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The analysis of DC and AC conductivity in the detection of water tree degradation in XLPE cables ¹

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Abstract—Water tree degradation in underground XLPE insulated cables is a growing problem with many cables experiencing failure well before their predicted design life. Time domain dielectric testing techniques such as Return Voltage (RV) measurement and Polarisation-Depolarisation Current (PDC) measurement and frequency domain techniques, broadly referred to as Frequency Domain Spectroscopy (FDS) provide ways of detecting water tree degradation in cables. This paper describes the results from PDC and FDS measurements performed on three groups of cables; refurbished field aged cables, non-refurbished field aged cables and new cables. An analysis of the DC and AC conductivity of the cables and how they affect the relaxation processes of a dielectric is undertaken. Finally, recommendations are made about the condition assessment of water tree degraded XLPE cables using the techniques described and the estimated condition of the test cables is given.

Index Terms—XLPE cable, water tree, polarisation/depolarisation current, frequency domain spectroscopy, cable aging.

I. INTRODUCTION

Water tree degradation in underground XLPE insulated cables is a growing problem. Many underground distribution systems are experiencing failure well before the predicted design life of the cables, that is, the predicted design life of XLPE cables before the discovery of water tree degradation. In the deregulated environment effective maintenance schemes are essential for cost efficient management of power system equipment. Underground cable networks are no exception and the ability to accurately and efficiently diagnose water tree degraded cables is very desirable.

Non-destructive measurement methods in the time and frequency domain have shown their ability to access the condition of insulation systems in power system equipment. Perhaps the three most notable non-destructive methods are Polarisation/Depolarisation Current (PDC) measurements and Return Voltage Measurements in the time domain, and broadly, Frequency Domain Spectroscopy (FDS) in the frequency domain. This paper concentrates on PDC and FDS measurements performed on 3 sets of cables, each in differing condition. The first set are refurbished field aged cables, the second set are non-refurbished field aged cables and the third set are new, un-aged cables. The two sets of field aged cables have been taken from an area of distribution network which is known to be severely affected by water tree degradation. This 10km length of line had to be abandoned after 23 years because of multiple failures and post failure optical analysis revealed the failure mechanism to be water trees [1]. The results presented in this paper are from preliminary tests which have been performed

before the start of an accelerated aging experiment on the above mentioned cable lengths.

This paper will investigate the contributions to the charging current, such as the conduction current and the dielectric response function and how these quantities affect frequency domain characteristics such as loss tangent peaks. Also a detailed analysis on the AC conductivity will be performed and a Contribution of Relaxation (COR) factor will be introduced to quantify the strength of relaxation/polarisation processes in a dielectric. Finally, an estimate of the condition of the field aged cables will be made based on the above analysis techniques.

II. THEORY

A. Time Domain Polarisation Measurements [2]-[6]

If a homogeneous electric field is applied to a dielectric, the current density of the material can be written as:

$$J(t) = \sigma E(t) + \frac{dD}{dt} \quad (1)$$

The current density, $J(t)$ consists of two components, one component being due to the DC conductivity, σ , the other being due the electric displacement $D(t)$. The dielectric displacement can be defined as:

$$D(t) = \underbrace{\epsilon_{\infty} E(t)}_{\text{rapid}} + \underbrace{P(t)}_{\text{slow}} \quad (2)$$

where ϵ_{∞} is the ‘high frequency permittivity’ which is the result of the instantaneous response of the polarising species and is not of interest in the time scales used in this paper. The polarisation of the dielectric, $P(t)$, is a slower phenomenon and is described by:

$$P(t) = \epsilon_0 \int_0^t f(t-\tau) E(\tau) d\tau \quad (3)$$

Where $f(t)$ is the dielectric response function, which describes the time varying relaxation processes of a material. If we consider the case where an insulation with a geometrical capacitance of C_0 is charged with a step voltage U_0 , then the following expression for the charging current can be derived:

$$i_{\text{polarisation}}(t) = C_0 U_0 \left[\frac{\sigma}{\epsilon_0} + f(t) \right] \quad (4)$$

Once the step voltage is removed and the insulation system is shorted to ground, the depolarisation current can be written as:

$$i_{\text{depolarisation}}(t) = -C_0 \cdot U_0 \cdot [f(t) - f(t+t_1)] \quad (5)$$

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Where t_1 is the duration of the time during which the voltage had been applied to the test object. If the polarisation time is sufficiently long, so that $f(t+t_1) \approx 0$ the response function is assumed to be proportional to the depolarisation current. From (2) we can write (3).

$$i_{\text{depolarisation}}(t) = -C_0 \cdot U_0 \cdot f(t) \quad (6)$$

From these two equations (4) and (6) of the polarisation and depolarisation currents the dielectric response function $f(t)$ and the conductivity σ can be determined. Fig. 1 shows the nature of the polarisation current after applying a DC voltage U_0 and of the depolarisation current during the short circuit.

