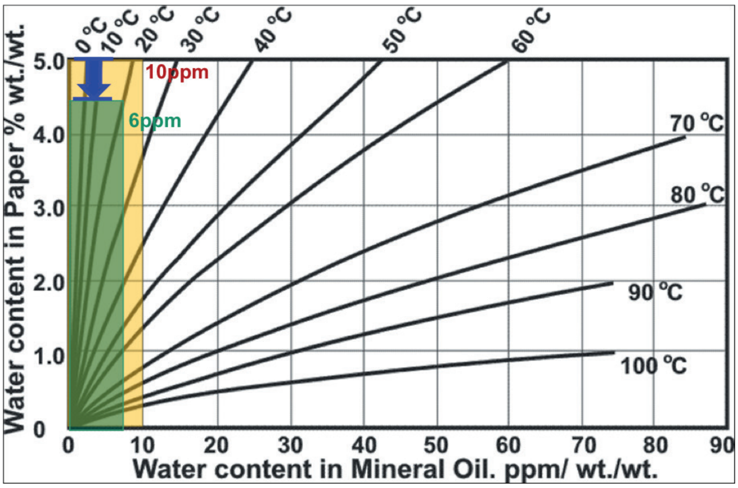
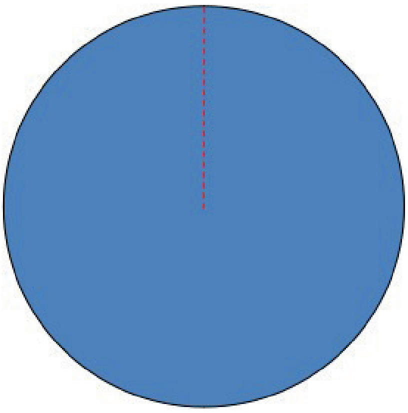


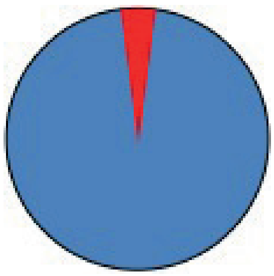
Fig 8. Paper % wt./wt. to water ppm/wt./wt. absorption at specified temperatures. A small oil ppm wt. changes the paper % ppm wt/wt. dramatically

Water content test results can vary considerably, as it is hard to know where the water is situated (is it in the oil, OR is it in the paper?) and what percentage ppm does it, occupy within the total transformer insulation. this will also be dependent on the temperature the transformer is working at, and can will influence the overall Tan Delta (df) value and the overall insulation breakdown strength, to a large degree.

A rise of 6 to 10 ppm equates to a 4ppm increase in water content in the oil (Fig 8) . If measured with an OTS this would NOT show the effect of the absorption of an extra ½ % or (5,000 ppm) of water into the paper/cellulose – which may have been absorbed at the same time! This is an enormous amount, as a half percentage of water in the paper weighs many kilograms. As a 4ppm in the oil volume an equivalent increase of 5,000 ppm will be imbedded in the PAPER. When we see oil breakdown often occurring at around 40 ppm when carrying out an oil dielectric breakdown test, what is not evident from the oil breakdown test, is that the equivalent PAPER moisture will have increased by an order of 30-50,000 ppm – equal to over 100 kg of water present in this major part of the insulating material, a typical mass of oil Vs cellulose is shown in (Fig 9)



20ppm (parts per million) in 25 tons of oil



3% water in 2.5 tons of cellulose

Fig 9. Water Mass Content of a transformer for paper and cellulose

Power transformers moisture levels

Power transformer insulation consists of oil impregnated cellulose and free oil. Almost all water is in the cellulose:

25 tons of oil with water content of 20 ppm = 0,5 kg

2.5 tons of cellulose with 3% water content = 75 kg

Locating the total moisture content within the transformer is not always easy. As seen in the above representation, the large majority of free water will not be found by the application of the standard - **OIL DIELECTRIC STRENGTH (EN 60156) test.**

