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Electrical and Mechanical Condition Assessment of Low Voltage Unshielded Nuclear Power Cables Under Simultaneous Thermal and Mechanical Stresses: Application of Non-Destructive Test Techniques

RAMY S. A. AFIA[1,3], MUSTAFA EHTASHAM[2,3], AND ZOLTÁN ÁDÁM TAMUS[3], (Member, IEEE)
[1]Department of Electrical Power and Machines Engineering, Faculty of Engineering, Helwan University, Cairo 11792, Egypt
[2]Department of Electrical Engineering, Faculty of Engineering and Technology, Gomal University, Dera Ismail Khan 29050, Pakistan
[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)

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ABSTRACT Low voltage cables play a crucial role in the safe and reliable operation of nuclear power plants. This paper discusses the effect of simultaneous combined thermal and mechanical stresses on the overall insulation of unshielded low voltage power cables used in nuclear power plants. Cable samples based on XLPE/CSPE insulation were exposed to thermal-mechanical combined accelerated aging tests for an extended period lasted to 907 hours. Time and frequency domain dielectric spectroscopy were applied to reveal the degradation level of the core insulation and jacket due to combined stresses. The former technique was conducted through the measurement of the decay and return voltage slopes, while the latter technique was based on the measurement of the complex permittivity. Moreover, the mechanical properties of the cable insulation were investigated by applying the measurement of the Shore D hardness. The results showed that the combined aging affects both the electrical and mechanical properties of the overall insulation. The complex permittivity at 100 Hz, the decay voltage slope, and the hardness had an upward trend with aging, while the return voltage slope showed an inverse trend. In addition, the results of the electrical and mechanical measurements showed strong correlation with aging time and further correlation was observed between the dielectric and mechanical properties. The correlation between aging time and test results suggests that the presented test methods are promising tools for in situ condition monitoring of low voltage unshielded cables in nuclear power plants.

INDEX TERMS Accelerated combined aging, CSPE, dielectric spectroscopy, extended voltage response, low-voltage cables, Shore D hardness, XLPE.

I. INTRODUCTION

For the safety of the nuclear power industry, it is essential to successfully implement the quality assurance and quality control. Besides, for ensuring the nuclear safety and long-term operation, all Nuclear Power Plant (NPP) elements have to be with a high degree of reliability and integrity, in particular, the nuclear reactors, concrete structure, heat exchangers, and cable systems [1]–[3]. In November 2020, there are 442 nuclear reactors in service all over the world with a total net electrical capacity of 392,335 MW and there are 53 more under construction which will increase the net capacity by 56,276 MW. Among the 442 reactors, 299 are Pressurized Water Reactors (PWR) and 65 are

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Boiling-Water Reactors (BWR) [4]. The operation of both PWR and BWR reactors requires thousands of kilometers of electrical cables [3], [5].

In NPPs, several cable types are used, such as low and medium voltage (LV&MV) power cables, instrumentation and control (I&C) cables, special cables, and general service cables [6]. These cables provide the link between the plant safety and control systems via signaling to control equipment, plant operators, and safety systems [7], [8]. Through the normal operation of the plant, cables are exposed to multiple stresses such as electrical, mechanical, thermal, and environmental stresses [9]. The presence of theses stresses stimulates the desire for a better understanding of cable insulation degradation [5]. Concerning long-term operation, polymers are widely adopted as the primary cable insulation and jacketing, where the most common types are cross-linked polyethylene (XLPE) and ethylene propylene rubber (EPR) [10], [11]. During the formulation of polymeric materials, additives such as brominated and chlorinated compounds with antimony oxide are added to obtain fire retardancy [12]. Antioxidants are required to delay the onset of polymer degradation therefore, extending its lifetime. In situ, these additives may get released from the polymer matrix due to chemical reactions; hence, they migrate from the insulation by diffusion to the environment [13]. Therefore, the oxidation process is accelerated, which leads to not only the formation of carbonyl and hydroxyl products [14] but, also changes in the morphological and macromolecular structures [15]. Consequently, the electrical, mechanical, physical, and chemical properties will degrade [9].

