CONDITION MONITORING OF THERMALLY AGED LOW VOLTAGE CABLES WITH POLARIZATION-DEPOLARIZATION CURRENT TESTING

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ABSTRACT

Polarization-depolarization current (PDC) measurements have been used to assess the condition of medium voltage (MV) cables, however to date little research has been done to apply this test method to LV cables and their unique designs and constructions. Recent research sponsored by EPRI evaluated the ability of PDC to monitor aging in thermally aged cables. In this paper the results obtained on thermally aged 24 conductor shielded and 3 conductor unshielded cables are presented. A variety of diagnostic 'metrics' derived from polarization and depolarization currents data were trended as a function of aging time and compared to traditional material property results.

KEYWORDS

Polarization-depolarization current, PDC, dielectric spectroscopy, FDDS, LFDS, chlorososulfonated polyethylene, Ethylene propylene rubber, XLPE, indenter modulus, density, OIT.

INTRODUCTION

The potential of frequency domain dielectric spectroscopy (FDDS) to assess the condition of aged low-voltage (LV) cables has been investigated by a number of research groups since the mid-1990s. EPRI Technical Report TR-105581: [1] and more recently the European Advance Project [2][3][4][5][6] highlighted the capability of this technique to track change in material properties as a result of aging. A few other independent studies have provided more insight into the potential of FDDS for LV cables condition monitoring. Chailan et al. demonstrated the applicability of dielectric spectroscopy to monitor thermal aging of EPR [7] and CSPE [8] materials. The method was also found to be able to detect changes in the insulation properties induced by irradiation [9, 10]. 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.

In a number of the studies just mentioned, very low frequency (below 0.1 Hz) FDDS results were found to be sensitive to the level of aging of the insulation under test. However, from a practical standpoint, tests conducted below 0.1 Hz take a much longer time, which may limit their applicability in the field. The use of time domain DC polarization / depolarization current (PDC) measurements can be complementary to FDDS, exhibiting some practical and scientific benefits [11]. Practically, PDC measurement data gathered in the time domain over fairly short periods of time (e.g. < 1000s) can be converted to the very low frequency domain (e.g. ~10^{-4} to 10^{-1}Hz), through a curve fitted Fast Fourier Transform (FFT) [12] or an approximating relation such as the Hamon approximation [13]. This approach is referred to as time domain dielectric spectroscopy (TDDS). Scientifically, PDC data (analyzed either directly in the time domain or through mathematical conversion in the frequency domain) includes information relating to both depolarization and polarization dielectric behavior, which can provide additional information regarding dielectric response phenomena. Aging studies focusing on PDC testing have shown the presence of diagnostic markers sensitive to medium voltage cable water-treeing / wet-aging insulation degradation [14, 15], and more recently to MV cable thermal aging [16].

This literature review highlights the benefits of using PDC testing to support the application of FDDS to assess the condition of LV cables in the fields. Recent EPRI sponsored research investigating the applicability of FDDS to monitor the condition of multiconductor LV cables, and also included evaluation of the PDC technique. The results summarized in this paper present data collected on thermally aged 24 conductors, shielded LV control cable and 3 conductors, unshielded power cables used in US nuclear power plants. Sensitivity of data collection to test configuration, test temperature, test voltage were also addressed in this study, however not all results are discussed in this paper.

EXPERIMENTAL

Cable Samples

The LV cables used for this study included:

- A 24/C cable manufactured in 1979 and rated 600V. Its construction includes 2 conductors #12AWG (3.31mm2), 22 conductors #20AWG (0.518mm2), ethylene-propylene rubber (EPR) with bonded chlorosulfonated polyethylene (CSPE) layer insulation, shield, CSPE jacket.
- A 3/C cable rated 600V. Its construction include 3 conductors #12AWG (3.31mm2) FR-XLPE insulation, CSPE jacket. A cross-sectional picture of both cables is provided in Figure 1.

