LOW FREQUENCY DIELECTRIC SPECTROSCOPY AS A CONDITION MONITORING TECHNIQUE FOR LOW VOLTAGE CABLE IN NUCLEAR PLANTS

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ABSTRACT

The condition monitoring of low voltage (LV) cables in nuclear power plants has historically relied on material-based examination. Recent research sponsored by EPRI evaluated the ability of low frequency domain spectroscopy (LFDS) to monitor aging in thermally aged cables. In this paper the results obtained on a thermally aged 24 conductor shielded LV control cable are presented. LFDS tests were performed on short single insulated wires and the whole cable in the 10^{-3} to 10^{6} Hz and 10^{-3} to 10^{3} Hz range, respectively. A variety of diagnostic 'metrics' derived from the variable frequency dielectric response data were trended as a function of aging time and compared to traditional material property results.

KEYWORDS

LFDS, dielectric spectroscopy, chlorososulfonated polyethylene, CSPE. Ethylene propylene rubber, EPR, indenter modulus, density, multiconductor.

INTRODUCTION

EPRI sponsored this research because of the void in electrical test techniques available to identify degradation in low voltage cables. Cable degradation can be over long lengths of a cable, but typically it is localized. dielectric spectroscopy (DS), which can be performed from the cable terminations, has been used for decades to characterize dielectric properties of a wide range of materials, especially polymers [1] . However, it remained mostly a laboratory technology until its potential to assess the condition of cable insulation materials started to be explored. Within the context of polymeric cable insulation investigation, the frequency range of interest for DS has mostly been limited to between ~10^{-3} Hz and 10^{3} Hz as this covers the dielectric relaxation phenomena of strongest interest. Low frequency dielectric spectroscopy (LFDS) is the terminology used in this paper to cover that frequency range, and to distinguish it from broadband dielectric spectroscopy, which can extend in practice to frequencies up to ~10^{12} Hz [1].

The potential of LFDS to monitor cable insulation degradation, more specifically thermal aging, was investigated in EPRI Technical Report TR-105581: [2] on single, short (approximately 10cm long), wire samples with a variety of insulation types. Non-conventional low frequency (10^{-3} Hz to 10^{4} Hz) tan δ results (obtained using time domain dielectric spectroscopy techniques) were found to change with thermal aging and measurement temperature for most types of insulation materials included in the study. The applicability of LFDS testing on multi-conductor cables was also investigated and for unshielded multi-conductor configurations, testing conductor-to-conductor was found to be a realistic alternative.

More recently, the European ADVANCE project [3] investigated a number of condition monitoring techniques on LV cables with combined thermal and radiation aging. Among the electrical techniques investigated, LFDS showed the most promising results. In particular, between 10^{-2} Hz and ~10^{6} Hz, test results on shorts single wire samples showed that both real (ε') and imaginary (ε'') parts of permittivity of XLPE, EPR-based and EPDM-based insulations increased over the whole frequency range. The variation of ε' was more evident at low frequency, while ε'' increased markedly also in the high frequency range. The change in electrical properties appeared to correlate well with traditional material-based characterization techniques. This research led to the publication of a series of papers with additional details about the work with LFDS [4, 5, 6]. Linde et al. subjected XLPE insulation to combined thermal and radiation aging under different conditions [4]. ε' and ε'' were found to increase with increasing aging. ε'' at 100 Hz in particular was found to increase linearly with the density of the material. The same team also showed that the imaginary permittivity ε'' correlated well with the material relaxation time, as measured by nuclear magnetic resonance [5]. Verardi et al. [6, 7, 8] also reported good correlation between elongation at break and the real and imaginary part of the permittivity at 10^{-2} Hz for EPR insulated cables subjected to simultaneous thermal and radiation aging.

A few other independent studies have provided more insight into the potential of LFDS for LV cables condition monitoring. Braun highlighted the sensitivity to thermal aging of dielectric loss measurements at very low frequency (10^{-2} Hz and lower) for a number of insulation materials [9]. Careful test configuration selection was noted to be important to ensure reliable and repeatable results. Chailan et al. demonstrated the applicability of dielectric spectroscopy to monitor thermal aging of EPR [10] and CSPE [11] materials. The method was also found to be able to detect changes in the insulation properties induced by irradiation [12, 13, 14]. It should be noted that most of these studies focused on the characterization of material samples (e.g. single core insulated wires, thin films/slabs), rather than practical cable samples. Recent work on XLPE insulated cables [15, 16, 17] further demonstrated the potential of LFDS to assess the condition of thermally aged cables and to link the measured changes in dielectric properties to physical change in the material. It should be noted that only shielded medium voltage cables were considered in these studies.

