Application of Non-Destructive Condition Monitoring Techniques on Irradiated Low Voltage Unshielded Nuclear Power Cables

EHTASHAM MUSTAFA [1,3], **RAMY S. A. AFIA** [2,3], **AND ZOLTÁN ÁDÁM TAMUS** [3], (Member, IEEE)

[1] Department of Electrical Engineering, Faculty of Engineering and Technology, Gomal University, Dera Ismail Khan 29050, Pakistan
[2] Department of Electrical Power and Machines Engineering, Helwan University, Cairo 11792, Egypt
[3] Department of Electric Power Engineering, Budapest University of Technology and Economics, 1521 Budapest, Hungary

Corresponding author: Zoltán Ádám Tamus (tamus.adam@vet.bme.hu)

ABSTRACT In this paper, the effect of radiation stress on the overall degradation of jacket and insulation of low voltage unshielded power cable used in nuclear power plants is discussed. The XLPE insulated and CSPE jacketed cable samples were exposed to a total dose of 400 kGy γ-irradiation with 0.5 kGy/h dose-rate. Dielectric spectroscopy; complex permittivity, and extended voltage response; namely slopes of decay and return voltages were used to study the effect of the irradiation on the cable with an aim to establish the application of these techniques for a non-destructive condition monitoring of the unshielded cables. Shore D hardness was also used to investigate the mechanical characteristic of the cable. It was observed that the radiation stress affected the electrical and mechanical properties of the cable polymeric components i.e. insulation and jacket. The imaginary part of permittivity at low frequency; 100 Hz, the slope of return voltage, and hardness showed a significant increase with absorbed dose showing the effect of irradiation on the jacket and insulating material, as well. A strong correlation was observed between the imaginary part of permittivity at 100 Hz, slopes of return voltage, and hardness. The results show the dielectric measurement techniques are potential non-destructive condition monitoring methods for the unshielded low voltage nuclear power plant power cables for on-site diagnosis.

INDEX TERMS CSPE, dielectric spectroscopy, extended voltage response, gamma radiation, low voltage unshielded cables, shore D hardness, XLPE.

I. INTRODUCTION

The supply of reliable and affordable electrical energy and low carbon emission makes nuclear power plants (NPPs) an attractive source of electrical energy. Currently, the NPPs have a considerable share of the worldwide generation of electrical energy which is expected to increase by 17% by the year 2050 [1]. The safe and reliable operation of the NPPs is dependent on structures, systems, and components [2]. The low voltage (LV) cables are one such component, which supply power and control signals to equipment that are safety-related. These cables make thousands of miles in the NPPs and are also deployed in the containment area, which makes

them exposed to harsh conditions, where Fig. 1 shows the types of stresses in the NPPs environment [3].

Since the jacket and insulation of the cables are composed of polymers, the design of the cable varies with the application of the cable, such as instrumentation and control (I&C) and power [4]. These polymers are also formulated with various types of additives, such as anti-oxidants, flame retardants, plasticizers, and dyes. Out of different kinds of environmental stresses in the NPP, the radiation, oxygen, and thermal stressors take place in everyday operation [5]. The contribution of radiation stress in the presence of oxygen adds a particular dimension to the degradation of the LV cable. Under the radiation stress, the chemical structure of the polymer is altered, which could start with the decomposition of antioxidants and then proceed with the chemical reactions

The associate editor coordinating the review of this manuscript and approving it for publication was Nagarajan Raghavan [ID].
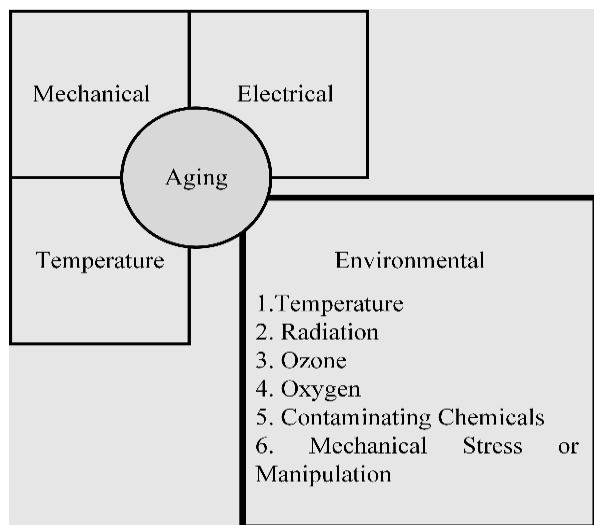
FIGURE 1. Aging and types of stresses in NPP [3].

such as oxidation, cross-linking and chain scission [6]. This will result in the degradation of the chemical, mechanical, and electrical properties of the polymer and may result in functional failures, such as short circuit and cable breakdown, which has a serious effect on the safety of the nuclear facility. Thus making the condition monitoring (CM) of these cables inevitable, which is considered as an extremely important step for the maintenance of the qualification of the cables used in the NPP [7]–[9]. The CM could be for reliable operation during normal conditions but also for the plant life extension and design-based events (DBEs). The preferable characteristics of the CM methods have been outlined by the International Atomic Energy Agency (IAEA) [5].

Till now most of the research on the CM has been focused on destructive methods, which are related to the mechanical [5], [10] and chemical [11]–[19] properties of the polymer insulation materials. But for the online CM, these methods possess problems of being not only destructive but also intrusive. These methods focus on the chemical characterization of the polymer insulation rather than the functional properties, which are essential from the point of view of the plant operation and life extension.

Since the primary function of the cable insulation (inner insulation and jacket) is the isolation of conductors, the integrity of these components is determinant. Due to the physio-chemical changes with aging, the dielectric properties of the cable insulation, which are the basic characteristics, are also influenced. Out of the LV cables, power cables make approximately 15% of the total LV cables [20]. These cables are either shielded or unshielded and are used to supply power to the safety-related motors of pumps and valves, motor control centers, heaters, and transformers. In the last few years, the methods which have been introduced for the investigation of the effect of aging on electrical properties of LV cables are line resonance analysis (LIRA) [21], dielectric spectroscopy [22], and Time-domain Reflectometry (TDR) [23].

In these electrical methods, the researchers have aimed to study the effect of radiation stress on the insulation and jacket material separately, since the integrity of both components is critical to maintain the qualified conditions of cables [4], [5]. Recently, most of the research has been focused on the LV shielded cables especially instrumentation and control (I&C) cables [24]–[26], since the measurement of electrical properties of insulation can be easily executed by the different connection of the test equipment to the shielding and conductors of tested cable. The on-site measurement capability and non-destructive nature of the dielectric measurement methods generate a need for the development of these methods to investigate unshielded cables, such as power cables. Nevertheless, in the case of the unshielded cables, the measurements of dielectric properties of the dielectric polymeric components, i.e., jacket and core insulation, is not a simple task. Since this kind of cables has only one conductive core, therefore connection of the test equipment is not obvious. One possible solution is using a surface electrode on the jacket. By connecting the equipment to the surface electrode and the conductive core, the resultant of the dielectric characteristics of the jacket and core insulation can be measured. Moreover, using non-destructive electrical CM techniques by this connection enables to evaluate the overall state of the cable without separating the insulation and jacket, thus making the task of the overall condition assessment of the unshielded cable practicable.

