Abstract: Determining the aging state of low-voltage nuclear power plant cables using a nondestructive and reliable condition monitoring technique is highly desirable as the cables experience multiple aging stresses during the service period. This paper deals with the implementation and investigation of such nondestructive techniques, which can detect the overall aging state of low-voltage instrumentation and control (I&C) cables, which are subjected to accelerated thermal aging. The dielectric spectroscopy, extended voltage response, and polarization–depolarization current as nondestructive electrical aging techniques were used for the investigation purpose, while the elongation at break was also adopted as a mechanical measurement and for comparison. Prominent variations in the electrical parameters for the insulation and jacket were observed, whereas the elongation at break for both materials also decreased under thermal aging. Based on the electrical techniques, aging markers were selected that showed a strong correlation with the aging and elongation at break, proving the ability of the adopted electrical methods as a nondestructive condition monitoring technique.

Keywords: nuclear power plant; low-voltage cables; thermal aging; electrical aging markers; dielectric spectroscopy; extended voltage response; polarization–depolarization current; elongation at break

1. Introduction

As reported in the International Atomic Energy Agency (IAEA) Report [1], many nuclear power plants (NPPs) have been designed for 30–40 years, for which there has been an indication of underestimating the aging phenomenon during operation as well as during the design phase. The significant contribution of the NPPs to the worldwide electric generation has prompted the many nuclear operators to seek the life extension of the plants up to 80 years since this form of energy is cheap and less time-consuming. Since safety is a key feature of the reliable operation of the NPPs, the aging management of the components, systems, and structures has been implemented [2,3]. Low-voltage (LV) cables are an important part of NPP components, which are more than 1500 km in length and considered irreplaceable not only during the service but also during life extension cases. The requalification and effective aging management of these cables require condition monitoring (CM) techniques.

The LV cables in the NPPs have the responsibility of delivering power and control signals to such equipment, which are very essential for operational safety. During their service time, these cables in the NPP environment are exposed to radiation, thermal, electrical, and mechanical stresses [4]. For the control and instrumentation cables, thermal aging is a critical factor, as compared to irradiation [5]. For the case of NPPs, the polymeric nature of the cable insulation and jacket under thermal and radiation leads to the molecular
structure alteration, hence influencing the macroscopic properties, a topic that for many years has driven many researchers to investigate the different aspects [5–8].

To date, most of the available CM techniques are destructive and are laboratory-based, requiring a small sample of the polymeric material to be investigated. However, the utmost desired feature of the CM is to be nondestructive and applied as an online method in the field conditions [9,10]. Dielectric properties are important characteristics of polymeric insulation, which have a direct impact on the stable operation of cables [11,12]. Line resonance analysis (LIRA), dielectric spectroscopy, and time domain reflectometry (TDR) [7,10,13–18], being nondestructive and based on the dielectric properties investigation, have been adopted in recent times with most of the research focused on the insulation and jacket separately, whereas extending the application of the electrical techniques for the online field conditions requires monitoring the overall state of the cable without the separation of the insulation and jacket.

The elongation at break (EaB) is often used to evaluate the end of life of polymeric materials [8,9,12]. Subsequently, the selection of suitable electrical aging markers from the electrical CM techniques and then establishing a correlation with the EaB is an important setup toward establishing the electrical techniques as viable. Hence, this work is a continuation of a series of work, where the investigation and implementation of the nondestructive electrical techniques on different types and composition of NPP LV cables under different stress types were carried out [19–22].

The subject of the investigation is the widely used ethylene–propylene rubber-insulated (EPR) and chlorosulphonated polyethylene (CSPE) jacketed-based instrumentation and control (I&C) NPP LV cable [23]. In contrast to our previous work, where the whole cable was irradiated and stressed, in this work, the whole cable was subjected to accelerated thermal aging for five different aging periods. The behavior of the cable’s polymeric materials, insulation, and jacket were examined with help of frequency domain dielectric properties, i.e., capacitance and tanδ in a broad range of frequencies. In addition, time domain dielectric properties were investigated with extended voltage response (EVR) and polarization–depolarization current (PDC). Electrical aging markers were selected from these methods, and a correlation was established with EaB, which was adopted for the determination of the mechanical integrity of the polymeric insulation.