While the past research reviewed above has demonstrated the ability of LFDS to track thermal and radiation induced degradation in LV cable insulation no data is available for whole cables subjected to aging. The results summarized in this paper address this knowledge gap by presenting data collected on a thermally aged 24 conductors shielded LV control cable representative of cables currently installed in US nuclear power plants. Effect of test configuration, test temperature, test voltage were also addressed in this study.

EXPERIMENTAL

Cable Sample

The LV cable used for this study was manufactured in 1979 and is rated 600V. Its construction includes 2 conductors #12AWG (3.31mm2), 22 conductors #20AWG (0.518mm2), ethylene-propylene rubber (EPR) insulation with bonded chlorosulfonated polyethylene (CSPE) layer insulation, shield, CSPE jacket. A cross-sectional picture of this cable is provided in Figure 1. This cable type is commonly found in US nuclear power plants.

Figure 1 Cross-section of cable sample.

Thermal Aging

Samples approximately 18.60m long were cut for the bulk aging experiment. Smaller 0.30m sections were also obtained for material tests, including individual wires removed from the cables' assembly.. The long cable samples were wrapped around metallic mandrels approximately 40 times their diameter for the purpose of thermal aging. The mandrels were placed inside a large walk-in oven for thermal exposure with the cable ends routed out to allow for electrical testing at various temperatures and time intervals. The shorter individual sections of cables and individual wires were hung in the same oven above the mandrel. The aging temperature was set at 110°C with a tolerance of ± 2°C and between 100 and 200 volumetric air changes per hour. The temperature was recorded at multiple locations inside the oven. The aging was stopped at regular intervals to perform electrical testing of the whole cables and remove smaller samples for material and electrical characterization per the procedures described below. The intent of aging was not to relate accelerated aging to actual life in the plants but to achieve information at different levels of thermal degradation.

Mechanical and Physical Tests

While tensile elongation is commonly used to monitor LV cable insulation degradation, tensile testing of composite insulation does not yield useful result. The insulation external CSPE layer ages faster than the underlying EPR material and leads to premature fracture of tensile specimens during testing. Because of the unique behavior of this composite material, tensile testing was not used to monitor aging. It should also be indicated that the jacket properties were also monitored during aging, but these results are not included in this paper since it is focused on monitoring of the insulation material.

Density

Density of the material was measured by the displacement method, as described in ASTM D792 [18]. The medium used for the test is de-mineralized water at room temperature. A small specimen of insulation is weighed in air and subsequently in water. A density measurement kit is used to measure the weight of the sample in water. The water temperature is measured with an accuracy of 0.1°C (0.18°F). The specific gravity of the material was calculated according to the equation in ASTM D792 [18].

Indenter Modulus

The indenter modulus was measured with the original EPRI indenter following well documented methodology [19] and IEC 62582-2 [20]. To test the insulation, an individual wire is used. The specimen is secured with the head clamp and its surface compressed by the indenter tip at a constant speed of 5.4 mm/min. The load, in Newtons, is recorded as a function of displacement up to a maximum of 9 N at which point the tip is retracted to avoid damaging the specimen. The indenter modulus corresponds to the slope of the resulting curve in the 4.5 N to 8.5 N range.

Electrical Tests

Electrical testing in this study was focused on LFDS with the addition of polarization / depolarization current (PDC) measurements to obtain very low frequency dielectric response data. Two sets of distinct tests were performed: testing of the 18.60m cable being aged and testing of individual wires to characterize the properties of the insulation materials. Since the frequency range studied for this work went from the 10^{-3} to ~10^{6} Hz region and voltages up to 200Vpk were utilized, multiple devices with different characteristics were used. Influence of test tempeature was studied by performing tests at 20°C, 40°C and 80°C at each test interval. Influence of test voltage was also considered by varying the voltage up to 200 Vpk at selected intervals.