This article has been focused to study the impact of radiation stress on the overall degradation of cross-linked polyethylene (XLPE) insulated and chloro-sulphunated polyethylene (CSPE) jacketed based LV unshielded power NPP cable. The cable samples were subjected to five different aging periods under the same radiation dose rate. Two different electrical diagnostic methods, dielectric spectroscopy and extended voltage response (EVR) were used to investigate the changes in the dielectric properties with aging. The Shore D hardness as a mechanical property was also measured after each absorbed dose. All of the methods were non-destructive and the results obtained were very helpful to analyze the cable at the macroscopic scale. The correlation between the aging markers obtained from the electrical tests and the mechanical test was established which helped in understanding the structural changes under the irradiation. The work is a practical step towards the implementation of the electrical techniques as a non-destructive method for the CM of the LV unshielded cables in NPP and to forecast the remaining lifetime of the cable as has been suggested by the Light Water Reactor Sustainability Program Nondestructive Evaluation (NDE) report [27].

The paper has been structured as the composition of the cable and its characteristics, radiation aging, measurement of the electrical properties; dielectric spectroscopy and EVR, measurement of mechanical properties; Shore D hardness are presented in Section II. In Section III and IV, the results of the measurements and discussion have been presented, respectively. A correlation between the change in the imaginary
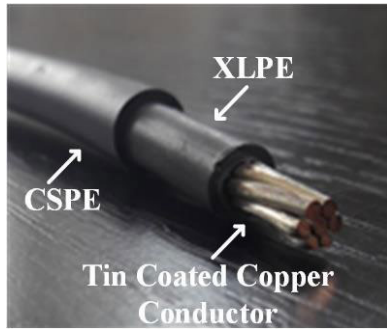
FIGURE 2. The NPP LV power cable sample under research.

part of permittivity, EVR, and Shore D hardness has been established in Section V, while the conclusion and discussion on future perspectives have been presented in the last section.

II. EXPERIMENTAL SETUP

A. CABLE SAMPLE

The NPP unshielded cable sample under study was RSCC- manufactured and composed of chloro-sulphunated polyethylene (CSPE) as a jacket, cross-linked polyethylene (XLPE) as primary insulation, and a tin-coated copper conductor, Fig. 2. The overall diameter of the conductor was 4.826 mm, while the thickness of the insulation and jacket was 1.143 mm and 0.762 mm. The other specifications of the cable were:

i. Rated Voltage: 600 V
ii. Rated Temperature: 90°C
iii. Conductor Size: 6 AWG
iv. Class 1E Nuclear Cable

As per the guidelines of IAEA [4], a short length of the insulation was cut out from the conductor and a short length of the jacket was cut out from the insulation from both the ends of the cable sample.

B. RADIATION AGING

The radiation aging was performed at the Institute of Isotopes Co., Ltd., Hungary with a γ–ray sourced, ^{60}Co. Five cable samples were used for radiation aging, being exposed to 80 kGy, 160 kGy, 240 kGy, 320 kGy, and 400 kGy at 25°C with a dose rate of 0.5 kGy. The dose rate was selected to reduce the effect of diffusion-limited oxygen (DLO) as per the guidelines of IAEA [4].

C. MEASUREMENT

1) DIELECTRIC SPECTROSCOPY

The dielectric spectroscopy was carried out in two frequency ranges: 10 mHz to 1 kHz and from 2 kHz to 500 kHz by investigating the complex permittivity. The investigation in the former frequency range was measured using an OMICRON Dirana, Fig. 3 while the later frequency range was measured using Wayne Kerr Precision Component Analyzer 6430, Fig.4. For both the devices, RC parallel configuration was used and the complex permittivity ($\dot{\varepsilon}$) of the cable insulation
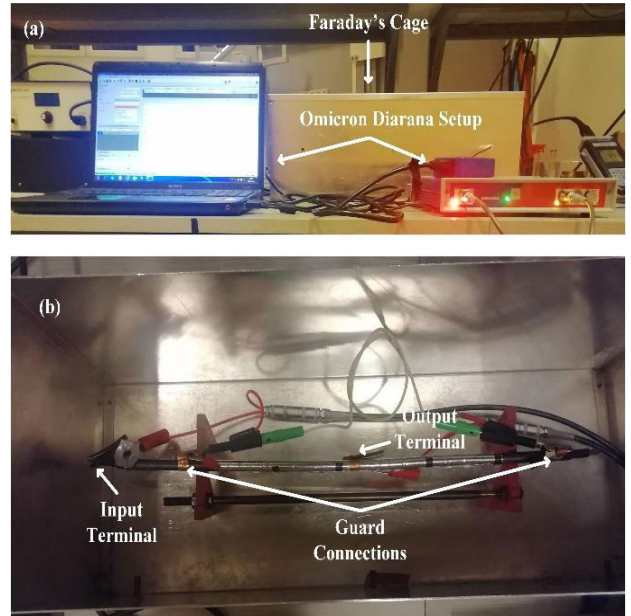

FIGURE 3. (a) OMICRON Dirana setup, (b) connection of cable sample for OMICRON Dirana.
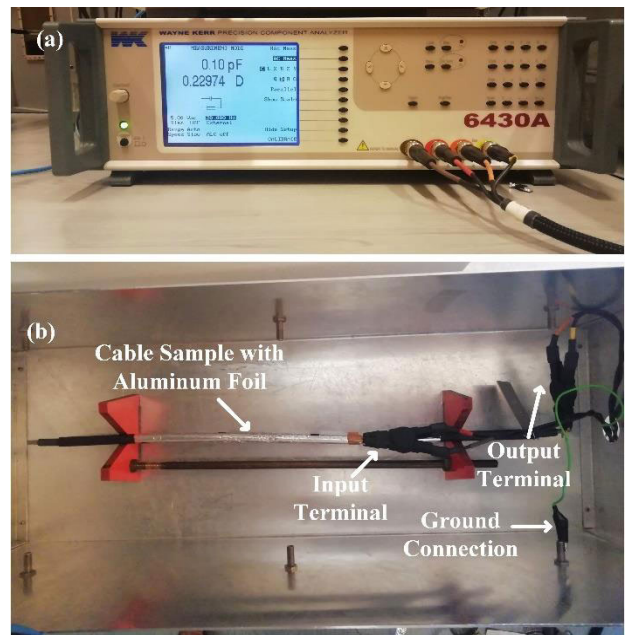

FIGURE 4. (a) Weyne Kerr precision component analyzer 6430, (b) connection of cable sample for Weyne Kerr precision component analyzer.