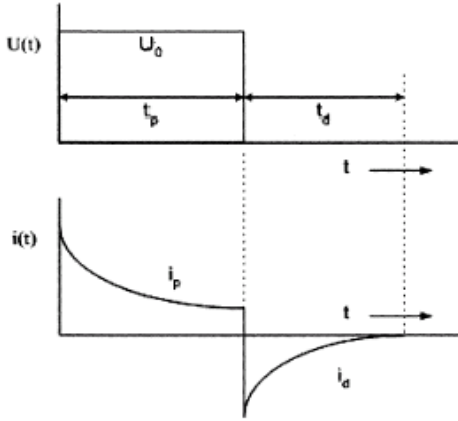


Fig. 1 Principle of polarisation/depolarisation current measurement.

B. Frequency Domain Dielectric Spectroscopy (FDS) [5]-[8]

Frequency Domain Spectroscopy measurements consist of measuring diagnostic parameters, such as the loss tangent, $\tan \delta$ and the complex capacitance, at different frequency points over a range of typically 0.1-1mHz to 1kHz. If we consider the insulation to be a combination of resistive and capacitive elements, a current will flow through the insulation with resistive and capacitive parts. The total current flow will be the resultant of these resistive and capacitive parts, and the phase angle between the resultant current and the imaginary axis is called the loss angle δ . This angle represents the deviation of the insulation from an ideal capacitance, where the current is purely capacitive.

Therefore, the capacitance of the insulation will be a complex capacitance, with real and imaginary parts.

$$\tilde{C}(\omega) = C'(\omega) - jC''(\omega) \quad (7)$$

The complex capacitance can be related to the complex permittivity by a geometric factor, shown below:

$$\tilde{C}(\omega) = C'(\omega) - jC''(\omega) = (A/w) \cdot (\epsilon'(\omega) - j\epsilon''(\omega)) \quad (8)$$

Where A is the plate area of the capacitance and w is the

distance between the two plates.

The complex susceptibility can also be related to the complex permittivity:

$$\tilde{\chi}(\omega) = \chi'(\omega) - j\chi''(\omega) = (\tilde{\epsilon} - \epsilon_\infty)/\epsilon_0 \quad (9)$$

Where:

$$\tilde{\epsilon}(\omega) = \epsilon'(\omega) - j\epsilon''(\omega) \quad (10)$$

A dielectric will also have a complex conductivity in the frequency domain. This AC conductivity is due to relaxation processes, however, it is also intimately linked with the DC conductivity, which is a steady state phenomenon and has nothing to do with relaxation [7]. This relationship is expressed by:

$$\begin{aligned} \tilde{\sigma}(\omega) &= \sigma'(\omega) + \sigma_{dc} + j\sigma''(\omega) = j\omega\tilde{\epsilon} \\ &= j\omega(\epsilon'(\omega) - j\epsilon''(\omega)) \end{aligned} \quad (11)$$

When discussing the dielectric properties, it is a matter of personal preference whether one chooses the $\tilde{\sigma}(\omega)$ or the $\tilde{\chi}(\omega)$ representation, but the former will be more linked to transport and the later to polarisation [7]. In the context of this paper, the conductivity will be used to express the dielectric properties in the frequency domain. The following relationship describes the true ac conductivity and how it is related to the susceptibility:

$$\sigma'(\omega) = \sigma(\omega) - \sigma_{dc} = \epsilon_0 \omega \chi''(\omega) \quad (12)$$

In the above equation (12), we define $\sigma(\omega)$ as being the real part of the complex conductivity, $\tilde{\sigma}(\omega)$. The imaginary part of the dielectric susceptibility, $\chi''(\omega)$ can be determined directly from equations (8) and (9). If the complex capacitance is known, the complex permittivity can be calculated if the geometry is known. The high frequency permittivity, ϵ_∞ is a purely real value and therefore, $\chi''(\omega)$ will simply be equal to the imaginary part of the complex permittivity $\epsilon''(\omega)$ divided by the permittivity of free space. The DC conductivity, σ_{dc} can be estimated from the steady state charging current after the dielectric response function has decayed to a very low value. Therefore, from equation (4) we can say that the remaining polarisation current will be approximately equal to the steady state conduction current.