Frequency Domain Dielectric Spectroscopy

Frequency domain dielectric spectroscopy (FDDS) testing is used to illustrate the frequency dependence of the dielectric loss (tangent delta) and capacitance of a test object, although voltage, time and temperature dependence characteristics of tan δ and capacitance can also be illustrated through multi-variable measurements. FDDS results are obtained from direct, highly accurate measurements of the complex impedance over variable voltage and frequency, calculated using Ohm's Law Z* = U/I (where Z and U/I are complex entities). Although various impedance models can be used to interpret the results, the complex capacitance model is very often used in insulation diagnostics to represent results. This model represents the insulation impedance as a complex capacitance where C''/C' represents the dielectric losses (tangent delta). The real part of capacitance (C') represents the material capacitance while the imaginary part (C'') represents a unit-less parameter which can be comprehended as the 'un-normalized' dielectric loss. A real un-shielded cable insulation system can be modeled as a nonlinear circuit with nonlinear resistive and reactive components resulting in a dielectric response which varies with frequency and changes with insulation thermal deterioration and geometric variations.

$$Z(\omega) = \frac{1}{j\omega C(\omega)} \; where$$

$$C(\omega) = C'(\omega) - jC''(\omega) \text{ and}$$

$$C'(\omega) = Re\left\{\frac{1}{j\omega Z(\omega)}\right\}$$

$$C''(\omega) = -Im\left\{\frac{1}{j\omega Z(\omega)}\right\}$$

$$\tan\delta(\omega) = \frac{C''(\omega)}{C'(\omega)}$$

Practically, the FDDS technique involves the application of a variable frequency AC voltage applied to the cable under test, in order to measure capacitance and tangent delta. As noted previously, the time it takes for an AC waveform to complete one cycle increases as the frequency decreases. Due to time constraints, 'pure' FDDS tests typically do not usually go lower than 10^{-1} or 10^{-2} Hz. The use of time domain PDC measurements can be complementary to FDDS, providing both practical and scientific benefits [21]. Practically, PDC measurement data gathered in the time domain takes a much shortrer period of time (e.g. < 1000s) and can then be converted to the very low frequency domain (e.g. ~10^{-4} to 10^{-1} Hz), using a curve fitted Fast Fourier Transform (FFT) [22] or an approximating relation such as the Hamon approximation [23]. This approach is referred to as time domain dielectric spectroscopy (TDDS)

Measurement Grounding Configurations

The electrical tests measurements in this study considered various grounding configurations:

- The grounding for the mandrel upon which the test cables were mounted – both grounded mandrel (GM) and floating mandrel (FM) variants were considered.
- The unshielded test cable return conductor (e.g. measurement electrode) grounding – both grounded specimen test (GST) and ungrounded specimen test (UST) variants were considered.

The mandrels were either kept grounded or floating to assess the influence of varying un-shielded cable test configurations, measurement configurations and thermal aging degradation to the presence (or lack of) a well-defined ground plane. While these aspects were considered as part of the overall study they are not incorporated in this paper due to the large amount of data produced. The data presented in the Results section are based on the most appropriate configurations.

Test Configurations

The use of multi-conductor unshielded cables leads to a large number of possible test configurations. One of the key objectives of the project was to assess the influence of these different configurations on the results and to determine optimal test protocols to monitor LV cable aging with LFDS. To achieve this objective the cable was baseline tested (i.e. pre-aging) under a number of different scenarios. The test configurations selected for baseline testing in this project were themselves based on trials and simulations performed before the start of aging. Aging interval testing configurations were streamlined based on an analysis of pre-aging configurations for reciprocity, measurement sensitivity, sensitivity to ground plane influence and field test practicality. Because of the large amount of data associated with this configuration study it is not discussed in this paper. The test results presented in the Results section are based on the most appropriate test configurations.

RESULTS

Material Tests

Density and IM tests results on the cable insulation are presented in Figure 2 and Figure 3, respectively. In both cases normalized values are reported. Tests performed on all the different insulation colours revealed slight differences in properties. To account for these differences the results for each colour were normalized to the unaged value and averaged together at each interval. The density and IM results clearly exhibit an increase with increasing thermal aging, characteristic of a loss of ductility and hardening.

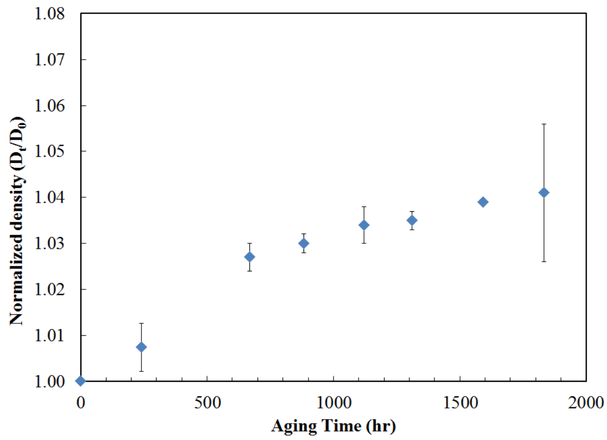

Figure 2: Normalized density as a function of aging time.