was investigated. Where the complex permittivity comprises of the real part (ε') and imaginary part (ε'') of permittivity and is described as:

$$\dot{\varepsilon} = \varepsilon' - j\varepsilon'' \tag{1}$$

The dielectric constant or the real part of permittivity defines the ability of the material to store energy in response to the application of the external electric field. While the imaginary part of permittivity is known as the dielectric loss of the material and represents how the energy is
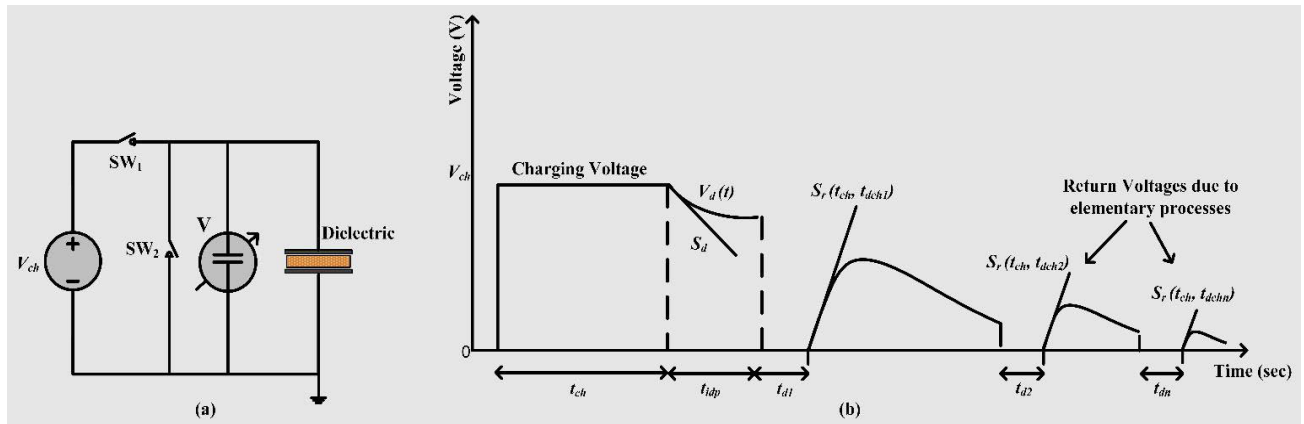
FIGURE 5. Extended voltage response (a) circuit (b) timing diagram [33].

dissipated [28]–[30]. The real and imaginary part of permittivity were calculated from the recorded data with the help of the expressions:

$$\varepsilon' = \frac{C(\omega)}{C_o} \qquad (2)$$

$$\varepsilon'' = \frac{1}{2\pi f R C_o} \qquad (3)$$

In (2) and (3), C_o is the reference capacitance, which was calculated based on the known dimensions of the electrodes and the cable, f is the particular frequency during measurement and R being the resistance at that particular frequency.

During the measurement, the conductor was connected with the input signal electrode. On the outer surface of the cable was covered by a 29 cm length aluminum foil from where the output signal was measured. To avoid any pickup from the external noise during measurement, the cable samples were placed in a Faraday's cage, as shown in Fig. 3 (b) and Fig. 4 (b). The applied voltages for OMICRON Diarana and Wayne Kerr were set at 100 V_{rms} and 5 V_{rms}, respectively.

2) EXTENDED VOLTAGE RESPONSE

The EVR is an advanced form of the voltage response method, which has been established in recent times. The method has shown its ability to study the slow dielectric polarization processes which have high time-constants inside the material while having successfully been implemented on LV distribution cables, high voltage cables, and transformer insulations [31]–[35]. The EVR measurement of under the investigated cable samples was carried out by charging the cable for 4000 seconds (t_{ch}) at 1000 V DC voltage (V_{ch}) by closing the switch SW_1, Fig. 5 (a). At the end of the charging period, the switch SW_1 was opened as a result the DC voltage source was disconnected, which resulted in the generation of decay voltage ($V_d(t)$). After the disconnection period (t_{dip}), the switch SW_2 was closed, due to which the cable was discharged for 20 different discharging periods (t_{dn}). This period ranged from 1 second (t_{d1}) to 2000 seconds (t_{d20}), thus giving a wide range of slow polarization spectrum, as shown in the timing diagram of Fig. 5 (b).

With the EVR technique, two voltage slopes; decay (S_d) and return (S_r) voltage slopes are measured, which are based on the two equations [36]:

$$S_d = \left(\frac{V_{ch}}{\epsilon_\infty}\right)\gamma \qquad (4)$$

$$S_r = \left(\frac{V_{ch}}{\epsilon_\infty}\right)\beta \qquad (5)$$

As from (4), the decay voltage slope is related to the specific conductivity (γ) of the insulation as the slope is generated when the insulation is separated from the voltage source after the charging period ends. This allows the charges present on the electrodes to discharge into the insulation material. While (5) shows the relationship between the return voltage slopes and polarization conductivity (β), which is the result of the short discharging period allowing the polarization processes which have high time constants to relax. These relaxation processes are shown as the polarization spectrum.

Fig.6 shows the measurement arrangement of the EVR for the cable samples.

Both the electrical measurement techniques were executed at a temperature of 25°C ± 2% and a humidity of 25% ± 2%.

3) SHORE D HARDNESS

The mechanical properties were investigated by measuring the Shore D hardness using Bareiss HPE II Hardness Tester. Like the electrical measurement techniques adopted in this work, the Shore D hardness is also non-destructive in nature.

The measurement of the hardness was carried out at 10 different points on the cable sample, by carrying out the evaluation on the two ends and center of the cable and at a temperature of 25°C ± 2%. Although the test method is empirical and is suitable for flat samples [37] but with the foot adapter, the measurement can be carried out on round surfaces. The hardness test was carried out only for comparative study.

III. RESULTS
A. DIELECTRIC SPECTROSCOPY
The real part of permittivity (ε') and imaginary part of permittivity (ε') for different absorbed doses are plotted for the
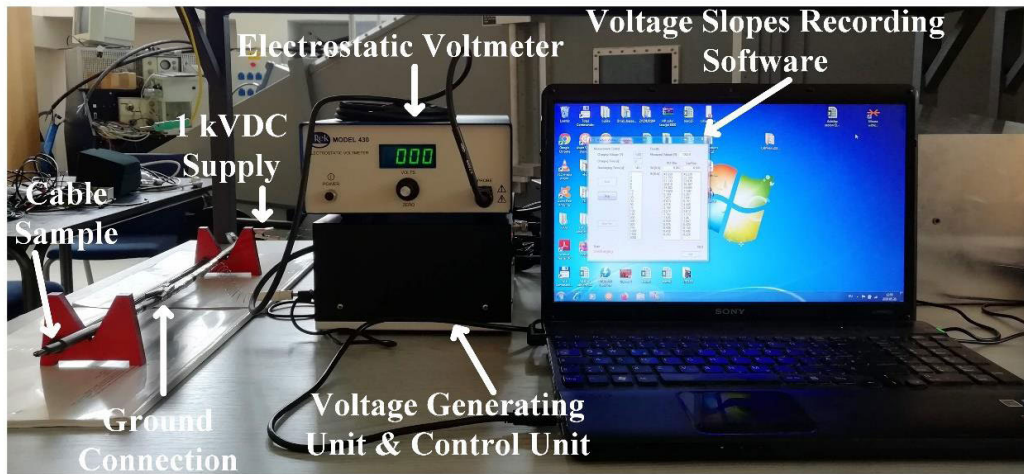
FIGURE 6. Extended voltage response measurement arrangement.
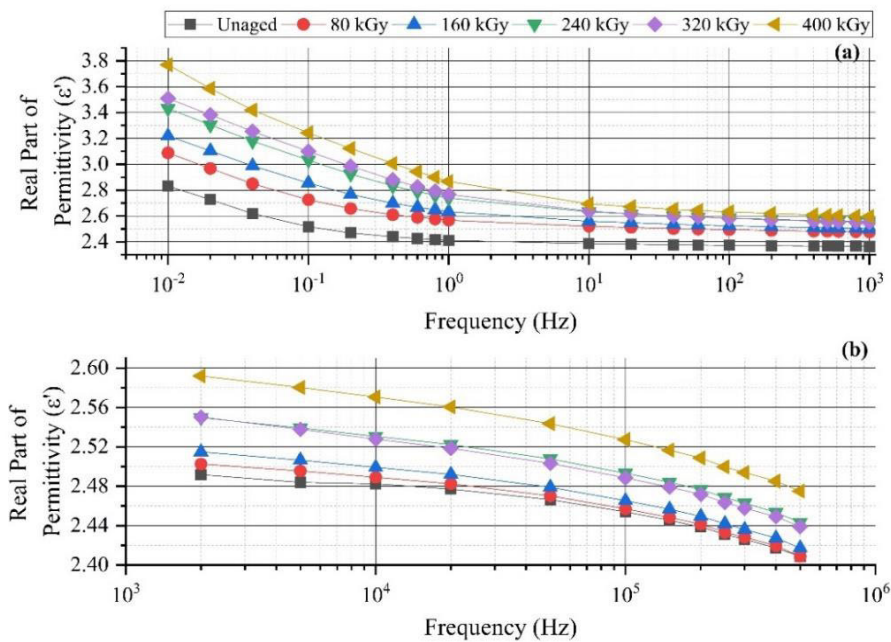