The paper has been organized as follows: Section 2 gives details about the experimental setup, cable sample, accelerated aging, adopted electrical, and mechanical measurement techniques. Section 3 discusses the results of the measurement, while the discussion is carried out in Section 4. The correlation of the electrical aging markers and EaB are established in Section 5, while the concluding remarks are given in Section 6.

2. Materials and Methods

2.1. Cable Specimen

The two-core LV cable under investigation is designed for I&C applications with an operating temperature of 90 °C, Figure 1. The inner insulation of the cable is composed of EPR, with a thickness of 0.76 mm, while the conductor has a radius of 0.732 mm. The external diameter of the cable is 12.5 mm with the outer jacket composed of CSPE.

2.2. Accelerated Thermal Aging

The cable specimens, half a meter in length, were exposed to accelerated thermal stress at a temperature of 120 °C. The accelerated aging was carried out in an air circulating oven at the High Voltage Laboratory, Budapest University of Technology & Economics, Hungary. Five cable samples were used for the study, and each sample was exposed to accelerated thermal stress of 167, 506, 842, 1174, and 1513 h, where the hours were based on the guidelines of the IAEA [2]. The jacket and the insulation were kept in contact during the whole aging period in order to realize the actual behavior of the cable during the field conditions.
2.3. Measurement

2.3.1. Capacitance and tanδ

The main aim of the research is to investigate novel electrical aging markers; tanδ was used for the analysis because the analysis based on the tanδ does not require the knowledge of the exact dimensions of cables for calculating real and imaginary permittivities, which can be difficult in the case of usual multicore I&C NPP cables. Therefore, the results of short cable samples can be generalized to real, much longer cable sections. The frequency domain measurement was carried out in two frequency ranges with the help of two different devices, with a description in Table 1. The capacitance and tanδ of the cable specimens were measured in the frequency range.

Table 1. Frequency domain measurement description.

| Frequency Range | Device                               | Input Voltage |
|-----------------|--------------------------------------|---------------|
| 10 mHz–1 kHz    | OMICRON Dirana                       | 100 V<sub>rms</sub> |
| 2 kHz–500 kHz   | Wayne Kerr Component Analyzer        | 5 V<sub>rms</sub>   |

The connections for OMICRON Dirana and Wayne Kerr Component Analyzer are shown in Figure 2a,b, while the measurement setups are depicted in Figure 2c,d. The accuracy of the Omicron Dirana is below 2% for the dissipation factor and 0.5% for the capacitance measurement, and these parameters are ±0.0002 and ±0.05% for the Wayne Kerr Component Analyzer, respectively. During the measurements, the outer surface of the cable sample was covered with an aluminum foil with a length of 29 cm. For the investigation of the capacitance and tanδ of the jacket, the input terminal was connected to the aluminum foil, and the output terminal was connected to the drain wire, and the two insulation cores were kept open-circuited. However, for the investigation of one particular insulation core, the drain wire acted as a source of the output signal, while the same core was a source for the input signal where the jacket and the other core were short-circuited. The measurements were carried out in a Faraday’s cage, an aluminum box measuring 58 × 20 × 20 cm, to keep from interfering with the measurements from the external noises. However, for the OMICRON Dirana, a guard connection was also used.
Figure 2. Connection diagram: (a) OMICRON Dirana, (b) Wayne Kerr Component Analyzer, and measurement setup, (c) OMICRON Dirana, and (d) Wayne Kerr Component Analyzer for capacitance and tanδ measurements.

2.3.2. Extended Voltage Response

The time domain EVR technique was adopted for the investigation of the degradation of the polymeric materials of the cable. The technique helps in understanding the slow dielectric polarization processes in polymeric materials. The EVR technique in the last few years has proved to be a valuable nondestructive electrical technique for the investigation of aging in insulation materials ranging from low-voltage to high-voltage equipment [24,25]. In our previous work, the in-depth working of the EVR was discussed [21,22].