The loss tangent is another important diagnostic property in the frequency domain and is equal to the ratio of the real part of the impedance to the imaginary part of the impedance. In terms of complex capacitance and permittivity:

$$\tan \delta = \frac{C''}{C'} = \frac{\epsilon''}{\epsilon'} \quad (13)$$

III. EXPERIMENTS

As stated in the introduction, the experiments that this paper is based on, were performed on three sets of 10 XLPE cables, each in differing condition. Two sets of cables are from a length of failed distribution network, which was abandoned after 23 years in service. One set of these field aged cables was refurbished by a silicon fluid injection method, while the other set was left in its original, aged condition. The third set of cables is brand new. All three sets are single core, 22kV cables and have been cut into lengths of approximately 7.5m long.

The experiments discussed in this paper were preliminary tests before the start of an accelerated aging experiment. Therefore, the three sets of cables are immersed in 3 separate water filled tanks, to give the cables an adequate supply of water during the aging process [1]. Their designations were therefore organised by their tank number as shown below:

- Tank 1 – Refurbished field aged cables
- Tank 2 – Non-refurbished field aged cables
- Tank 3 – New cables

Therefore the fifth cable in Tank 1 would be designated T1-5.

FDS measurements were performed with the IDA200 equipment from Programma [9] and the PDC measurements were performed using University of Queensland designed equipment [3]. The details on the above measuring devices are described in the references given.

IV. RESULTS AND DISCUSSION

A. Polarisation/Depolarisation Current (PDC) measurements

PDC measurements were performed on a number of samples from all three sets of cables. In preliminary tests, the charging/discharging time used was 10000 seconds, similar to times used on power transformers. However, because of the very low loss nature of XLPE, it was found that as the charging and discharging current decayed, they proceeded below a noise floor, which obscured the magnitudes of the currents. Thus, it was decided that just as much relevant information could be obtained with charging/discharging times of 300-500 seconds and digital filtering.

The digital filtering significantly reduced the noise on the signal and allowed a good approximation of the final steady state value of the charging current and thus a good approximation of the DC conductivity.

For the discharging currents however, it was found that, without the presence of a driving voltage, depending on the noise conditions during the test, the discharge current was often so obscured by noise as to render it immeasurable. This was especially the case with the new cables (Tank 3), with only a

couple giving useful readings of discharging current. The situation was slightly improved with the field aged non-refurbished cables (Tank 2), with several cables yielding a useful discharge current, and better still with the field aged refurbished cables (Tank 1), with all the cables showing measurable discharge currents.

Because the discharge current is controlled exclusively by the dielectric response function $f(t)$ in time (see equation (6)) it is easy to draw some simple conclusions from its magnitude. As stated earlier, the dielectric response function describes the time varying relaxation processes of a dielectric. Therefore, it is simple to conclude that materials with a higher magnitude of discharge current, and thus dielectric response function, will have stronger relaxation/polarisation processes. In a non-polar polymer, these polarisation processes can arise in the form of polar impurities (such as water). We can then deduce that the refurbished field aged cables contain the highest amount of polarisable materials, followed by the non-refurbished field aged cables and, not surprisingly, the new cables contain the least. This trend was observed by measurements taken in the frequency domain also, and will be discussed later.

B. Contributions to the charging current

If we examine the polarisation current equation (4), we can see that the polarisation current can be broken up into two parts, one part being due to the conduction σ , and the other part being due to the dielectric response function $f(t)$. In classical dielectric behaviour the polarising and depolarising currents should be identical with a constant DC current due to a constant DC conduction being superimposed onto the charging current only [8]. However, the analysis of the charging current showed a deviation from classical behaviour.

To examine the contribution to the charging current the dielectric response function was needed and therefore the discharging current. As stated earlier, the refurbished field aged cables had the highest and thus the most defined magnitude of discharging currents. Therefore, it was the charging and discharging currents from these cables that was initially analysed to study the contributions to the charging current.

Such an analysis is shown in Fig. 3 below. The line with the highest initial magnitude is the charging current, the line with the second highest initial magnitude is the current due to the conductivity and the line with the lowest initial magnitude is the discharging current. The point in time marked t_{co} will be explained in a later section.