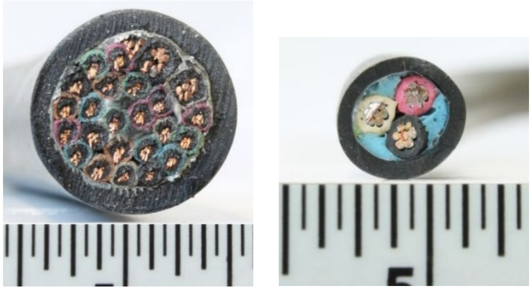

Figure 1 Cross-section of 24/C and 3/C cable samples.

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 interrupted 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 the most common method to monitor LV cable insulation degradation, tensile testing of composite insulation such as the one found in the 24/C cable 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. In addition, for the 3/C XLPE cable the level of aging reached during the study did not result in significant tensile elongation degradation. Because of these unique behaviors tensile testing was not included in this paper.

Density

Density of the material was measured by the displacement method, as described in ASTM D792 [17]. 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 [17].:

Indenter Modulus

The indenter modulus was measured with the original EPRI indenter following well documented methodology [18] and IEC 62582-2 [19]. 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 1 lb. (4.5 N) to 1.9 lb. (8.5 N) range.

Oxidation Induction Time (OIT)

OIT was conducted according to ASTM D3895 [20]. In this test a small insulation specimen, about 10 mg, is placed in an aluminum pan without a lid. The pan, along with an empty reference pan, is placed in the Differential Scanning Calorimeter (DSC). The sample is then heated up to the required temperature at a fast rate (50°C/min) and maintained at this temperature for 5 minutes under nitrogen atmosphere. The atmosphere is then switched to oxygen (purity 99.6%) and maintained until onset of oxidation characterized by an exothermic reaction. The OIT is the time between the introduction of oxygen and the point at which the extrapolated base line meets the extension of the oxidation peak. The temperature set-point for the OIT experiment is generally determined through an Oxidation Induction Temperature experiment and a few trials.

Electrical Tests

Electrical testing in this paper focuses on polarization / depolarization current (PDC) measurements. Two sets of distinct tests were performed; testing of the 18.60m cable being aged and testing of individual specimens to characterize the properties of the insulation materials. 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 between 10 and 200 Vpk at selected intervals.

Polarization / Depolarization Current Testing

The PDC technique is used for directly measuring the DC polarization or depolarization current time domain response, or indirectly measuring dielectric properties at lower frequencies through time-frequency conversion (TDDS). Ultimately, both measurements are sensitive to the same dielectric relaxation phenomena, but the analysis of depolarization current separate from polarization current allows for a separation of static 'quasi-conduction' DC current (i_{qc}) effects in a dielectric from the time variant capacitive and absorption DC current (i_{cap} and i_{abs}) effects. This discrimination is illustrated in the formulae below, with t representing measurement time:

$$i_{pol}(t) = i_{cap}(t) + i_{abs}(t) + i_{qc}$$

$$i_{depol}(t) = i_{cap}(t) + i_{abs}(t)$$

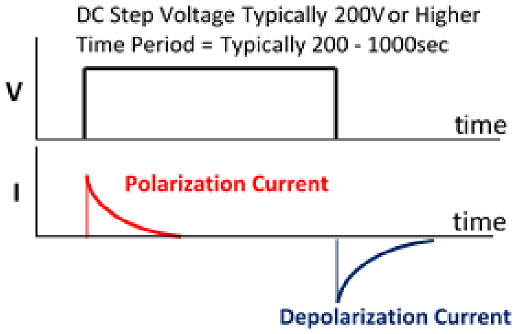

Figure 2: PDC test protocol.

It is noted that in the context of traditional insulation resistance (IR) testing of power equipment, the quasi-conduction current i_{qc} can also be represented by separate, static 'conductance' current (I_G) and 'leakage' current (I_L) components. Practically, the PDC technique involves a DC step voltage being applied to the power cable while the charging or polarizing current is recorded. After a certain amount of time, the DC step voltage is shorted and the discharging or depolarizing current is recorded. This process is illustrated in Figure 2. As noted previously the polarization and/or depolarization current data can be analyzed directly in the time domain, or transformed to the frequency domain via a curve fitted FFT or other approximating relation (such as the Hamon approximation).