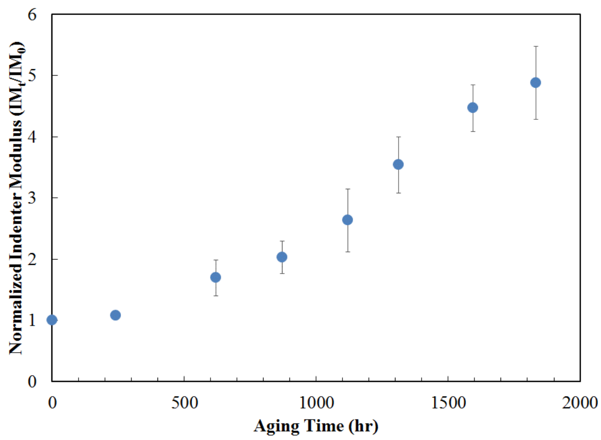

Figure 3: Cable insulation normalized indenter modulus versus aging time.

Electrical Tests

Temperature Sensitivity

Figure 4 and Figure 5 show the C' and C'' results at three different test temperatures (20˚C, 40˚C, and 80˚C) and 2 different aging intervals (I1=669 hr and I7=2052 hr). Test configuration, external grounding and measurement electrode grounding were held constant with a grounded specimen test (GST) test by energizing the 24 conductors and using the grounded shield as a return and grounding the mandrel. These results exhibit clear temperature dependence when all else is held constant. This is clearly observed if one compares the relative change as a horizontal 'offset'. The data presented also illustrates that such relative changes are observable independent of the aging level.

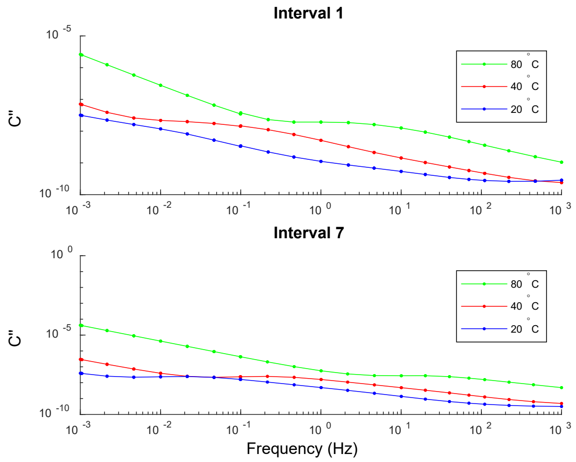

Figure 4: Comparison of different test temperatures for C'' at an early and late aging interval.

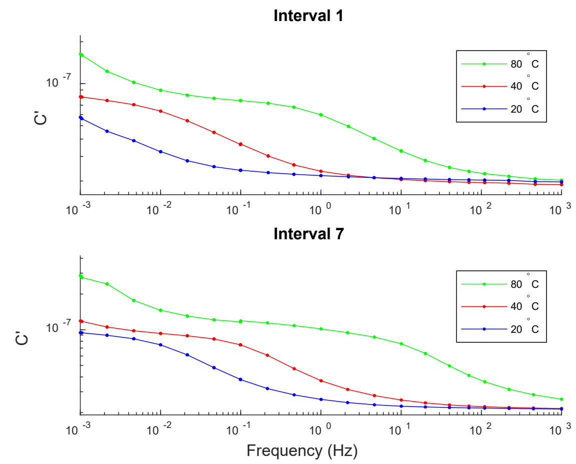

Figure 5: Comparison of different test temperatures for C' at an early and late aging interval.

Voltage Sensitivity

Two different applied voltages (10Vpk and 200Vpk) were considered in order to explore the dependence of voltage on test measurement data. Test temperature was held constant at 40˚C, and the maximum thermal aging intervals was selected (I7=2052 hr). A single representative test configuration, similar to the one described above, were considered with varying external and measurement electrode grounding (ungrounded specimen test (UST) vs GST test). As seen in Figure 6 and Figure 7, the C' and C'' for the noted cable configurations do not exhibit a significant level of voltage dependence within the range considered. This is observed if one compares the absence of any significant 'offsets' between the 10Vpk and 200Vpk measurements shown.