As can be seen in Fig. 3 below, the current flowing due to the conductivity is anything but constant. This transient, time dependent conductivity dominates the initial magnitude of the charging current quite significantly. Therefore it can be assumed that the conductivity consists of at least two parts, a time varying conduction $\sigma_{var}(t)$ and a constant DC conduction σ_{dc} , which

must be the sole conduction term after the dielectric enters an electrical equilibrium or steady state.

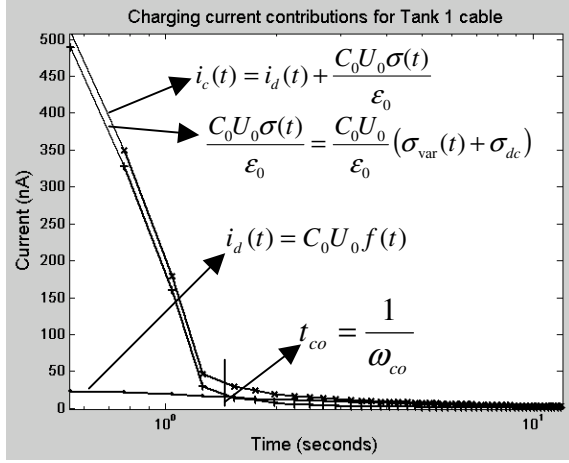


Fig. 3 Charging current contributions for a refurbished field aged cable

Therefore equation (4) could afford to be re-written as:

$$i_c(t) = C_0 U_0 \left[\frac{\sigma_{\text{var}}(t) + \sigma_{dc}}{\epsilon_0} + f(t) \right] \quad (14)$$

Because the discharge current (and thus the dielectric response function) is so small as to hinder measurement (<2nA) for the non-refurbished field aged cables and the new cables, yet the initial magnitude of their charging currents are still significantly large (200nA-500nA), it is safe to say that the current due to the time varying conductivity $\sigma_{\text{var}}(t)$ dominates the initial transient response of these cables as well. Therefore, because the initial transient response corresponds to the response at high frequencies in the frequency domain, it may be possible to infer that the high frequency regions of the FDS measurements will be affected by the conduction component.

C. Frequency Domain Spectroscopy (FDS) measurements

After performing the FDS measurements it was found that the magnitude of loss is greatest for the refurbished field aged cables and lowest for the new cables, with the non-refurbished field aged cables in between. This agrees with the same trend seen in the charging and discharging currents, which was mentioned earlier.

An interesting result seen in the FDS measurements was the appearance of loss peaks, which neither author has seen mentioned in existing literature for XLPE cables to date. The loss peaks discovered were subtle and only obvious in a linear magnitude, log frequency scale, rather than a log magnitude, log frequency scale. Loss peaks were seen in all the loss tangent measurements for the refurbished field aged cables but only in some of the non-refurbished field aged cables. These loss peaks can be seen in Fig. 4 below. The majority of the new cables exhibited a flat loss tangent response.

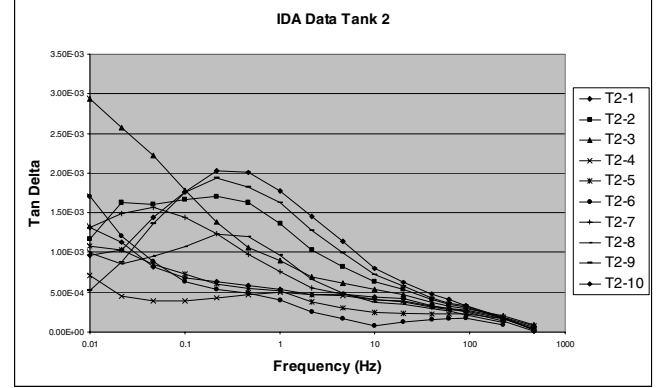
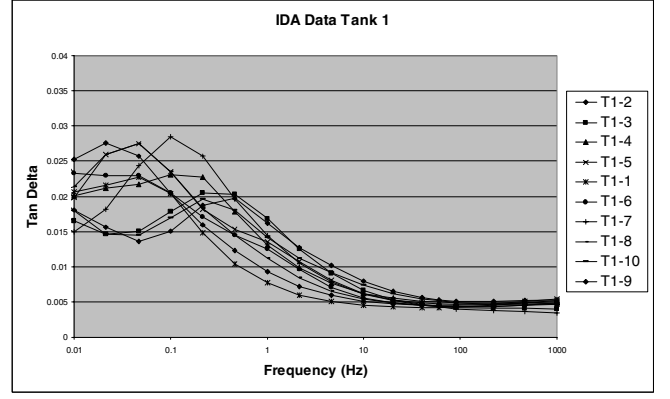