V. HIGH VOLTAGE DIELECTRIC TESTS ON OIL (EN60156). IS THIS VALID DATA?

- **Other dialectric strength tests - for oil properties only?**
- **Megger oil test sets - verify Oil dialectric breakdown in kV/mm**
- **At power frequency only**
- **Small changes in water ppm contents, can reduce the breakdown voltage dramatically But any moisture not resident in the oil is not detected by this test method - paper water is basically un-interpreted**

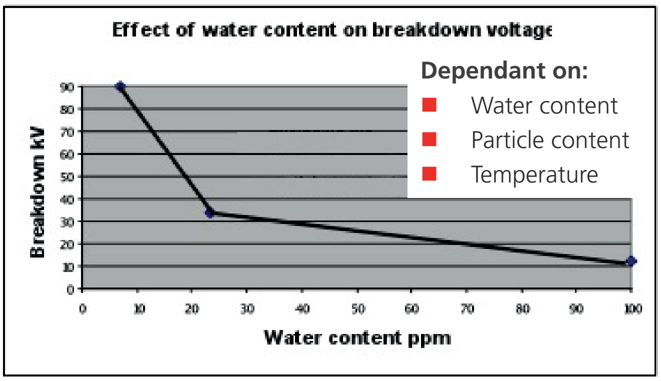


Fig 10. Breakdown kV of OIL withstand - drops rapidly as ppm water increases

The power frequency dielectric test to show oil dielectric breakdown strength, such as when using the Oil Test Set (OTS), is still the normal measure of insulating oil or similar insulating liquid quality. The OTS value can be most useful but will still only be considered as a guide to the total water content.

It is quite an inaccurate way to establish water content in a transformer when kV values are compared to moisture content as seen in(fig 10). Arguably though it remains the only recognised non-evasive test method currently available.

VI. INDIVIDUAL TEMPERATURE CORRECTION (ITC)

Question) IF THESE METHODS DO NOT DETECT WATER PRESENCE, WHAT CAN WE DO?

Answer) ENHANCE OUR STANDARD TEST PROCEDURES

THE IMPLEMENTATION OF ARRHENIUS EQUATION

By combining the use of Diagnostic Frequency Response (DFR), with the new Independent Temperature Compensation (ITC) invention, in combination with it the additional function of the Arrhenius equation, a powerful accurate and automatic set measuring techniques can be performed.

The new technique is based on the fact that a measured DF of I.R value will at a temperature correspond to a certain frequency, stay linked by a proportional representation to one another. The previous DFR measurements can be analysed by the use of a Frequency Domain / Temperature Domain plot' (fig 11a & b) show the commonality of the terms graphically.

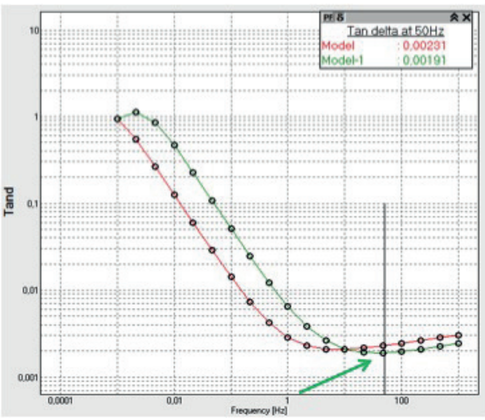


Fig 11 a) Frequency Domain Plot

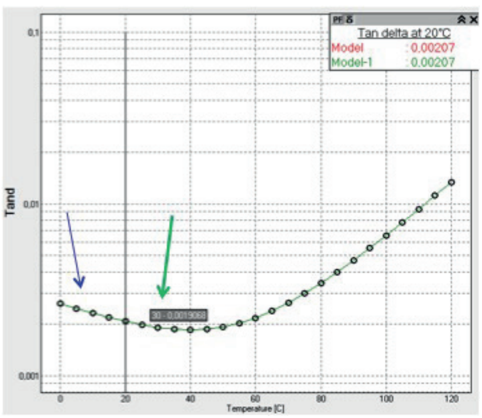


Fig 11 b) Temperature Domain Plot

By modelling this to the particular insulation system in the transformer. Now encompassing a new methodology, ITC (Megger Patent 1 3000282-9), we can further enhance the DFR measurement and simultaneously convert to the measured values to an exacting end result.