Measurement Grounding Configurations

The electrical tests 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 PDC. 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. For the aging interval testing, the list of configurations was further streamlined based on an analysis of 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. As noted in the previous section, test results presented in the Results Section are based on the most appropriate test configurations.

RESULTS

Material Tests

The results of the density and IM tests for the 24/C cable insulation are presented in Figure 3 and Figure 4, 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 exhibit an increase with increasing thermal aging, characteristic of a loss of ductility and hardening.

The results of the OIT tests for the 3/C cable insulation are provided in Figure 5. As noted for the 24/C cable, normalized values are reported. The OIT is observed to decrease with increasing thermal aging, which is characteristic of gradual depletion of antioxidants in the XLPE insulation. It should be highlighted that at the level of aging reached in this study the 3/C cable insulation is not displaying any physical degradation since it still retains measurable levels of antioxidants.

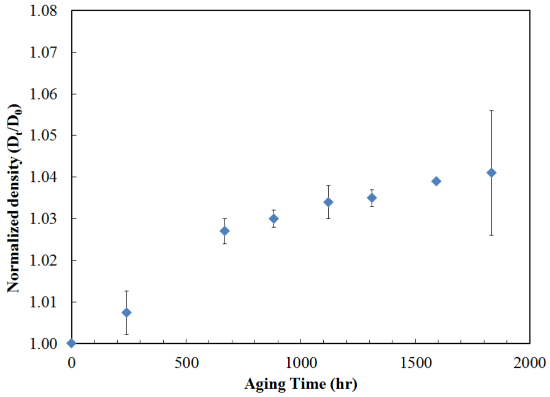

Figure 3: 24/C Cable normalized density versus aging time.

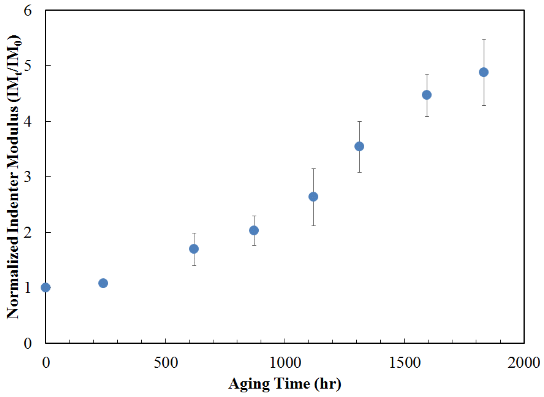

Figure 4: 24/C Cable insulation normalized IM versus aging time.

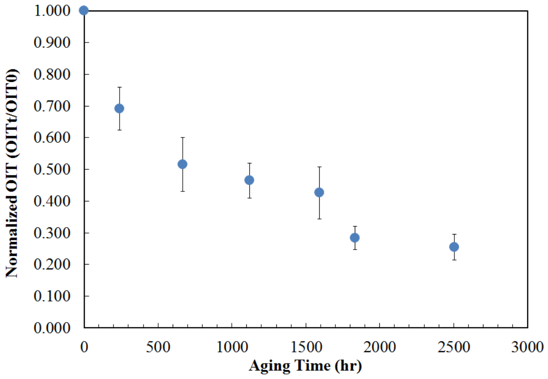

Figure 5: 3/C Cable insulation normalized OIT versus aging time.

Electrical Tests

Temperature and Voltage Sensitivity

Influence of test temperature and voltage on FDDS results is discussed in another paper in more details. For PDC measurements similar effects were noted, with Figure 6 showing the influence of test temperature on polarization current results for the 24/C cable. Test configuration, external grounding and measurement electrode grounding were held constant with a GST test by energizing the 24 conductors and using the grounded shield as a return and grounding the mandrel. The magnitude and slope of the current data are found to change with temperature. These changes are observed at all aging intervals as seen in the figure. Similar effects were present in the depolarization plots and were consistent for both cables included in this paper (not shown). PDC results did not exhibit any evidence of practically significant levels of voltage dependence in the 10Vpk to 200Vpk considered in this study.