FIGURE 7. The real part of permittivity (ε') vs. frequency range (a) 10 mHz to 1 kHz (b) 2 kHz to 500 kHz for different absorbed dose.

two frequency ranges in Fig. 7 and Fig. 8, respectively. In each figure, graph (a) is plotted for a range of frequencies; 10 mHz to 1 kHz while graph (b) is plotted for 2 kHz to 500 kHz.

An increase in the real part of permittivity with absorbed dose was observed for all frequencies except for very high frequency, 100 kHz to 500 kHz. The increase was more prominent at the low frequencies as compared to high frequencies.

The imaginary part of permittivity increased for all the frequency range at all absorbed dose, except at very high frequency, 100 kHz to 500 kHz. For the first two aging times, at a frequency above 100 kHz, the imaginary part of permittivity either showed no change or decreased slightly. However, with the increase of the aging times, the values

increased. But the change was not so prominent as compared to the values at low frequencies, which will be discussed with more detail in the next section.

B. EXTENDED VOLTAGE RESPONSE

The results of EVR are shown in Fig.9, as a slope of decay voltage against the absorbed dose, Fig. 9 (a). While a log-log graph for the return voltage slopes against the discharging time for each absorbed dose is plotted in Fig. 9 (b). The decay voltage slope increased as the samples were exposed more to the radiation stress. Similarly, the return voltage slope increased with an increase in the absorbed dose for all the discharging periods.
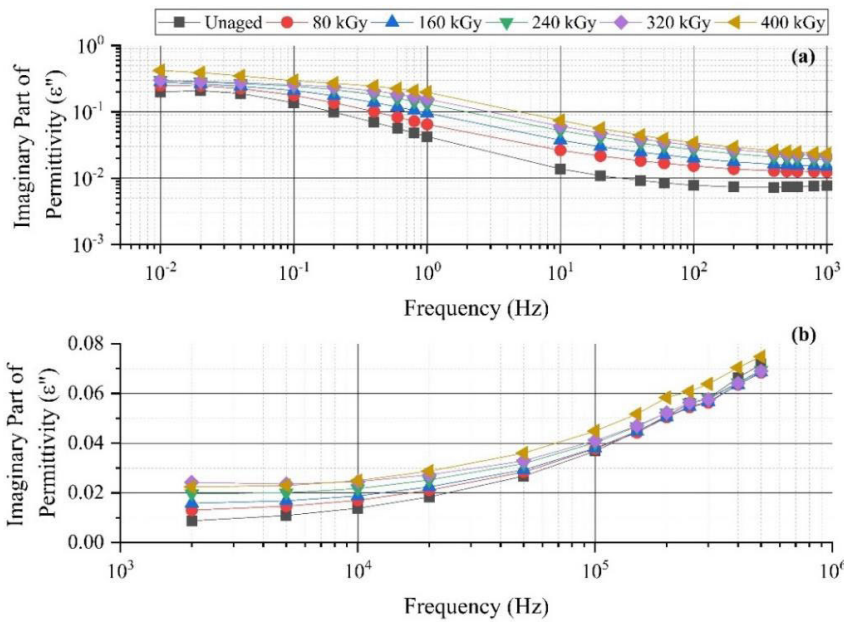
FIGURE 8. The imaginary part of permittivity (ε'') vs. frequency range (a) 10 mHz to 1 kHz (b) 2 kHz to 500 kHz for different absorbed dose.
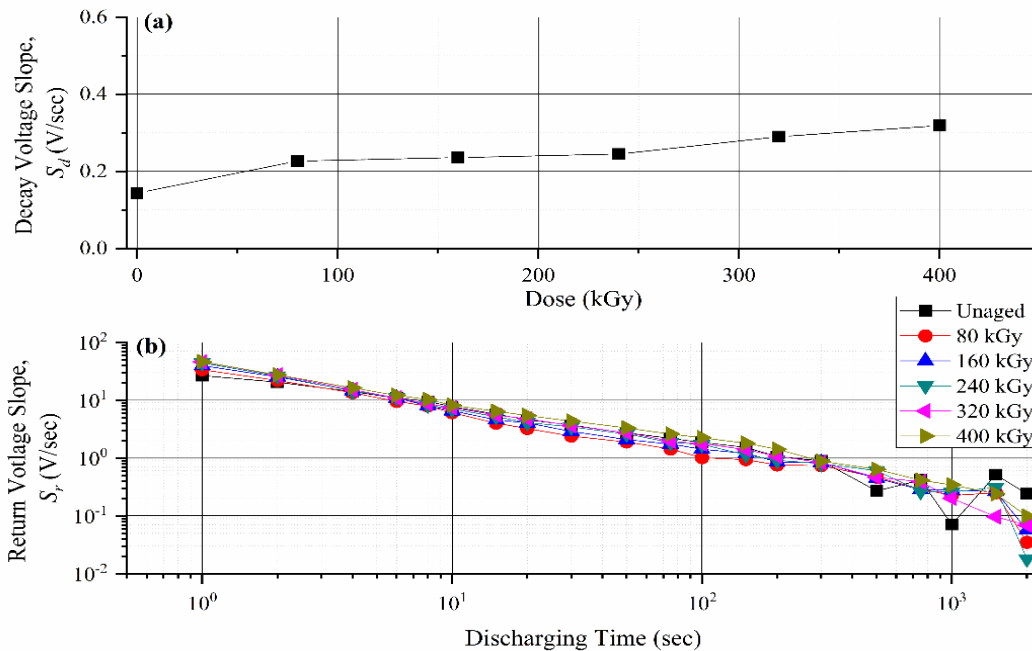

FIGURE 9. EVR measurement (a) S_d vs. aging hours, (b) S_r vs. discharging time for a different absorbed dose.