The temperature of the test object is measured at its working temperature and then automatically converted using the calculations based on the Arrhenius law. Here, temperature change and activation energy can be expressed by the formula:-

$\kappa = \kappa_0.\exp^{(-Wa/kT)}$; With activation energy Wa ; & Boltzmann constant k

This, when carried out automatically by the test instrument, will improve present techniques currently employed.

Eq 1

$$A_{xy}(T_1,T_2) = e\,\frac{-E_{xy}}{k_b}\left(\frac{1}{T_1}\,\frac{1}{T_2}\right)$$

Eq 2

$$IR(t, T_2)=1/A_{xy}(T_1, T_2)*IR(A_{xy}(T_1, T_2)*t, T_1)$$

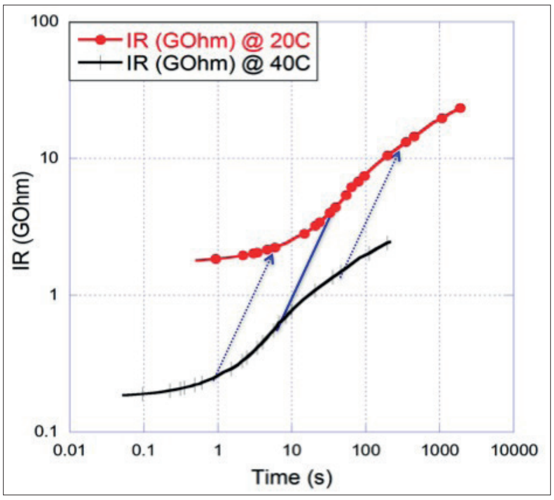


Fig 12. From Eq. 1/Eq. 2 like terms are plotted as: (t) α (R) function

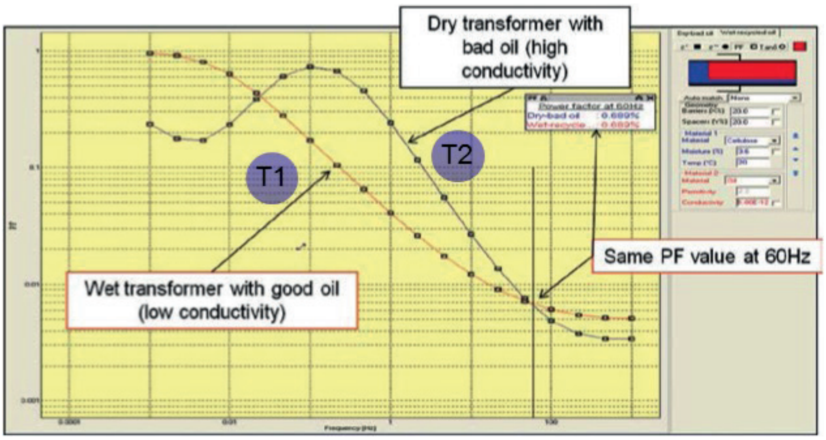


Fig 13, curves of a wet (T1) and a dry (T2) transformer, are obvious when tested at a low sweep frequency – however an oil conductivity test would again disagree!

The new technique is based on the fact that

1. at any given frequency a 2. similar temperature will have a 3. corresponding measurement 4. this can be made at a different temperature and 5. the frequency of the two Results 6. will be brought to a corrected value , see (Fig 12).

In a graphical form, showing the terms of IR and time (t), it can be shown that there is now a direct relationship between these terms. With this established the task of converting terms in the equations below are possible.

Thus, any resistance (associated with any temperature at which resistance was measured) can be corrected back to a 20°C reference to a high degree of accuracy.

Fig 13 verifies that by using very very low frequency (VVLF) the moisture content in the papers of a transformer is clearly discernable.

When handling measured data good filtering is essential, many types of filtering are today available. Analogue could be employed over a small range of decades, but where many decades of frequency are involved, filtering say in the range of 1kHz – 1mHZ, or six decades only the use of digital filtering is practical. When measuring with DC only this will be more prone to noise induction, as the impedance at high frequencies will be very low.