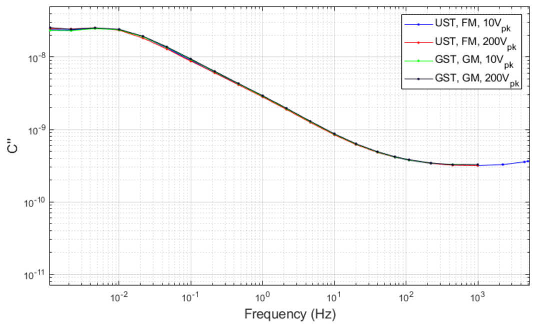

Figure 6: Comparison of C'' between different grounding and voltages.

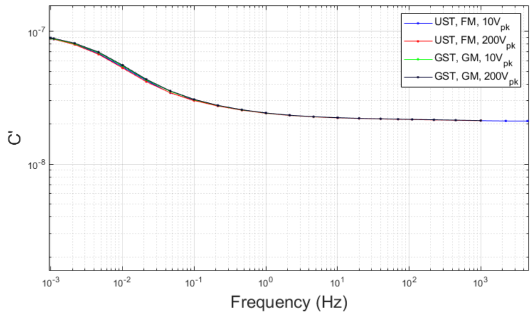

Figure 7: Comparison of C' between different grounding and voltages.

Sensitivity to Aging

Results for UST tests with the 24 conductor energized and return through the floating shield are presented in Figure 8 and Figure 9 for C' and C'', respectively, for all the aging intervals. External grounding, test temperature and applied voltage were held constant at Floating Mandrel, 40˚C, and 200Vpk, respectively. The LFDS data exhibited very clear changes in dielectric frequency response with thermal aging. Specifically, the C' data showed variation over the whole frequency range between 0.001 to 1MHz, although the effects are most clearly visible between 0.001 to ~10Hz. The C'' data showed a variation in the polarization peak (visible in the low frequency region of ~0.02 to 1Hz) with aging, as well as a variation in the low frequency dispersion (the non-linear increases observed in the low frequency region of ~0.001 to 0.02Hz) with aging. The tan δ (C'' / C') data, not shown here, reflected a combination of the same characteristics observed in the C'' and C' data, however the division of the two characteristics created regions of non-uniform variation. Similar results were observed when energizing the central conductor and return through the 23 surrounding conductors (floating), albeit with C' and C'' values orders of magnitude smaller.

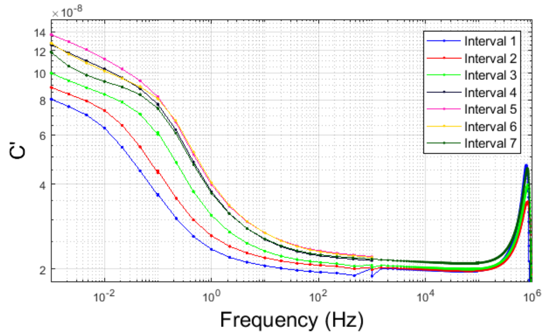

Figure 8: C' frequency response vs. thermal aging.

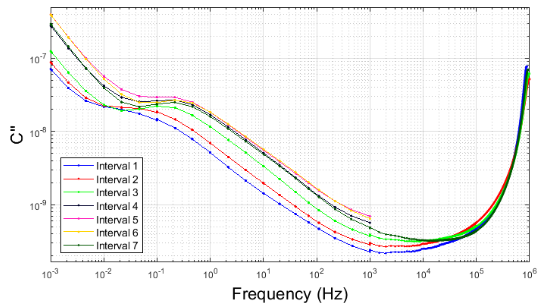

Figure 9: C'' frequency response vs. thermal aging.

The variations observed with aging in the LFDS data are most clearly observed from the quantitative analysis of diagnostic 'metrics'. The metrics show that C' and C'' values at selected frequencies including 0.001, 0.01, 0.1, 110, 10000Hz, maximum / minimum C'' and maximum C' nearly all show an increasing trend up to 1593 hours, after which the values decrease for the next 2 intervals. The decreasing trend from 1593 hrs onwards is also more prominently visible at certain representative frequencies for C' or C''. The magnitudes of C' and C'' and noted trend behavior are increased at 40˚C compared to 20˚C The 80˚C data, albeit limited, also suggests similar behavior. Representative plots of C' at 1 mHz and 100 mHz are provided in Figure 10 to illustrate these findings. It should be noted that the observed trend was best defined for C' at lower frequencies as shown in that figure.