C. SHORE D HARDNESS

The average of Shore D hardness of the cable is plotted against the absorbed dose, shown in Fig. 10. It was observed that with each absorbed dose the hardness of the cable increased.

IV. DISCUSSION

A. DIELECTRIC SPECTROSCOPY

Ever since a polymer undergoes a degradation process such as absorption of radiation energy, there are changes in the molecular structure due to cross-linking, chain scission, and oxidation. The cross-linking and chain scission are considered to be opposite reactions to each other but they can occur at the same time in the polymer [26]. The reason for the degradation in the polymer depends on which of the reactions, cross-linking or chain scission, is dominant. The presence of oxygen is important for both processes. These molecular structure changes result in the generation of the molecules or polar groups, which respond to the external field through orientation. It is noteworthy that the type of polar group
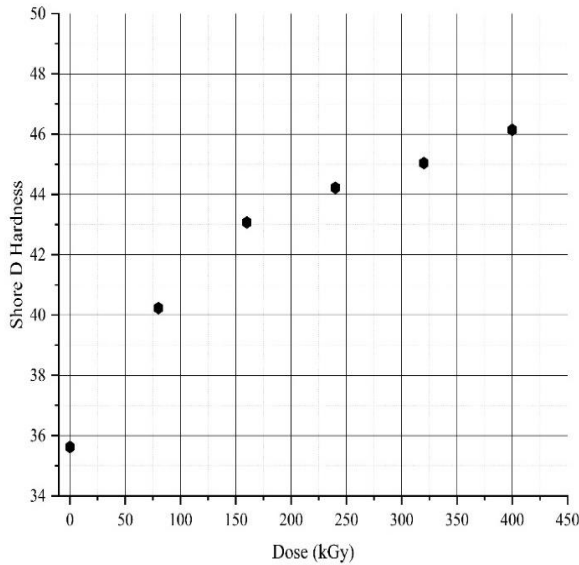
FIGURE 10. Shore D hardness against absorbed dose.

generated depends on the type of chemical reaction which has resulted in the generation of it.

The real part of permittivity is associated with the polarization while the imaginary part of permittivity is a quantity that is related to the losses inside the dielectric material. It is believed that the cross-linking results in the formation of a three-dimensional network within the polymer matrix which limits the orientation of the dipoles. Hence this reaction results in a decrease of the real part of permittivity. While the oxidation and chain scission result in the creation of small molecules that have the tendency to orientate themselves to the external field, causing an increase in the real part of permittivity [38]. In semi-crystalline polymers, such as CSPE and XLPE, there are randomly oriented crystalline and amorphous regions which are linked together with tie molecules [39]. The free radicals are generated both in crystalline and amorphous regions during radiation aging. In the crystalline region, the cross-linking and oxidation reactions are limited due to the restriction of motion of the molecular chain. While in the amorphous region cross-linking, chain scission and oxidation occur easily. Due to the presence of oxygen, chain scission dominated reactions in the amorphous region result in the generation of the polar groups, hence they will respond to the external electric field and the real part of permittivity increases [38].

The change in the real part of permittivity in reference to the unaged values for different frequencies is shown in Fig. 11. The change in the permittivity is more at the lower frequencies; 0.1, 10, and 100 Hz which is related to the interfacial polarization, in comparison to the higher frequencies. Even for the first three aging times, there is no change at the high frequencies. Also, the imaginary part of permittivity changed very little at 10 kHz while a decrease at 100 and 500 kHz was observed, Fig.12. These high frequencies, as reported in the literature [24], are related to the dipolar polarization of large species, such as oxidative products in the
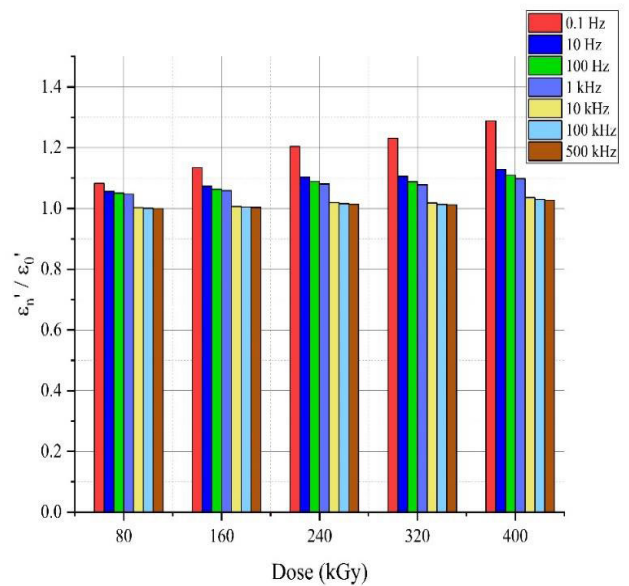

FIGURE 11. Change in the real part of permittivity (ε') for a different absorbed dose at 0.1 Hz, 10 Hz, 100 Hz, 1 kHz, 10 kHz, 100 kHz, and 500 kHz.
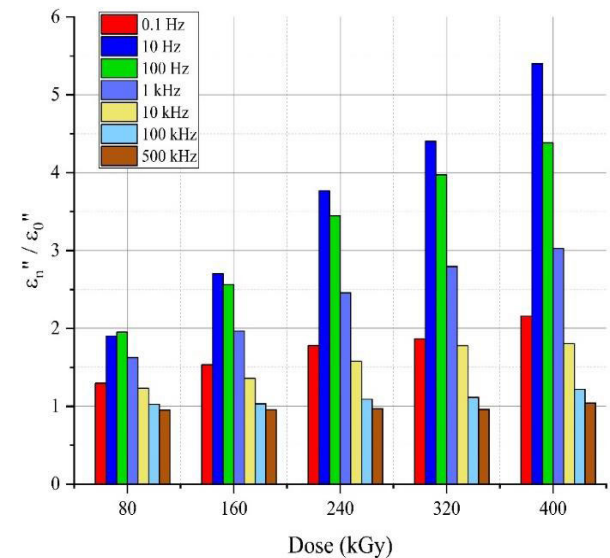

FIGURE 12. Change in the imaginary part of permittivity (ε') for a different absorbed dose at 0.1 Hz, 10 Hz, 100 Hz, 1 kHz, 10 kHz, 100 kHz, and 500 kHz.

polymer matrix. The change in the real and imaginary part of permittivity at high frequencies shows that these large oxidative products have been inhibited to be generated due to the presence of anti-oxidants, having the responsibility of impeding the polymer degradation. But the increase of absorbed dose has resulted in the decomposition of the anti-oxidants and resulted in the generation of polar molecules, which has been shown as an increase in the permittivity.