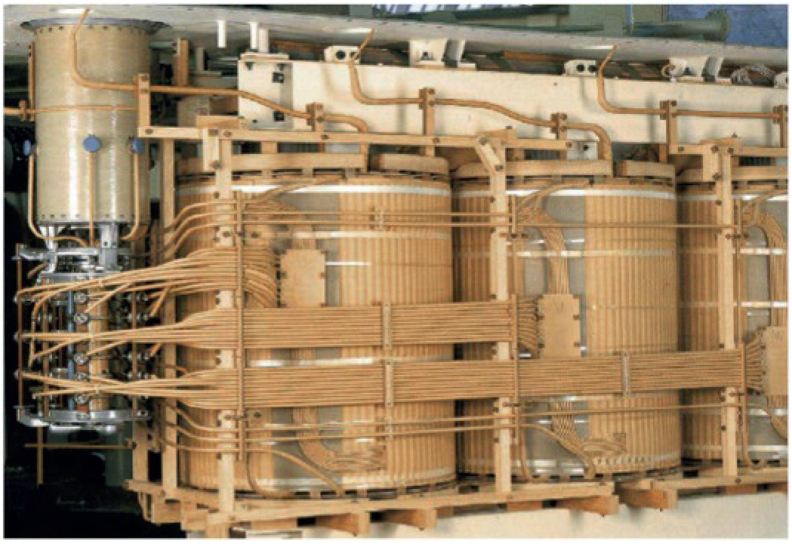


Fig14. Additionally X-Y modelling used to represent the component parts of the transformer geometry

VII. TRUE MOISTURE ASSESSMENT

Use of the currently available Dielectric Frequency Response (DFR) measuring techniques ARE A NEW SOLUTION available for providing non-invasive measurements on the total transformer moisture content. It can be readily seen from (Fig 13) that three major physical properties give rise to changes in both the 'X and Y' coordinate functions; these being, i) moisture present, ii) oil conductivity and iii) temperature (we will consider the geometry to have remained constant). The typical 'rotated S' shaped curve shows changes related to temperature. As the graph progresses to the higher frequencies, moisture alters both the high and low frequency areas, the mid- frequency indicates that each individual section shift reflects a change in a different measured parameter. If any CHANGE in the temperature term can be nullified by applying the Arrhenius equation then these corrected results will be evidenced in the **oil conductance change hence moisture presence within the test piece**.

The need to employ a sweep frequency rather than a fixed power frequency is clearly demonstrated in this case, as performing a passive 50/60Hz test would show the two units have the same 0.7% water content as characterised by IEEE 62-1995. These results indicate a warning/alert status. However the same tests performed using DFR clearly indicate that very different maintenance measures are required on the two transformers in figure 13:-

T1 – is WET - has good oil has low conductivity - so the rework requires the transformer's paper insulation to be dried out!

…'but on the other hand'

T2 – has DRY low moisture paper - but the curve now indicates that the insulation oil has high conductivity and needs replacing!

The specific frequency range where these individual changes in (d.f) take place are shown in Fig 15 (next page)