The functionality and integrity of cables are tested by qualification. The NPP cables should undergo a qualification process to ascertain their intended function not only during the normal operation of NPPs but, also during the design basis events (DBE), such as loss of coolant accident (LOCA) [16]–[18]. The 50% elongation at break (EaB) is an acceptance criterion for the assessment of NPP cables insulation. It is generally assumed that 50% EaB value will reveal the critical degradation level of polymeric insulations [19], [20]. This test technique cannot be applied to in-service cables as it requires large number of samples in addition, it is naturally destructive. Therefore, several test methods have been proposed with less samples, such as infrared spectroscopy, oxygen consumption, density, and oxidation induction time / temperature [21].

As it is well known, the normal lifetime of NPPs is 40 years and prior to the completion of the license period, operators may apply for license renewal to extend the running time of NPPs by 20 years [22]. In USA, most of plant operators considering the extension to 80 years operation period through second license renewal [5]. Since, the cost of cables replacement is not affordable, non-destructive evaluation (NDE) of cable systems in NPPs is of utmost importance. Several non-destructive condition monitoring (NDCM) techniques have been presentenced, for instance, the evaluation of the dielectric loss factor [23], Line Resonance Analysis (LIRA) [24], and the return voltage measurement [25]. Also, dielectric response has been introduced as a reliable and applicable NDCM technique to assess various insulation systems including EPR, XLPE, and CSPE materials, as well [21]. In [26], the dielectric spectroscopy measurement combined with Shore D hardness was a very auspicious tool in the detection of radiation ageing. Other test techniques were mentioned by the International Atomic Energy Agency (IAEA) report [27].

Recently, researchers are focusing on electrical testing methods such as insulation resistance (IR) and the impedance as they can detect the defects along the cable, however, they cannot pinpoint the fault location and in many cases, they do not provide reasonable trend with aging [27], [28]. Other testing techniques, such as Time Domain Reflectometry (TDR), Frequency Domain Reflectometry (FDR), reverse TDR, and Stepped Frequency Wave Reflectometry (SFWR) can precisely identify the location of faults, but they cannot differentiate whether the fault is in the polymeric insulation or in the conductor [29], [30]. The assessment of the insulation integrity of NPP cables is a big challenge as there is no single sufficient and reliable technique can be used, multiple tests should be conducted.

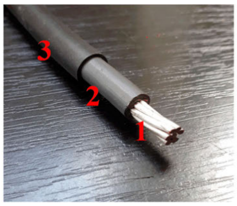
This work aims to extend the knowledge of the dielectric response analysis, the return voltage measurement as well as, the assessment of the mechanical properties of low voltage unshielded cables which are promising tools for the lifetime management of polymeric insulations in NPPs. Most of the studies use irradiation and elevated temperature for accelerated ageing, however some locations at NPPs, the bending radius of cables reaches critical values and the effect of mechanical ageing can be significant [18]. The presented work investigates the whole insulation of low voltage power cables used in nuclear facilities under simultaneous thermal and mechanical stresses since the entire cable has been subjected to an accelerated aging tests where both the core insulation and outer jacket were kept intact. The testing devices used in this work were portable that require no special sample preparation and, in principle they may be used for onsite evaluation of cables.

This paper has been formulated in six sections. In section II, the experimental work was presented where a detailed description was given for the cable samples, the accelerated aging tests, the measurement of time and frequency domain parameters, and the Shore D hardness. The obtained results were shown in section III and discussed in section IV. A correlation has been established in section V between the time and frequency domain parameters as a function of the aging time and between the mechanical and electrical parameters. Finally, the conclusion and discussion on future prospects were shown in the last section.

II. EXPERIMENTAL WORK

A. CABLE SAPECIMENS

The presented work has been carried out on samples of Class 1E low voltage (600 V) unshielded power cable used in nuclear power plants. The cable manufacturer is Rockbestos "RSCC" company, USA. As shown in Fig. 1, the cable comprises the following parts: Annealed, tin-coated copper Class B stranded conductor having a cross-sectional area of 6 AWG, core insulation of XLPE and chlorosulphonated polyethylene (CSPE) jacket with a thickness of 45 and 30 mils, respectively. The overall cable diameter was 0.34 inch. As demonstrated in Fig. 1 and according to the guidelines of IAEA, the sample length was 0.5 m and from both sides of the samples, 1 and 3 cm has been peeled from the core insulation and the jacket, respectively. The cable samples were conditioned at 70 °C for 24 hours prior to starting the aging to remove any moisture within the samples.