The prominent change of the real and imaginary part of permittivity at the low frequencies, i.e., 0.1 Hz, 10 Hz, and 100 Hz, with each dose rate is due to the chain scission-dominate reaction, which results in the generation of
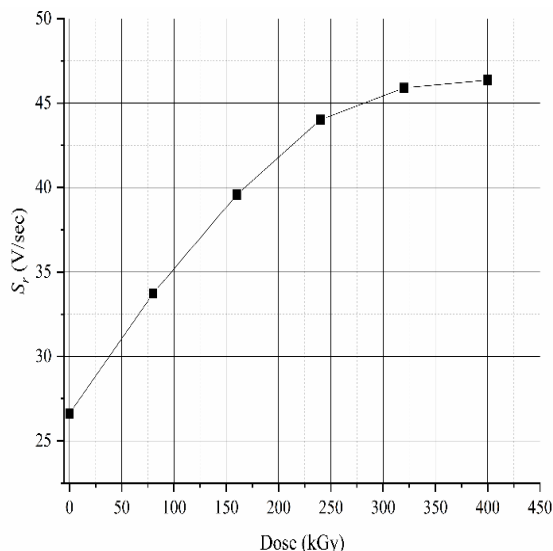
FIGURE 13. S_r at 1 sec variation against absorbed dose.

chemical species such as hydroxyl groups. These chemical species are either trapped between the amorphous and crystalline regions, known as a physical interface, or between the two polymer materials' boundaries, knows as a chemical interface, since the insulation and jacket are intact during the whole process. In addition to the interfacial polarization, the increase of the real and imaginary part of permittivity at frequencies 1 kHz and 10 kHz shows that the presence of chemical products which are resulting in the increase of dipolar polarization.

B. EXTENDED VOLTAGE RESPONSE

The increase in the interfacial polarization with each absorbed dose is also evident with the increase of S_r values for the whole polarization spectrum, where the term is related to the slow polarization processes such as interfacial, as mentioned in Section II. For the brevity, the S_r values for each absorbed dose at 1 sec is shown in Fig. 13.

The increase of the decay voltage slope with each aging time (see Fig. 9 (a)) shows that due to the irradiation, the polymer backbone has been damaged. This has resulted in the generation of the carbonyl groups (C=O) due to the presence of oxygen [40]. These groups act as a shallow trap with a low energy field and act as a source of charge transportation, hence allowing the accumulated charges on the electrodes to discharge into the polymer and resulting in the increase of conductivity, which reflects in the increase of decay voltage with aging.

The increase in the values of S_d and S_r depicts the increase in the intensity of the generation of chemical species and their trapping with the absorbed dose, which confirms the phenomenon of the degradation of the cable.

C. SHORE D HARDNESS

Meanwhile, it was observed that the hardness of the cable increased with aging, the results also show that due to aging, defects have been introduced in the polymer. As a
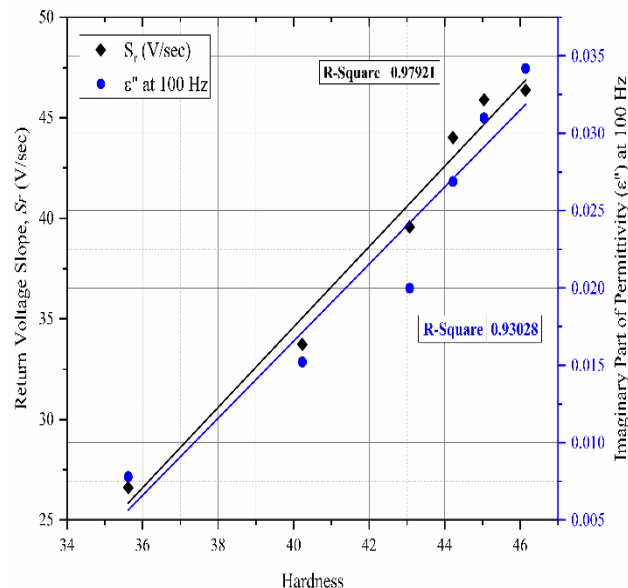

FIGURE 14. Correlation between S_r at 1 sec and change of ε'' at 10 Hz with Shore D hardness.

consequence, there has been a loss of plasticizer and hence an increase in the hardening of the polymer has been observed. It has also been reported that the hardness of the semi-crystalline polymers is influenced by their crystalline structure, which is harder than the amorphous one [41], [42].

Also under γ-irradiation, the cross-linking reaction increases the hardness of the polymer as compared to the chain scission. Hence, for the irradiated sample, the increase in the Shore D hardness with each absorbed dose suggests the contribution of cross-linking reaction along with very little or no damage happened to the crystalline region of the polymer. During the irradiation, there is a slight hardness in the amorphous region which also adds to the overall hardness of the polymer as has been reported for polyethylene (PE) [43], which could also be attributed to the increase of the hardness of the cable.

V. CORRELATION BETWEEN ELECTRICAL AND MECHANICAL PROPERTIES

The correlation between the measured electrical and mechanical properties has been established among the imaginary part of permittivity at 100 Hz, return voltage slope at 1 sec, and Shore D hardness, shown in Fig. 14. The linear regression fit shows the quantities have a strong correlation with each other and aging with high values of R^2. Hence, the imaginary part of permittivity at 100 Hz and S_r at 1 sec can be used as good aging indicators for the detection of degradation in the unshielded cables.

VI. CONCLUSION

This paper focuses on the radiation aging of LV unshielded power cables used in NPPs. The main aim of the work was to establish the electrical and mechanical CM techniques for the unshielded cables, where a lot of research work

has still to be done. The cable as a whole was subjected to radiation stress for five different dose periods and the changes in the physical-chemical properties were diagnosed using electrical and mechanical techniques. The change in the real, the imaginary part of permittivity at seven different frequencies, decay and return voltage slopes, and the hardness was investigated. A correlation between the imaginary part of permittivity at 100 Hz, return voltage slope, and hardness was also established.

The change in the real and imaginary part of permittivity was more at the low frequencies, i.e., 0.1 Hz, 10 Hz, and 100 Hz, which are related to the interfacial polarization. The increase in the return voltage slope also showed an increase in the intensity of the interfacial polarization. It was established that these changes were due to the chain scission at the amorphous region, which resulted in the generation of polar species. These species were either trapped in the region between the amorphous and crystalline regions or between the interface of the jacket and insulation, as they were intact.

The irradiation effect has resulted in a slight hardening of the amorphous region which added to the overall hardness of the cable, which was recognized due to the cross-linking reaction and loss of plasticizers. The very little change in the imaginary part of permittivity at the high frequencies was recognized due to the antioxidants, which inhibited the generation of large oxidative polar molecules. In the end, based on the experimental results a strong correlation between the electrical and mechanical aging markers; imaginary part of permittivity at 100 Hz and return voltage slope at 1 sec and hardness was observed. High R^2 values showed the potential of the quantities as a good aging indicator.

The results obtained through the electrical and mechanical measurements showed the effectiveness of the techniques to be used as the non-destructive CM techniques for the irradiated unshielded LV power cables. A further step towards the validation of the results would be to take into account of other mechanical properties, especially elongation at break (EaB), and chemical properties such as oxidation induction time (OIT) and Fourier Transform Infrared Spectroscopy (FTIR). This will help in having an in-depth analysis of the radiation aging at the molecular level.

REFERENCES

[1] A. Rising. (2019). *World Nuclear Performance Report 2019*. [Online]. Available: https://www.world-nuclear.org/our-association/publications/global-trends-reports/world-nuclear-performance-report.aspx

[2] Y.-S. Chang and A. Mosleh, "Probabilistic model of degradation of cable insulations in nuclear power plants," *Proc. Inst. Mech. Eng., Part O, J. Risk Rel.*, vol. 233, no. 5, pp. 803–814, Oct. 2019, doi: 10.1177/1748006X19827127.