Fig. 4. Loss tangent measurements
Top – Refurbished field aged cables (Tank 1)
Bottom – Non-refurbished field aged cables (Tank 2)

The physical process giving rise to a loss peak is invariably a dipolar re-orientation [8]. Because water is a dipolar material, it seems that a loss peak should be expected in cables that have significant water tree degradation. In the case of the refurbished field aged cables, which have had the water removed and replaced with a silicon fluid, some other type of dipolar material must have been introduced during the process. Whether the dipolar material is actually the silicon fluid or some other part of the process is unknown. As would be expected, the new cables, with very few dipolar or ionic impurities, have an almost flat response with no loss peaks.

D. Correlation between the frequency domain loss peaks and the contributions to the charging current

Looking at Fig. 3 it can be seen that the initial transient response is dominated significantly by the transient, time varying conduction component, which was mentioned before. However, upon closer examination, it can also be seen that there is a certain period of time where the current due to the dielectric response function contributes the most to the charging current. This period of time is finite, as the dielectric response function is a decreasing function and the current due to it will eventually drop below the magnitude of the steady state DC conduction current. However, because the loss peaks in the frequency domain are related to the polarisation processes in the dielectric, and so is the dielectric loss function, $f(t)$ in the time domain, it is expected that they will be related. It was thought that the point in time at which the current due to the dielectric response function

becomes the dominant contribution to the charging current could be related to the frequency of the cables' corresponding loss peak. This point is marked in Fig. 3. Therefore the following relationship was to be tested:

$$\frac{1}{t_{co}} = \omega_{co} \propto \omega_p \quad (15)$$

Where t_{co} is the crossover time where the current due to the dielectric response function dominates the charging current, instead of the conduction current, ω_{co} is the corresponding point in the frequency domain and ω_p is the frequency of the loss peak.

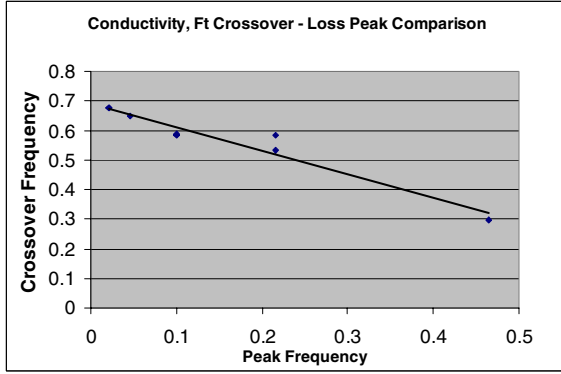


Fig. 5 ω_{co} vs ω_p comparison

Fig. 5 above shows the comparison between ω_{co} and ω_p , where the solid line shows a linear correlation fit. It should be noted that the above figure shows the comparison for 8 refurbished field aged cables, but in two instances, the points are so close together that they cannot be resolved separately at this scale. The linear fit that describes the correlation can be expressed as:

$$\omega_{co} = -0.8\omega_p + 0.7 \quad (16)$$

Therefore from this correlation, it may be stated that the earlier in time that the dielectric response function dominates the charging current equates to a reduced peak frequency. Therefore, it may also be said that the stronger the relaxation processes are, compared to the initial conduction processes, the smaller the frequency of the loss peak.

E. A methodology for the ranking of cables with respect to degree of degradation

As stated earlier, the AC conduction of a dielectric is due to relaxation processes, which results in charge storage, but the DC conduction is a steady state process due exclusively to the transport of carriers under a constant voltage and involves no charge storage [8]. If we consider the real part of the complex conductivity described in (11) (as stated earlier, let us refer to this real part simply as $\sigma(\omega)$) which is related to the loss part of the susceptibility, we can see it consists of two parts, the true AC conductivity, $\sigma'(\omega)$ and the steady state DC conductivity, σ_{dc} . To examine the contribution of the relaxation processes to the real part of the complex conductivity, $\sigma(\omega)$, we will examine the

true AC conductivity, $\sigma'(\omega)$ and its contribution to $\sigma(\omega)$. Fig. 6-8 shows both $\sigma'(\omega)$ and $\sigma(\omega)$ plotted against frequency for a cable in each of the three different types of cables. These quantities were calculated using equation (12).