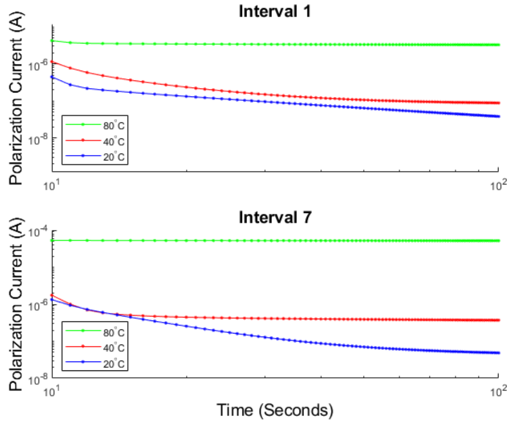

Figure 6: Comparison of different test temperatures for polarization current for 24/C cable.

Sensitivity to Aging

PDC testing of the two cables was conducted at increasing levels of thermal aging. The tests were conducted in a UST configuration, with the 24 conductors energized and return through the floating shield for the 24/C cable, and with 2 conductors energized and return through the floating third conductor for the 3/C cable. External grounding, test temperature and applied voltage were held constant at Floating Mandrel, 40˚C, and 200Vpk, respectively. Polarization and depolarization data for the 24/C cable are presented in Figure 7 and Figure 8, respectively, for all the aging intervals. These results show variations with thermal aging. More specifically, the polarization current response exhibits curve shifts over the whole time range from 10 to 1000s, although the effects are most clearly visible between 20s and 1000s. Similar curve shifts are observed in the depolarization current response, most clearly in the 60s to 1000s range.

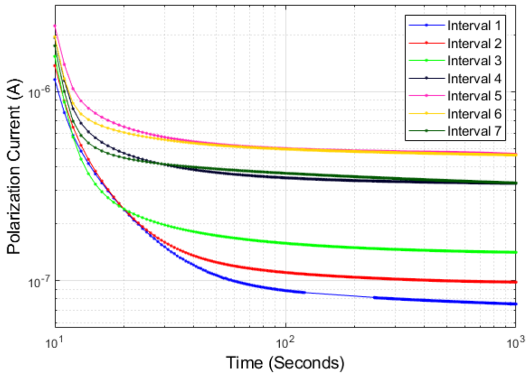

Figure 7: Polarization current for 24/C cable versus thermal aging. Configuration UST (1-24) E, Shield L, FM, 200Vpk.

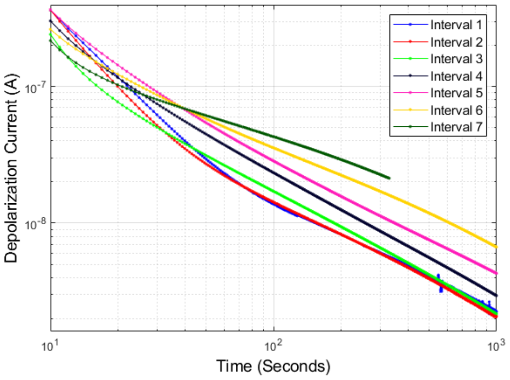

Figure 8: Depolarization current for 24/C cable versus thermal aging.

The polarization and depolarization current curves for the 3/C cables showed only minimal shift in the result as a result of thermal aging. Depolarization data is provided in Figure 9 to illustrate this point.

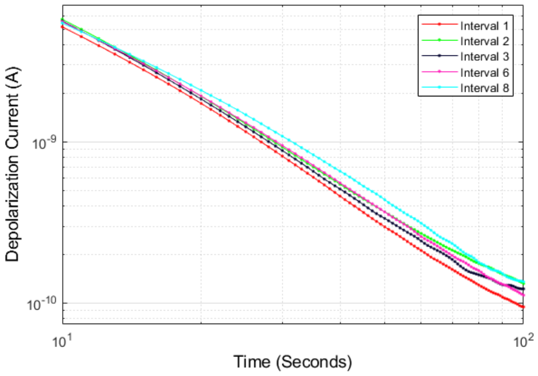

Figure 9: Depolarization current for 3/C cable versus thermal aging.