INSULANT CONDITION - CHANGES TO D.F PLOT

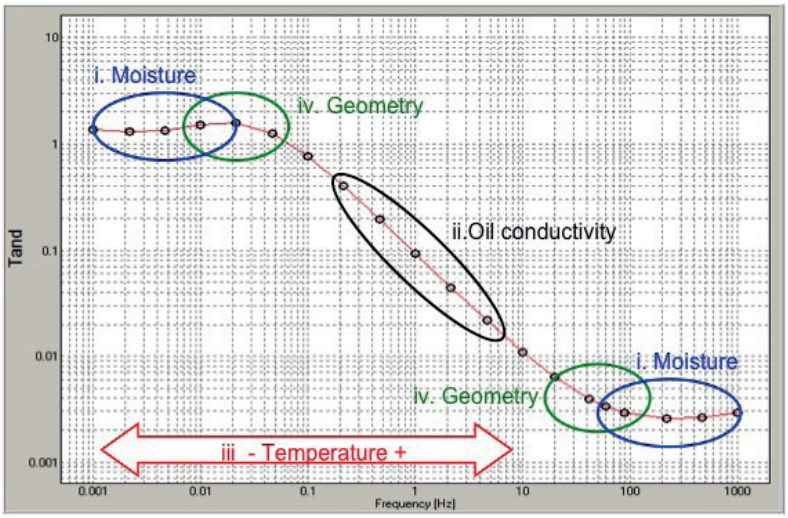


Fig 15. Three properties that effect D.F values in the various frequency ranges

XI. DISCUSSION

Insulation and the measurement of initial insulation values when new, or on aged insulation, to evaluate the remaining quality on any major item of plant is important. It is often performed over very many decades of time, so it is vital to have accuracy in testing, thus ensuring the working reliability of any plant in operation. However over the last fifty years electrical manufacturing industries have produced a wider range of ever more effective insulation materials. These generally allow for less volume to be employed, for the same dielectric strength capability. So we have, due to these technological advances, managed to reduce material volumes used, save on weight and hence transportation costs. However the ways of measuring the electrical properties of these materials have generally remained unchanged in over a century.

Both AC and DC testing methods need careful filtering. Modern digital technology variable frequency methods lend themselves better to AC testing rather than DC.

X. CONCLUSIONS:

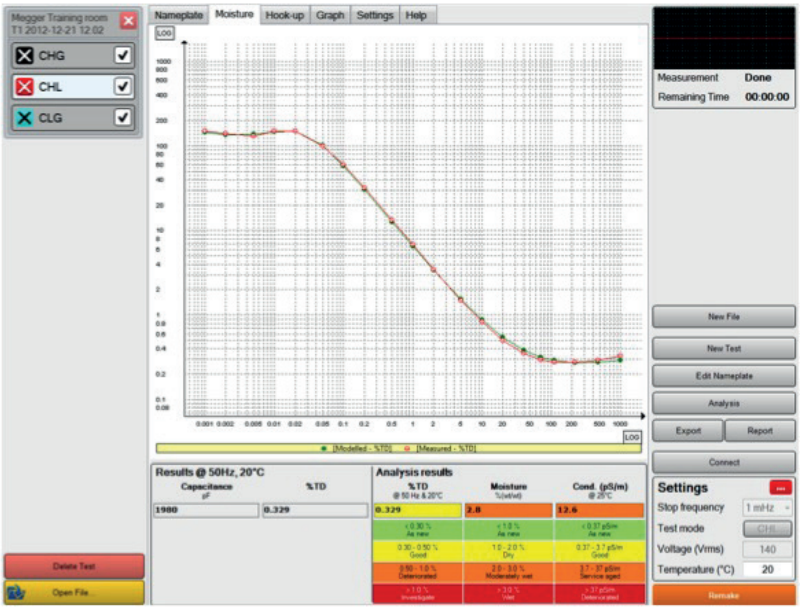
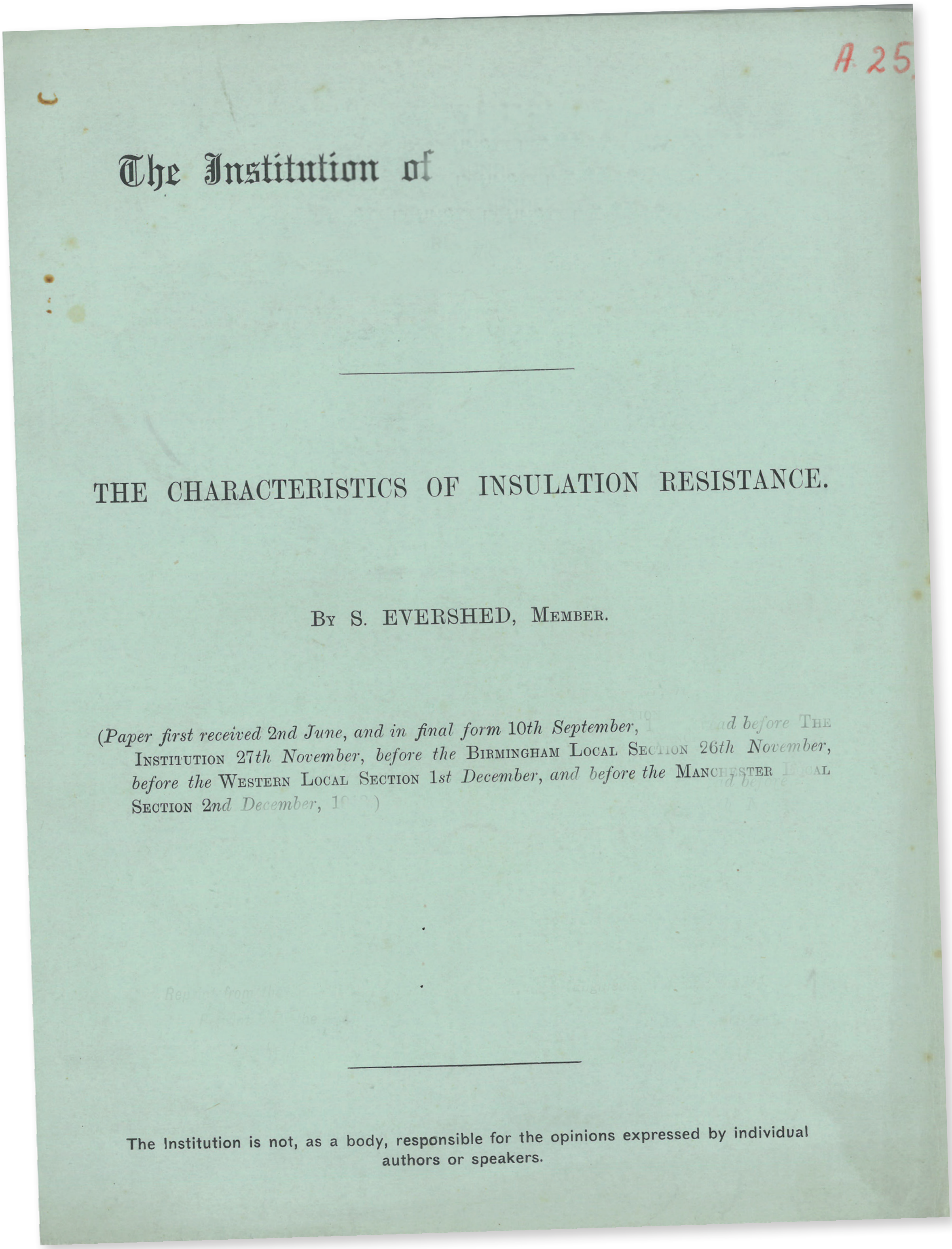