[3] E. Mustafa, R. S. A. Afia, and Z. Á. Tamus, "Condition monitoring uncertainties and thermal–radiation multistress accelerated aging tests for nuclear power plant cables: A review," *Periodica Polytechnica Electr. Eng. Comput. Sci.*, vol. 64, no. 1, pp. 20–32, Sep. 2019, doi: 10.3311/PPee.14038.

[4] International Atomic Energy Agency (IAEA), "Benchmark analysis for condition monitoring test techniques of aged low voltage cables in nuclear power plants," Int. At. Energy Agency (IAEA), Vienna, Austria, Tech. Rep. IAEA TECDOC-1825, 2017.

[5] International Atomic Energy Agency (IAEA), "Pilot study on the management of ageing of instrumentation and control cables. Results of a co-ordinated research programme 1993-1995," Int. At. Energy Agency (IAEA), Vienna, Austria, Tech. Rep. IAEA-TECDOC-932, vol. 1, 1997.

[6] H. M. Banford and R. A. Fouracre, "Nuclear technology and ageing," *IEEE Elect. Insul. Mag.*, vol. 15, no. 5, pp. 19–27, Sep. 1999, doi: 10.1109/57.793826.

[7] *IEEE Standard for Qualifying Electric Cables and Splices for Nuclear Facilities*, IEEE Standard 383-2015, Oct. 2015.

[8] *IEC Nuclear Power Plants—Instrumentation and Control Important to Safety—Management Of Ageing of Electrical Cabling Systems*, Standard IEC 62465, 2010.

[9] *IEEE Standard for Qualifying Class IE Equipment for Nuclear Power Generating Stations*, IEEE Standard 323-1974, Sep. 1974.

[10] International Atomic Energy Agency (IAEA), "Assessment and management of ageing of major nuclear power plant components important to safety: In-containment instrumentation and control cables," Int. At. Energy Agency (IAEA), Vienna, Austria, Tech. Rep. IAEA-TECDOC-1188, vol. 2, 2000.

[11] B. Bartoníček, V. Hnát, and V. Plaček, "Life-assessment technique for nuclear power plant cables," *Radiat. Phys. Chem.*, vol. 52, no. 1, pp. 639–642, 1998, doi: 10.1016/S0969-806X(98)00172-8.

[12] K. Anandakumaran, W. Seidl, and P. V. Castaldo, "Condition assessment of cable insulation systems in operating nuclear power plants," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 6, no. 3, pp. 376–384, Jun. 1999, doi: 10.1109/94.775626.

[13] L. R. Mason, T. E. Doyle, and A. B. Reynolds, "Oxidation induction time correlations with radiation dose and antioxidant concentration in EPR and XLPE polymers," *J. Appl. Polym. Sci.*, vol. 50, no. 9, pp. 1493–1500, Dec. 1993, doi: 10.1002/app.1993.070500902.

[14] K. T. Gillen, R. A. Assink, and R. Bernstein, "Condition monitoring approaches applied to a polychloroprene cable jacketing material," *Polym. Degradation Stability*, vol. 84, no. 3, pp. 419–431, Jun. 2004, doi: 10.1016/j.polymdegradstab.2004.01.018.

[15] T. Seguchi, K. Tamura, T. Ohshima, A. Shimada, and H. Kudoh, "Degradation mechanisms of cable insulation materials during radiation–thermal ageing in radiation environment," *Radiat. Phys. Chem.*, vol. 80, no. 2, pp. 268–273, Feb. 2011, doi: 10.1016/j.radphyschem.2010.07.045.

[16] K. T. Gillen, M. Celina, and R. L. Clough, "Density measurements as a condition monitoring approach for following the aging of nuclear power plant cable materials," *Radiat. Phys. Chem.*, vol. 56, no. 4, pp. 429–447, Oct. 1999, doi: 10.1016/S0969-806X(99)00333-3.

[17] J. V. Gasa, Z. Liu, and M. T. Shaw, "Relationship between density and elongation-at-break of naturally and artificially aged cable materials used in nuclear power plants," *Polym. Degradation Stability*, vol. 87, no. 1, pp. 77–85, Jan. 2005, doi: 10.1016/j.polymdegradstab.2004.07.009.

[18] K. T. Gillen, R. Bernstein, R. L. Clough, and M. Celina, "Lifetime predictions for semi-crystalline cable insulation materials: I. Mechanical properties and oxygen consumption measurements on EPR materials," *Polym. Degradation Stability*, vol. 91, no. 9, pp. 2146–2156, Sep. 2006, doi: 10.1016/j.polymdegradstab.2006.01.009.

[19] R. L. Clough and K. T. Gillen, "Radiation-thermal degradation of PE and PVC: Mechanism of synergism and dose rate effects," *Radiat. Phys. Chem.*, vol. 18, nos. 3–4, pp. 661–669, Jan. 1981, doi: 10.1016/0146-5724(81)90189-8.

[20] R. J. York, J. B. Ulrich, G. Murphy, and D. G. Prather, "Mitigation of aging in low voltage power cables in nuclear power plants," M.S. thesis, Dept. Mater. Sci. Eng., Univ. Tennessee, Knoxville, TN, USA, 2015. [Online]. Available: https://pdfs.semanticscholar.org/f553/015aa212ccc869b99e0df1c8fcb0c19d459f.pdf?_ga=2.67236049.1715050367.1599652745-1112992936.1599652745

[21] M. Ekelund, P. F. Fantoni, and U. W. Gedde, "Thermal ageing assessment of EPDM-chlorosulfonated polyethylene insulated cables using line resonance analysis (LIRA)," *Polym. Test.*, vol. 30, no. 1, pp. 86–93, Feb. 2011, doi: 10.1016/j.polymertesting.2010.11.003.

[22] L. Verardi, D. Fabiani, and G. C. Montanari, "Electrical aging markers for EPR-based low-voltage cable insulation wiring of nuclear power plants," *Radiat. Phys. Chem.*, vol. 94, pp. 166–170, Jan. 2014, doi: 10.1016/j.radphyschem.2013.05.038.

[23] C.-K. Lee, G.-Y. Kwon, and Y.-J. Shin, "Condition assessment of I&C cables in nuclear power plants via stepped-frequency waveform reflectometry," *IEEE Trans. Instrum. Meas.*, vol. 68, no. 1, pp. 215–224, Jan. 2019, doi: 10.1109/TIM.2018.2834179.

[24] S. V. Suraci, D. Fabiani, A. Xu, S. Roland, and X. Colin, "Ageing assessment of XLPE LV cables for nuclear applications through physico-chemical and electrical measurements," *IEEE Access*, vol. 8, pp. 27086–27096, 2020, doi: 10.1109/ACCESS.2020.2970833.

[25] E. Linde, L. Verardi, D. Fabiani, and U. W. Gedde, "Dielectric spectroscopy as a condition monitoring technique for cable insulation based on crosslinked polyethylene," *Polym. Test.*, vol. 44, pp. 135–142, Jul. 2015, doi: 10.1016/j.polymertesting.2015.04.004.