During the measurement, the cable polymeric materials, i.e., insulation and jacket, were charged with a 1000 V DC voltage source for 4000 s, separately. After which, the voltage source was disconnected, during which a parameter decay voltage slope (S₀) was measured, which is based on the decay voltage. During discharging of the respective polymeric material, another parameter return voltage slope (S₁) was recorded for 20 discharging times. With the plot of S₁ against the discharging times, a polarization spectrum was obtained.

For the investigation of the jacket, the DC voltage source was connected to it with an aluminum foil of 29 cm wrapped over the cable, while the ground connection was made to the drain wire, and the two cores were kept open-circuited, Figure 3. Whereas
for the insulation core investigation the particular core was charged with the DC voltage source and the drain, the other core and the jacket were connected to the ground. Figure 4 shows the measuring arrangement of the EVR for the cable samples. All the electrical measurements were carried out at 25 °C ± 2 °C.

Figure 3. Extended voltage response (EVR) measurement: (a) setup and (b) connection diagram.

Figure 4. Capacitance vs. frequency, EPR insulation: (a) 10 mHz to 1 kHz, (b) 2 kHz to 500 kHz, CSPE jacket, (c) 10 mHz to 1 kHz, and (d) 2 kHz to 500 kHz for different thermal aging periods.
2.3.3. Polarization–Depolarization Current

PDC, a time domain technique, was also adopted in this work for the investigation of the degradation in the polymeric materials of the subjected cable samples. The technique consists of the measurement of the polarization and depolarization currents. The technique is useful in studying structural changes inside polymeric materials with help of the dielectric response and conductivity [26–32].

The OMICRON Dirana was used for the PDC measurement in this research work, Figure 2a. The electrical connection configuration of the jacket and the insulation cores were the same as for the dielectric spectroscopy measurement with the OMICRON Dirana. However, the DC charging voltage was set to 200 V for a period of 5000 s, and the depolarization time was 1000 s.

2.3.4. Elongation at Break

The effect of the thermal degradation on the mechanical property of the cable’s polymeric materials was investigated with the help of elongation at break (EaB). According to the standard for the qualification of the LV cables, EaB as mentioned is a requested condition [33]. The measurement was carried out on 6 tabular samples from unaged and each thermally stressed jacket and insulation samples. The measurement was carried out at room temperature on a universal testing machine (Instron 5566).

3. Results

3.1. Capacitance and \( \tan \delta \)

The measured capacitance values of the jacket and insulation for the two frequency ranges are shown in Figure 4. The EPR insulation capacitance plotted for the low-frequency range is shown in Figure 4a, while that for the high-frequency range is shown in Figure 4b, and Figure 4c,d are capacitance plots at a low and high frequency for the CSPE jacket. For both polymeric materials, the profile of the capacitance at low- and high-frequency ranges for unaged and stressed cable samples was the same as at the lowest frequency; the capacitance had a maximum value and with the sweeping of frequency toward higher values, it started to decrease.

With the aging time in the whole low-frequency range, an increase was observed in the capacitance values for the EPR insulation and the CSPE jacket, while in the high-frequency range, except for a decrease in the capacitance after the second and third thermal cycles for the EPR insulation and the CSPE jacket, respectively, an increase was observed with each thermal cycle for both polymeric materials.

Figure 5 depicts the \( \tan \delta \) at the low- and high-frequency range for the EPR insulation and the CSPE jacket. In the matter of the EPR insulation and low-frequency range, \( \tan \delta \) starting with a high value at 0.01 Hz, declined with the increase in frequency, reaching its minimum value at a certain frequency, and then it started to increase. The same behavior was observed after the first thermal cycle. However, after the second and third thermal cycles at 0.01 Hz, the \( \tan \delta \) had its maximum value, which decreased with the sweeping of frequency and reached a minimum value at 1 kHz. The fourth thermal cycle had a different effect on the profile of \( \tan \delta \), while at 0.01 Hz, it had a low value, which started to increase and reached a maximum value at 1 Hz and then started to decrease, attaining the minimum value at 1 kHz. The fifth thermal cycle had the same profile, with two peaks: one at 0.05 Hz and the other at 10 Hz.