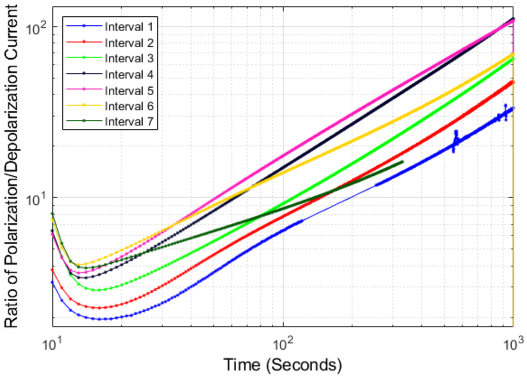

Figure 10: Ratio of polarization and depolarization data for 24/C cable versus thermal aging.

To better analyze changes in the polarixation and depolarization current and elucidate the longer time dispersion characteristics in the time domain data, mathematical treatments have been utilized by dielectric researchers and test practitioners. These treatments include plotting the ratio of polarization / depolarization current over time [14], plotting the depolarization x time product (I_{depol} x t) versus time, commonly referred to as

'Isothermal Relaxation Current' (IRC) analysis [15] and finally plotting the depolarization x time product (Idepol x t) versus Idepol. The ratio of polarization / depolarization data and IRC are provided in Figure 10 and Figure 11, respectively, for the 24/C cables. These plots also show shifts over the whole time and current range, although the effects are more clearly visible in specific regions.

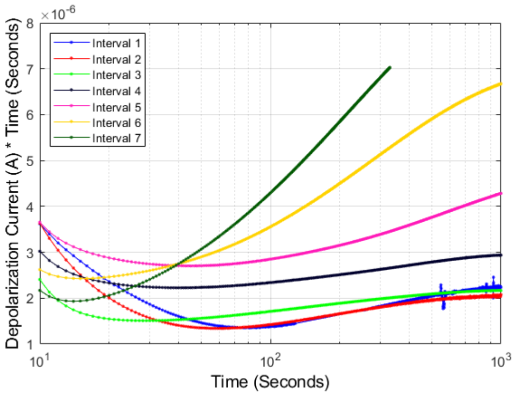

Figure 11: Isothermal Relaxation Current (IRC) representation for 24/C cable versus thermal aging.

The variations observed with thermal aging in the time domain PDC data are most clearly observed from the quantitative analysis of diagnostic 'metrics'. Representative metrics extracted at 10min for the 24/C cable, and 100s for the 3/C cable are shown in Figure 12 and Figure 13, respectively. Polarization current metrics for the 24/C cable taken at 10 minute show an increasing trend up to 1593 hours, followed by a decreasing trend for the last two intervals. This inflexion point in the results, which was also found in the FDDS experiments presented in a separate paper, was not observed in the depolarization current data which shows a generally increasing values throughout the aging program. The trends were more marked at higher test temperatures (40˚C and 80˚C). The polarization and depolarization cross plots at 40˚C, Figure 12, indicate how the two currents change in relation to each other throughout the aging program, where each point refers to a different aging interval. As the points diverge from a slope of one (the dashed line), a conduction current effect can be noted, as conduction current caused by thermal aging will manifest itself in polarization current, but not depolarization current. For this configuration, a conduction current effect is present up to the 1593 hrs interval, decreasing slightly afterwards. Comparable metrics were observed at 1 minute (not included in this paper). The 3/C only exhibited limited changes, indicating no signficant degradation of the insulation has taken place after approximately 2500 hrs. This finding is in agreement with the OIT results which showed that the XLPE insulation still had remaining antioxidants. This cable will undergo additional aging in follow-up research to reach higher levels of degradation and to confirm that the findings from the 24/C cable also apply to this insulation type. Figure 14 shows a cross-plots comparing a selected whole-cable aging marker for the 24/C cable (IRC at 100s and 40˚C) to normalized physical aging markers IM and Density. Very good correlation was observed between the two sets of data.