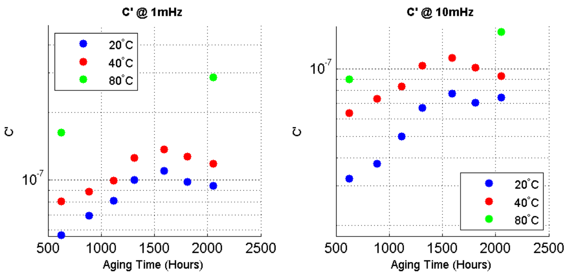

Figure 10: C' at 1 mHz and 100 mHz frequencies versus aging time.

To gain technical insight into the trends noted above from the full-scale cable, the results were compared to data from individual single core specimens, as well as selected physical / chemical aging markers. The former can help understand the relationship between dielectric responses behaviors observed in full multi-conductor cables to behavior at the single conductor level, whereas the latter can help draw correlation of full-scale cable diagnostic trends to the evolution of physical / chemical aging. Figure 11 shows an example of a comparison plot from the full-scale cable diagnostic aging marker noted above (C' at 1 mHz), against the same aging markers from a single core specimen. The two trends exhibit a good correlation.

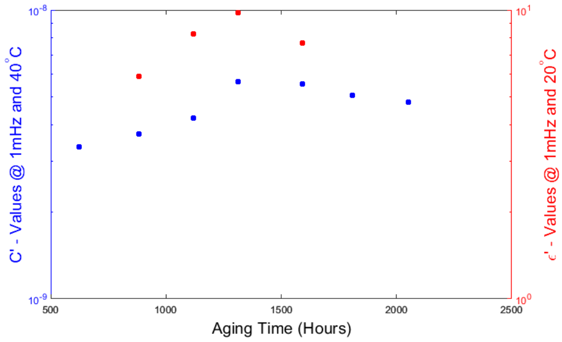

Figure 11: Comparison of C' and ε' at 1 mHz for whole cable and single core green samples.

Figure 12 shows a cross-plots comparing the whole-cable aging marker (C' at 1 mHz.) to normalized physical aging markers Indenter Modulus and Density. While good correlation was observed up to 1593 hr of aging, the same inflexion in the data noted earlier was observed.

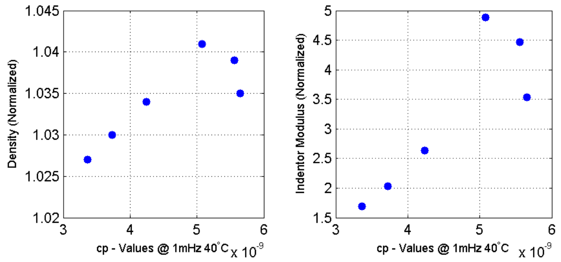

Figure 12: Cross-plot of material test results with LFDS aging markers.

DISCUSSION

The full-scale results obtained during this study highlighted the ability of LFDS to monitor changes in insulation properties as a result of thermal aging. This finding was supported by the similar results obtained with single core specimens which provided a more accurate measure of the evolution of the insulation material properties Dielectric response exhibited numerous features indicating signs of active dipole relaxation, electrical conduction and interfacial polarization processes. The 'signatures' of each underlying dielectric process changed with thermal aging, some more prominently than others. For instance, there was a clear evolution in the formation of a dipole relaxation peak up to approximately the 1312 hr to 1593 hr of aging, after which most of the following changes occurs in the electrical conduction and interfacial polarization processes in the 'very low' frequency region between approximately 0.001 to 0.2Hz, seen in both the C' and C'' data. The increased influence of these processes, notably interfacial polarization for the dual layer insulation used in this work, could explain the inflexion in the trend observed for the aging markers presented here. More fundamental research in the dielectric behaviour of such materials when subjected to thermal aging is needed to elucidate these results.

CONCLUSIONS

In summary, the electrical tests conducted in this study indicate that LFDS measurements can be sensitive enough to global aging effects in multiconductor LV cable insulation However, it is crucial to carefully consider experimental parameters and cable test configurations to achieve optimal results. Furthermore, the results from the study highlighted the unique and complex dielectric response characteristics to bulk thermal aging. Additional work on different insulation types and designs, currently ongoing, will allow better understanding of the effects of thermal aging on the dielectric response of multiconductor LV cables.

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GLOSSARY

FDDS: Frequency Domain Dielectric Spectroscopy
LFDS: Low Frequency Dielectric Spectroscopy
IM: Indenter Modulus
OIT: Oxidation Induction Time
PDC: polarization depolarization current
TDDS: Time Domain Dielectric Spectroscopy