For the high-frequency range, the \( \tan \delta \) with the maximum value at the lowest frequency, i.e., 2 kHz decreased and reached a minimum value at a certain frequency of 5-kHz for the unaged, first, second, and third cycles and 100 kHz for the fourth and fifth thermal cycles and then increased. Even though the effect of the thermal stress on the EPR insulation was observed as an increase in the \( \tan \delta \) values at all frequency points, i.e., low- and high-frequency range.
Figure 5. $\tan \delta$ vs. frequency, EPR insulation: (a) 10 mHz to 1 kHz, (b) 2 kHz to 500 kHz, CSPE jacket, (c) 10 mHz to 1 kHz, and (d) 2 kHz to 500 kHz for different thermal aging periods.

On the other hand, the $\tan \delta$ value for the CSPE jacket showed a different characteristic trend for frequency variation with each thermal cycle for the low-frequency range. For the unaged and after the first thermal cycle, the $\tan \delta$ started with a low value and then it started to increase, attaining its maximum value at 0.04 Hz and 0.02 Hz for the unaged cycle and first thermal cycle, respectively. Afterward, it continued to decrease, with a minimum value at 200 Hz for the unaged cycle and 400 Hz for the first thermal cycle, and then it followed an increasing trend. The effect of the thermal stress on the overall $\tan \delta$ values of the jacket was observed as an increase in its values for all cycles. But after the second, third, and fourth thermal cycles, the peak of the $\tan \delta$ shifted to 0.01 Hz, and the minimum value shifted to 400 Hz for the second, and then it shifted to 1 kHz for the third and fourth thermal cycles. After the last thermal cycle, the $\tan \delta$ had the same profile as for the third and fourth thermal cycles, but a peak was observed at 0.2 Hz.

Contrariwise, for the high-frequency case, the $\tan \delta$ values for the unaged sample had the lowest value at 2 kHz and started to increase and reached its peak at the highest frequency point. A similar trend was observed after each thermal cycle, except the last one, where a peak was observed at 5 kHz. Nonetheless, the $\tan \delta$ values showed an overall increase in their values after each thermal cycle for the high-frequency range.
3.2. Extended Voltage Response

The measured results of EVR for the EPR insulation and CSPE jacket are plotted in Figure 6. For the case of EPR, nonlinear behavior of the $S_d$ values was observed, as shown in Figure 6a. But an overall impact of thermal stress was observed as an increase in $S_d$ values. For the CSPE jacket, after an initial increase in the $S_d$ values after the first thermal cycle, Figure 6c, a gradual decrease was noticed. However, after the last thermal cycle, there was a prominent increase in $S_d$.

![Figure 6](image)

Figure 6. EVR measurement, EPR insulation: (a) $S_d$ vs. different thermal aging periods, (b) $S_r$ vs. discharging time for different thermal aging periods, CSPE jacket, (c) $S_d$ vs. different thermal aging periods, and (d) $S_r$ vs. discharging time for different thermal aging periods.

The $S_r$ profile for the EPR insulation under thermal stress was observed as an increase in the values, Figure 6b. Despite a nonlinear behavior of the $S_r$ values for the CSPE jacket, it was observed that the thermal stress resulted in an overall decrease in the $S_r$, Figure 6d.

3.3. Polarization—Depolarization Current

The polarization current and depolarization current results for the EPR insulation are plotted in Figure 7a,b, while the results for the CSPE jacket are plotted in Figure 7c,d. With each thermal cycle, the polarization and depolarization current for the EPR insulation increased, while for the CSPE jacket, a gradual decrease in the polarization and depolarization current was observed with each thermal cycle.
Figure 7. PDC measurement, EPR insulation: (a) polarization current, (b) depolarization current for different thermal aging periods, CSPE jacket, (c) polarization current, and (d) depolarization current for different thermal aging periods.

3.4. Elongation at Break

The effect of thermal stress on the EPR insulation and the CSPE jacket as analyzed by EaB was noticed as a constant decrease, Figure 8.