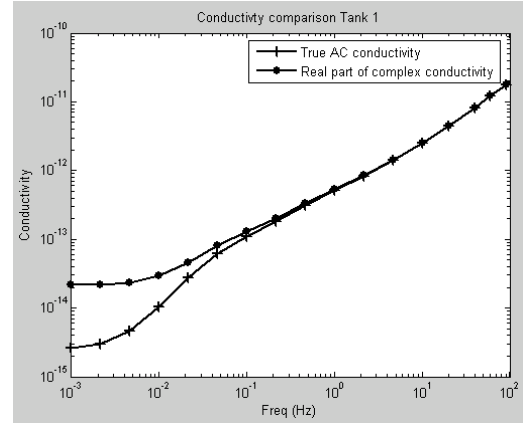


Figure 6 $\sigma(\omega)$ (o) and $\sigma'(\omega)$ (+) for a refurbished field aged cable

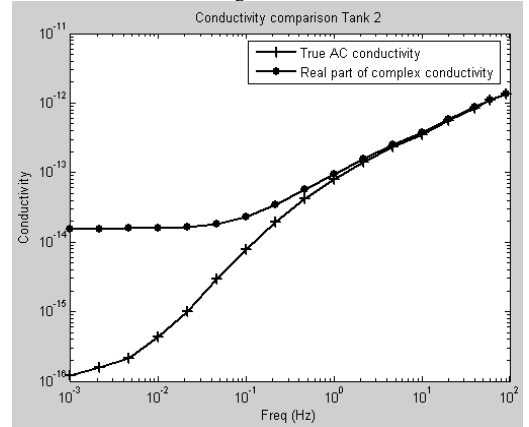


Figure 7 $\sigma(\omega)$ (o) and $\sigma'(\omega)$ (+) for a non-refurbished field aged cable

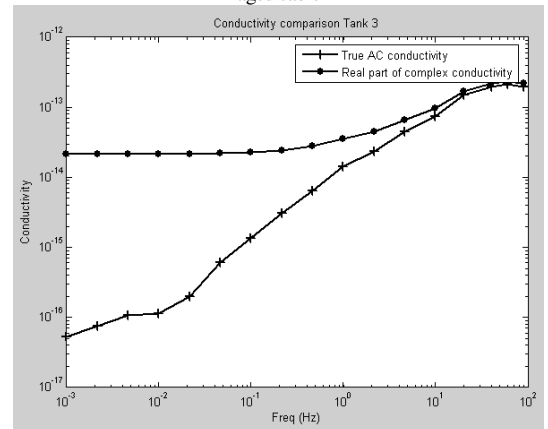


Figure 8 $\sigma(\omega)$ (o) and $\sigma'(\omega)$ (+) for a new cable

At high frequencies, the magnitude of $\sigma'(\omega)$ for all three cables is high in comparison to the magnitude of the steady state DC conductivity, which can be seen as the value of $\sigma(\omega)$ that is frequency independent at low frequencies, for all the cables.

Therefore, $\sigma'(\omega)$ dominates the real part of the complex permittivity $\sigma(\omega)$, in this high frequency region. The interesting result is the contribution of $\sigma'(\omega)$ to $\sigma(\omega)$ as the frequency decreases for the different types of cables. It can be seen that the DC conductivity for the new cables dominates $\sigma(\omega)$ much earlier, with decreasing frequency, than in dominates for the refurbished field aged cables in Fig. 6. The same can be said for the non-refurbished field aged cables, Fig. 7, but to a lesser extent. Therefore, because the steady state DC conductivity is independent of any polarisation processes, while the AC conductivity is due to relaxation phenomenon, it can be said that the greater the magnitude of the relaxation/polarisation phenomenon, the greater the frequency range it dominates $\sigma(\omega)$ and thus the less the overall difference between $\sigma'(\omega)$ and $\sigma(\omega)$.

It should be noted briefly at this point that the transient conductivity mentioned in a previous section, $\sigma_{\text{var}}(t)$, is not a relaxation process, otherwise its effects would be seen on the discharge current. However, because it is a sharply time varying conductivity, its presence would be contained within the high frequency region of the AC conductivity. Whether or not it could be separable from the relaxation processes in this high frequency region is unknown at this stage.