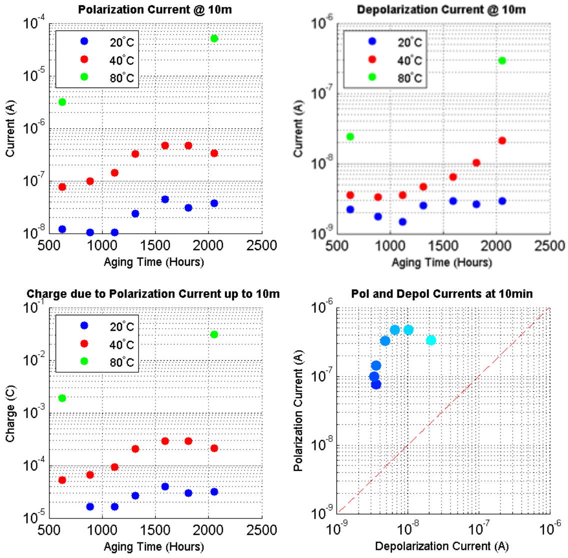

Figure 12: Representative time domain metrics taken at 10 minutes for the 24/C cable.

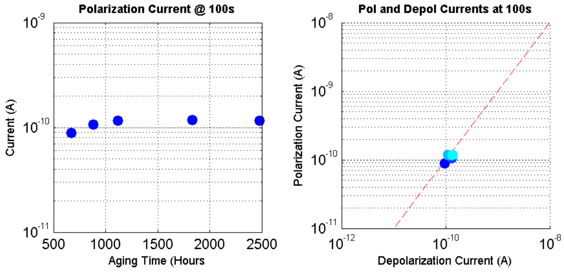

Figure 13: Standard time metrics taken at 100s for 3/C cable at 40^{0}C.

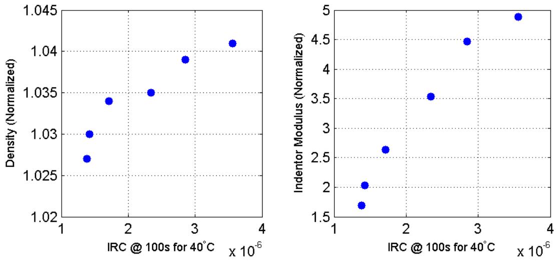

Figure 14: Cross-plot of material test results with PDC aging markers at 40^{0}C for the 24/C.

DISCUSSION

The full-scale results obtained during this study highlighted the ability of PDC to monitor changes in insulation properties as a result of thermal aging. The analysis of the PDC results, particularly the differences between polarization and depolarization responses, provide a deeper insight into the underlying effects affecting the insulations under test. The results for the 24/C cable show increases in electrical conduction effects, followed by a decrease. The depolarization current metrics and I_{pol} versus I_{depol} cross-plots also illustrate a clear increase in the absorption current (i_{abs}) effects throughout the aging program, which can relate to dipole relaxation, interfacial polarization or a combination thereof.

The limited changes observed in the dielectric response of the 3/C cable is related to the limited aging experienced by the insulation material. The dielectric response will be most influenced by structural changes in the polymer, mostly through increased crosslinking. In the absence of such modification the depletion of antioxidants, which represent less than 1% of the insulation material by weight, is expected to have little influence on dielectric processes. That being said, the limited trend observed appear to indicate that PDC measurements are sensitive enough to detect aging effects induced by the depletion of antioxidants.

CONCLUSIONS

The tests conducted in this study highlighted the potential of PDC measurements to monitor thermal aging in multiconductor cables. As noted for the FDDS results reported in another paper, the experimental parameters and cable test configurations have to be considered carefully to achieve optimal results. The data were also found to provide some insight into the dielectric processes affecting the insulation, especially by looking at differences between the polarization and depolarization data. PDC testing was also found to be appropriate to reduce the time to obtain reliable data in the low frequency range in comparison to FDDS testing. 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 and provide more data to support the use of PDC testing as a diagnostic tool for 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