Figure 8. Elongation at break against different thermal aging periods (a) EPR insulation and (b) CSPE jacket.
4. Discussion

Meanwhile, during the whole aging and measurement process, the insulation and the jacket were kept intact, but the behavior of the EPR insulation and CSPE jacket was investigated differently due to the thermal stress. In addition, the polymeric materials with different composition experience and different aging mechanisms, as a result, showed different responses. Henceforth, the discussion on the measurement results is carried out separately on the polymeric materials.

4.1. EPR Insulation

EPR is predominately a copolymer and has a stable saturated backbone and unsaturated side groups. The former provides good thermal–oxidative stability, while the latter, on the other hand, promotes interchain cross-linking. The cross-linking process results in the decrease in permittivity, while the chain scission causes an increase in permittivity. The existence of such structure in EPR allows the cross-linking to oppose the chain scission under thermal stress. However, under thermal stress, several aging mechanisms occur simultaneously, such as cross-linking, chain scission, chain oxidation, and macro mobility, which initiates a competition of dominance.

While analyzing the broadband frequency capacitance and tanδ by selecting the suitable frequencies, Figure 9, there was a significant increase in the capacitance and tanδ values in the interfacial polarization range, below 100 Hz, representing the occurrence of chain scission reaction, that became stronger with the increase of aging times. As reported, the interfacial polarization results charged into the dielectric under the electric field because of the imperfect diffusion of the space. As a consequence, they settled next to the physical and chemical interfaces.

![Figure 9](image-url)

Figure 9. Change in (a) capacitance and (b) tanδ for different thermal aging periods at 10 mHz, 100 mHz, 100 Hz, 1 kHz, 100 kHz, and 500 kHz for EPR insulation.

However, the initial decrease in the capacitance and tanδ values at higher frequencies, i.e., 100 kHz and 500 kHz, depicts the small role of oxygen in the degradation of EPR due to the presence of the jacket. Nevertheless, with more accelerated thermal aging, small voids and cracks formed in the EPR insulation [34] and expanded and in the presence of dipolar-natured oxygen during the aging, which allowed it to penetrate into the material. The oxygen bonded to the radicals resulted in the generation of dipolar species and hence chain oxidation became prominent. This aging mechanism is depicted with a prominent increase in the tanδ and capacitance values at 1 kHz and 100 kHz, a phenomenon reported in previous work regarding the thermal aging of EPR [35–40].

Meanwhile, simplifying the measured $S_r$ values by plotting the $S_r$ at 1 s, Figure 10, a noteworthy increase in the $S_r$ values is observed. $S_r$ is a quantity that represents the
slow polarization processes, such as interfacial, hence supporting the results of dielectric spectroscopy regarding the prominence of the phenomenon of the interfacial polarization.

Figure 10. $S_r$ at 1 second variation against different thermal aging periods for EPR insulation.

The presence of oxygen during aging results in the presence of carbonyl groups in nonpolar polymers such as EPR. These groups behave as shallow traps and act as low-energy sites, hence allowing new charge carriers from the electrodes to discharge in the polymer [6]. This results in an increase in conductivity. The phenomenon has been revealed by the prominent increase in the values of tan$\delta$ at 10 mHz and 100 mHz, whereas the significant increases in the overall $S_d$, relative conductivity, values, and conduction current, Figure 11a, also support the phenomenon.

Figure 11. Conduction current for different thermal aging periods (a) EPR insulation and (b) CSPE jacket.

The results of the electrical measurements suggest that under continuous thermal stress, permanent morphological changes took place in the EPR material, resulting in the degradation of the mechanical integrity of the EPR due to embrittlement, as suggested by the EaB results, Figure 8.
4.2. CSPE Jacket

Similar to the CSPE under irradiation stress, thermally stressed CSPE undergoes a series of aging mechanisms such as oxidation, cross-linking, chain scission, and dehydrochlorination, which is destruction and loss of Cl and is also attributed as a nonoxidative process [41–44]. Under thermal–oxidative stress, there is a generation of macromolecular radicals and small molecular radicals [43]; both respond differently to the low electric field as the latter one has higher mobility than the former one.