To quantify the difference between $\sigma'(\omega)$ and $\sigma(\omega)$, and thus to quantify the contribution of the relaxation phenomena to the real part of the AC conductivity, $\sigma(\omega)$, a Contribution of Relaxation (COR) factor was introduced. This factor was calculated by summing the difference between $\sigma'(\omega)$ and $\sigma(\omega)$ at each frequency point, dividing this sum by the number of frequency points, and then inverting the result. This is expressed below:

$$COR = \left(\frac{\sum_{n=0}^n \sigma(\omega_n) - \sigma'(\omega_n)}{n} \right)^{-1} \quad (17)$$

Where n is the number of frequency points. Because the COR factor is proportional to the magnitude of polarisation phenomena in a dielectric, its value should be able to be correlated with the magnitude of the loss peaks in the frequency domain, since they are also related to the polarisation phenomena. The result of such a correlation can be seen in Fig. 9 below.

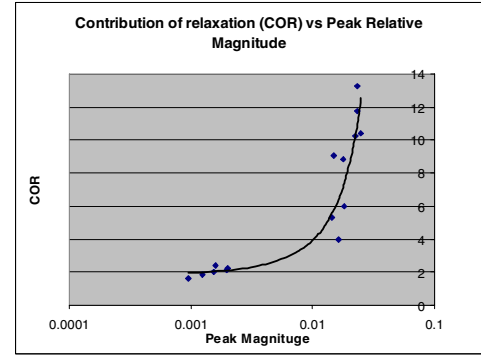


Fig. 9 COR factor vs Peak Relative Magnitude

The peak relative magnitude is the loss tangent magnitude of the peak with the high frequency loss (lowest loss) subtracted from it. The resultant exponential fit (black solid line) is expressed below:

$$COR = 1.8e^{77.8 * PkMag} \quad (18)$$

If we examine the limit $\lim_{PkMag \rightarrow 0}$ we can see that a flat loss type response in the frequency domain will have a COR of approximately 1.8 or less. Figure 10 shows the COR factor for cables out of the non-refurbished field aged and new cable groups, with no loss peak and showing a flat loss type response. It can be seen in Figure 10 that none of the cables with a flat loss type response exceeds a COR of approximately 1.5.

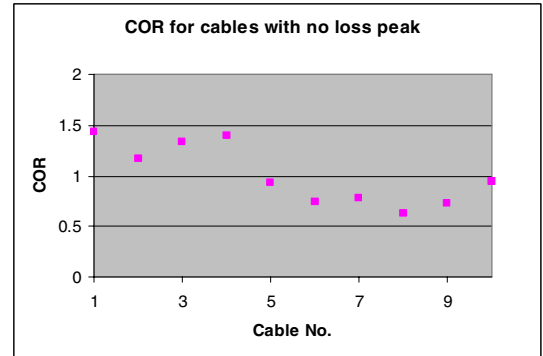


Fig. 10. COR for cables with no loss peak

A correlation of the COR factor was also made with the PDC measurements, where it was correlated with the ratio of the discharging current to the charging current at 1 second. In other words the ratio of dielectric response function to the charging current at 1 second and thus the percentage contribution of the dielectric response function.

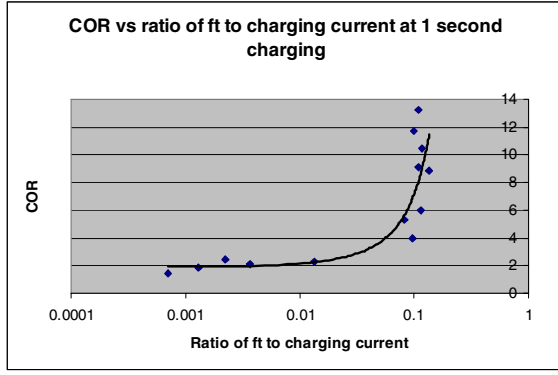


Fig. 11. COR vs ratio of ft to charging current at 1 second charging

The exponential fit in this case is:

$$COR = 1.88e^{13.3*ratio} \quad (19)$$

If we examine the limit $\lim_{ratio \rightarrow 0}$ again in this case, we can see that the COR factor will tend to 1.88 when the magnitude of discharge current becomes negligible compared to the charging current. As we have said already, the discharge current is due to the dielectric response function, thus when the magnitude of the discharge current becomes negligible, so does the dielectric response function.