Fig 16. Use of automatic graphical diagnostic techniques will give a true corrected representation of all the insulation conditions

By employing newer measuring methods to those already in use today, we can deal more easily with these more complex insulation mediums.

Whereby our measured/recorded results which are now very often kept as recorded results, are now a much truer indication of the actual insulation resistance value (quality). Known variants can be addressed successfully by the modelling of known values. Hence when practical measurements are undertaken in the field on large test pieces, enhanced test results can be obtained as shown in Figure 16. It is now possible to obtain higher accuracy of insulation resistance/conductance values, by using sweep frequency instead of DC or a single power frequency, previously available.

Percentage Tan Delta Vs Fq, with Moisture contents (%) and Conductivity pS/m & Capacitance, including an auto decision table, is now available from single test sweep!



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The Institution of

THE CHARACTERISTICS OF INSULATION RESISTANCE.

By S. EVERSHED, Member.

(*Paper first received 2nd June, and in final form 10th September,* [illegible] *d before* The Institution *27th November, before the* Birmingham Local Sec[illegible]ion *26th November, before the* Western Local Section *1st December, and before the* Manc[illegible]ster [illegible]al Section *2nd December,* 1[illegible])

The Institution is not, as a body, responsible for the opinions expressed by individual authors or speakers.

For the 2015 conference we will be presenting Sydney Evershed's seminal paper " The Characteristics of Insulation Resistance" The paper highlighted the effects of temperature and moisture upon insulation resistance and that these were being thoroughly investigated over a century ago. The 32 page conference paper was also read before the institution over a century ago.

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