[26] N. Bowler and S. Liu, "Aging mechanisms and monitoring of cable polymers," *Int. J. Prognostics Heal. Manag.*, vol. 6, pp. 1–13, Oct. 2015.

[27] K. L. Simmons, P. Ramuhalli, D. L. Brenchley, J. B. Coble, H. M. Hashemian, R. Konnick, and S. Ray, "Light water reactor sustainability (LWRS) program-non-destructive evaluation (NDE) R&D roadmap for determining remaining useful life of aging cables in nuclear power plants," U.S. Dept. Energy, Washington, DC, USA, Tech. Rep. PNNL-21731, Sep. 2012, doi: 10.2172/1097978.

[28] S. A. Dabbak, H. Illias, B. Ang, N. A. Latiff, and M. Makmud, "Electrical properties of polyethylene/polypropylene compounds for high-voltage insulation," *Energies*, vol. 11, no. 6, p. 1448, Jun. 2018, doi: 10.3390/en11061448.

[29] N. Bashir, H. Ahmad, and M. Shaffuan Suddin, "Ageing studies on transmission line glass insulators using dielectric dissipation factor test," in *Proc. Conf. IPEC*, Singapore, Oct. 2010, pp. 1062–1066.

[30] C. D. Paraskevas, P. Vassiliou, and C. T. Dervos, "Temperature dependent dielectric spectroscopy in frequency domain of high-voltage transformer oils compared to physicochemical results," in *Proc. IEEE Int. Conf. Dielectr. Liquids (ICDL)*, Coimbra, Portugal, Jun./Jul. 2005, pp. 275–278.

[31] E. Mustafa, R. S. A. Afia, and T. Z. Adam, "A review of methods and associated models used in return voltage measurement," in *Proc. Int. Conf. Diag. Electr. Eng. (Diagnostika)*, Pilsen, Czech Republic, Sep. 2018, pp. 69–72.

[32] Z. Á. Tamus, G. M. Csányi, Á. Szirmai, and A. Nagy, "Insulation diagnostics of high voltage equipment by dielectric measurements-Hungarian research and experience," in *Proc. Int. Sci. Symp.-Elect. Power Eng.*, 2016, pp. 7–13.

[33] G. M. Csanyi and Z. A. Tamus, "Investigation of dielectric properties of mixed PILC and XLPE cable insulation by the extended voltage response method," in *Proc. 6th Int. Youth Conf. Energy (IYCE)*, Budapest, Hungary, Jun. 2017, pp. 1–3.

[34] Á. Z. Tamus, Á. Szirmai, and B. Nemeth, "Comparison of voltage response and return voltage measurements of a transformer insulation model," in *Proc. 19th Int. Symp. High Voltage Eng. (ISH)*, Pilsen, Czech Republic, 2015, pp. 1–6.

[35] E. Mustafa, R. S. A. Afia, and Z. Á. Tamus, "Condition assessment of low voltage photovoltaic DC cables under thermal stress using non-destructive electrical techniques," *Trans. Electr. Electron. Mater.*, pp. 1–10, May 2020, doi: 10.1007/s42341-020-00201-3.

[36] E. Németh, "Measuring voltage response: A non-destructive diagnostic test method HV of insulation," *IEE Proc.-Sci., Meas. Technol.*, vol. 146, no. 5, pp. 249–252, Sep. 1999, doi: 10.1049/ip-smt:19990651.

[37] *Standard Test Method for Rubber Property-Durometer Hardness*, Standard ASTM D2240-15e1, ASTM International, 2015.

[38] Y. Gao and B. X. Du, "Effect of gamma-ray irradiation on permittivity and dielectric loss of polymer insulating materials," in *Proc. Int. Conf. High Voltage Eng. Appl.*, Shangai, China, Sep. 2012, pp. 229–232.

[39] S. G. Burnay and J. Dawson, "Reverse temperature effect during radiation ageing of XLPE cable insulation," in *Ageing Studies and Lifetime Extension of Materials*. Boston, MA, USA: Springer, 2001, pp. 493–497, doi: 10.1007/978-1-4615-1215-8_54.

[40] G. Chen, A. E. Davies, and H. M. Banford, "Influence of radiation environments on space charge formation in γ-irradiated LDPE," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 6, no. 6, pp. 882–886, Dec. 1999, doi: 10.1109/94.822031.

[41] International Atomic Energy Agency (IAEA), "Assessing and managing cable aging in nuclear power plants," IAEA, Vienna, Austria, Tech. Rep. Nuclear Energy Series No. NP-T-3.6, 2012.

[42] Y.-S. Chang and A. Mosleh, "Physics-based probabilistic model of the effects of ionizing radiation on polymeric insulators of electric cables used in nuclear power plants," U.S. Dept. Energy, Washington, DC, USA, Tech. Rep. GIRS-2019-002-1 under NEUP Project 15-8258, 2019.

[43] K. T. Gillen, R. Assink, R. Bernstein, and M. Celina, "Condition monitoring methods applied to degradation of chlorosulfonated polyethylene cable jacketing materials," *Polym. Degradation Stability*, vol. 91, no. 6, pp. 1273–1288, Jun. 2006, doi: 10.1016/j.polymdegradstab.2005.09.002.

EHTASHAM MUSTAFA was born in Dera Ismail Khan, Pakistan, in 1987. He received the B.Sc. and M.Sc. degrees in electrical engineering with a specialization in power from the University of Engineering and Technology, Peshawar, Pakistan, in 2009 and 2015, respectively. He is currently pursuing the Ph.D. degree in electrical engineering with the Budapest University of Technology and Economics, Hungary.

Since 2010, he has been working as a Lecturer with the Department of Electrical Engineering, Faculty of Engineering and Technology, Gomal University, Dera Ismail Khan. He has authored more than 25 research articles in well-reputed journals and conferences. His research interests include the study of insulation diagnostics, non-destructive diagnosis techniques for insulation materials, and insulation degradation with aging.

RAMY S. A. AFIA received the B.Sc. and M.Sc. degrees in electrical engineering from Helwan University, Cairo, Egypt, in 2008 and 2015, respectively. He is currently pursuing the Ph.D. degree in electrical engineering with the Budapest University of Technology and Economics, Budapest, Hungary.

He has been working as a Teaching Assistant with the Department of Electrical Power and Machines Engineering, Faculty of Engineering, Helwan University, since 2010. In March 2015, he was promoted as an Assistant Lecturer with the Department of Electrical Power and Machines Engineering. His research interests include aging mechanisms and condition monitoring of polymer insulating materials, non-destructive condition monitoring techniques of cables, and partial discharge measurement with very low frequency (VLF) as well as high frequencies.

ZOLTÁN ÁDÁM TAMUS (Member, IEEE) received the M.Sc., Ph.D., and Habilitation degrees in electrical engineering degrees from the Budapest University of Technology and Economics, Hungary, in 1997, 2011, and 2019, respectively.

Since 2001, he has been associated with the Department of Electric Power Engineering, Faculty of Electrical Engineering and Informatics, Budapest University of Technology and Economics. He has been serving as an Associate Professor with the same department. He has more than 90 research articles to his name. His research interests include electrical insulation technology, insulation diagnostics, electrical characterization, electrical breakdown, and the health effects of electromagnetic fields.

• • •