The near exact limit in both correlations is not surprising. In the first correlation as the peak magnitude approaches zero, this implies that:

- The dielectric has a small amount of polarisable materials, because as stated before, loss peaks only occur due to dipolar orientations [8].
- If there are minimal polarisable materials, the magnitude of polarisation processes will be less and thus the magnitude of the dielectric response function will be reduced. This is because, as stated earlier, the dielectric response function describes the time-varying behaviour of the polarisation processes in a dielectric.

In the second correlation as the ratio of the discharge current to the charging current approaches zero:

- This implies that the magnitude of the dielectric response function will become negligible, because the discharge current is directly proportional to the dielectric response function.
- Therefore, as stated in the above points, this implies that there is a small amount of polarisable materials present in the dielectric.

Therefore, the conclusion of these correlations is that when they approach their respective limits, the COR will tend to approximately 1.8 and it can be said that at this point, that the dielectric will contain a small/negligible amount of polarisable materials.

Therefore, we can see that it is possible to derive this COR factor from both time domain and frequency domain measurements. The factor quantifies the contribution of the polarisation/relaxation processes to the AC conductivity of a

dielectric. Because of this, the COR can be correlated to frequency and time domain quantities such as loss peak magnitudes and the dielectric response function, respectively.

It may be postulated that:

- A material with a COR of less than ~1.8 will have a flat frequency response, a negligible magnitude of dielectric response function and thus a negligible amount of polarisable materials.
- A material with a COR of greater than ~1.8 will have a loss peak in the frequency domain, with a magnitude related to the COR and a significant amount of polarisable materials.

Therefore with respect to water tree degradation, the longer the water tree, the greater amount of polarisable materials there are in the form of water. It may be expected that non-effected cables would have a COR of less than ~1.8, where severely affected cable would have a COR significantly greater than 1.8. This of course will need to be investigated with the future accelerated aging test being a good platform for this investigation. A correlation of the COR with optical water tree analysis would also be valuable in proving its worth.

Using the above quantities, we can rank the non-refurbished field aged cables with a COR of above 1.8 to give an estimate of the degree of degradation.

| Cable | COR factor |
|-------|------------|
| T2-2 | 2.42 |
| T2-10 | 2.27 |
| T2-9 | 2.10 |
| T2-7 | 2.01 |
| T2-8 | 1.87 |

Table 1. Non-refurbished field aged cables with a COR of above 1.8.

Therefore from this COR ranking, we can estimate cable T2-2 to be in the worst condition and T2-8 being in the best condition, for the cables with a COR greater than 1.8. All those cables with COR factors below 1.8 can be estimated to be in a reasonable condition.

V. CONCLUSIONS

This paper describes the results and some discussion on PDC and FDS measurements performed on three groups of cables; refurbished field aged cables, non-refurbished field aged cables and new cables. The two types of field aged cables were taken from a section of network which had been in service for 23 years and had suffered failure from water tree degradation.

An initial analysis was performed on the PDC measurements and simple conclusions for the conditions of the cables were made by examining the magnitude of the discharge current. Analysis of the charging current revealed a deviation from classical behaviour by having a transient, time varying conduction component in addition to a steady state DC current.

The FDS measurements showed similar trends as those seen in the PDC measurements, with the loss magnitude giving an indication of the overall condition of the cables. Loss peaks in all of the refurbished cables were found and in some of the non-refurbished field aged cables. A linear correlation between the frequency of the loss peaks and the point in time at which the current due to the dielectric response function became more dominant over the conduction current during charging, was also made.

An analysis of the AC conductivity was performed and a Contribution of Relaxation (COR) factor was introduced to quantify the difference between the real part of the AC conductivity and the AC conductivity with the DC conductivity removed. This COR factor gave an indication of the strength of the polarisation processes and was correlated with the magnitude of the loss peaks in the frequency domain and the magnitude of the dielectric response function in the time domain. Finally, values of the COR factor were given to provide an indication of the degree of water tree degradation in cables. More work needs to be done to confirm these findings and results will be published in future papers.

VI. ACKNOWLEDGEMENTS

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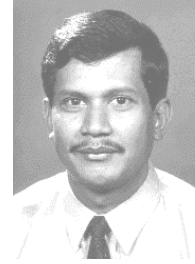
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Andrew J. Thomas is a PhD candidate at the University of Queensland's School of



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