Although there was an increase in the tanδ values below 1 kHz, Figure 12, the effect was not significant, and this shows that the oxidative processes play a small role in the initial stages of thermal aging in comparison to the dehydrochlorination process that results in the decrease in the mobility of the C–Cl dipoles and hence affects the relaxation phenomenon. In addition, the loss of Cl results in the carbon–carbon double bond, hence enhancing the cross-linking. The cross-linking being a three-dimensional network restricts the movement of the charges. The plot of the $S_r$ polarization conductivity values at 1 s, Figure 13, shows a decreasing trend, similar to the irradiated CSPE in our previous work [20], which shows the limited role of oxygen in the CSPE degradation, a phenomenon observed with the material [40,41,44,45].

**Figure 12.** Change in (a) capacitance and (b) tanδ for different thermal aging periods at 10 mHz, 100 mHz, 100 Hz, 1 kHz, 100 kHz, and 500 kHz for CSPE jacket.

**Figure 13.** $S_r$ at 1 second variation against different thermal aging periods for CSPE jacket.
Little or no change at higher frequencies, i.e., 100 kHz and 500 kHz, shows the limited role of oxygen in the degradation process as this corresponds to a small presence of dipolar species. On the other side, the presence of the small molecular radicals plays the role of shallow traps having low energy, hence allowing the charge transportation, which is evident from the change in the values of tan\(\delta\) at 10 mHz and 100 mHz and an overall increase in the \(S_d\) and conduction current, Figure 11b. However, the change in the values of \(S_d\) during the first four aging cycles is relatively constant, which could be due to the fact that the role of the shallow traps is limited at the earlier stages of aging, a behavior that is expected from the jacket to show under the stress. But at very high aging stress, the high jump in the \(S_d\) value reveals the enhancement of the traps, hence allowing the transportation of more charges.

The domination of the cross-linking and dehydrochlorination aging mechanisms with thermal aging leads to the hardening and less flexibility of the material [46]; hence, a decrease in the EaB in a regular fashion was observed for CSPE, Figure 14 [45,47].

![Figure 14. Change of elongation at break for EPR insulation and CSPE jacket.](image)

5. Electrical Aging Markers and Correlation with Elongation at Break

The selection of appropriate electrical aging markers was based on the establishment of the correlation between EaB and capacitance and tan\(\delta\) values at selected frequencies, \(S_r\) at 1 s and \(S_d\), for the EPR insulation and CSPE jacket. Another important aspect during the selection of aging markers was considering the aging mechanism and response of the polymeric materials to it.

As observed from our previous work, a prominent effect of oxidation in the degradation was observed in the same cable under irradiation. However, other aging mechanisms were also noticeable; high \(R^2\) was observed at different frequencies [20]. Thus, tan\(\delta\) at 100 Hz and \(S_r\) at 1 s were selected as electrical aging markers and are plotted in Figure 15. The selected aging markers have already shown a high correlation with degradation for different polymeric materials for a different construction of the cable [22,25]. Thus, the strong linear relationship, as shown with high \(R^2\) values, makes the selected electrical aging markers suitable for the detection of aging in the polymer even if the \(R^2\) value in the case of \(S_r\) is only 0.83503.
6. Conclusions

This research work focused on the implementation and investigation of nondestructive electrical CM techniques for the overall degradation of EPR/CSPE-based LV NPP cable due to thermal aging where prominent changes in the capacitance and tanδ values at both low and high frequencies were observed for both the insulation and the jacket. Oxidation and chain scission aging mechanisms were observed as the main cause of EPR degradation, which enhanced the interfacial and dipolar polarization phenomenon as a significant increase in the tanδ at 100 Hz and $S_r$ values was noticed, while charge transportation was also observed as there was an increase in the tanδ values at very low frequencies and $S_d$. Dehydrochlorination and cross-linking-based aging mechanisms were observed as dominant reactions for CSPE during the aging period, where $S_r$ values decreased significantly.

The tanδ at 100 Hz and $S_r$, aging markers, were found to correlate highly with aging and EaB, hence proving and showing the ability of the adopted electrical methods as nondestructive CM techniques for the LV cables keeping the insulation and the jacket intact.

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