1 Tin-coated copper conductor
2 XLPE core insualtion
3 CSPE outer jacket

FIGURE 1. Cable construction.

B. COMBINED ACCELERATED AGING

As mentioned above, the cable samples have been exposed to simultaneous combined thermal and mechanical aging. Since the IEEE-383 standard provides the general requirements and qualification techniques of Class 1E NPP cables, mechanical aging was done as per this standard as the cables should withstand the qualification tests. Hereby, the samples were coiled on a mandrel with outer diameter of 15 cm as per IEEE-383 standard [31]. Then, the cable set were placed in an air circulating oven at constant temperature of 120 °C according to the benchmark analysis for condition monitoring techniques of aged LV cables in NPPs published by IAEA [27]. The combined aging was conducted for 907 hours where the samples were taken out from the oven at periods of 176, 338, 507, 779, and finally after 907 hours for the measurement of the dielectric parameters. Fig. 2, shows the samples in the oven under combined aging.

C. FREQUENCY DOMAIN SPECTROSCOPY

The dielectric response analysis was based on the measurement of the complex permittivity ($\hat{\varepsilon}(\omega)$) over two frequency ranges using two different devices. The complex permittivity is widely used as an aging marker to assess the insulation degradation of nuclear cables. It is expressed as:

$$\hat{\varepsilon}(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega) \tag{1}$$

where: the real part $\varepsilon'(\omega)$ refers to the stored energy within the insulation while the imaginary part $\varepsilon''(\omega)$ is related to the energy loss "dissipation" [9], [17], [32], [33].

By employing the commercial dielectric response analyser type Dirana (OMICRON) and precision component analyzer type 6430A (Wayne Kerr Electronics), the complex permittivity has been explored over frequency band from 100 mHz to 1 kHz and from 2 kHz to 500 kHz, respectively.

FIGURE 2. Cable samples inside the oven for combined aging.

The calculation of the real and imaginary parts of permittivity were based on the measurement of the capacitance and resistance as in (2) and (3):

$$\varepsilon'(\omega) = \frac{C_m(\omega)}{C_0} \tag{2}$$

$$\varepsilon''(\omega) = \frac{1}{2\pi f C_0 R_m(\omega)} \tag{3}$$

where $C_m(\omega)$ and $R_m(\omega)$ are the capacitance and resistance measured at a particular frequency (f). C_0 is denoted as the reference geometric capacitance and it is related to the cable dimensions. Due to the cable was unshielded, a layer of aluminum foil of 29 cm length was wrapped on the cable jacket to provide the second measurement electrode, hence the geometric capacitance is expressed as (4) [34].

$$C_0 = \frac{2\pi\varepsilon_0 l}{\ln(R_2/R_1)} \tag{4}$$

where l is the length of the aluminum foil and ε_0 is the vacuum permittivity ($\varepsilon_0 = 8.854188 * 10^{-12} F/m$). R_2 and R_1 are the outer and inner insulation radius.

For low frequency analysis (100 mHz to 1 kHz), general dielectric test type configuration was chosen, Fig. 3 with a sinusoidal excitation voltage of 100 V_{peak} connected to the cable jacket "output" and the current sensing cable was connected to the cable conductor "CH1". In order to obtain accurate results and eliminating the surface leakage currents, two guard points have been connected at both ends of the cable jacket via copper strips as shown in Fig. 4.

While for the high frequency range (2 kHz to 500 kHz), the 6430A analyzer was used with bias voltage of 5 V_{rms} between the cable conductor and the aluminum foil "jacket", Fig. 5.

Practically, the presence of noise and electromagnetic interferences is unavoidable therefore, the measurements

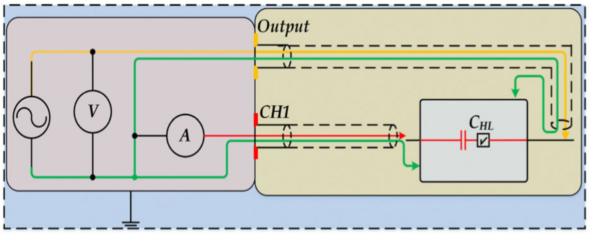


FIGURE 3. General dielectric test configuration.

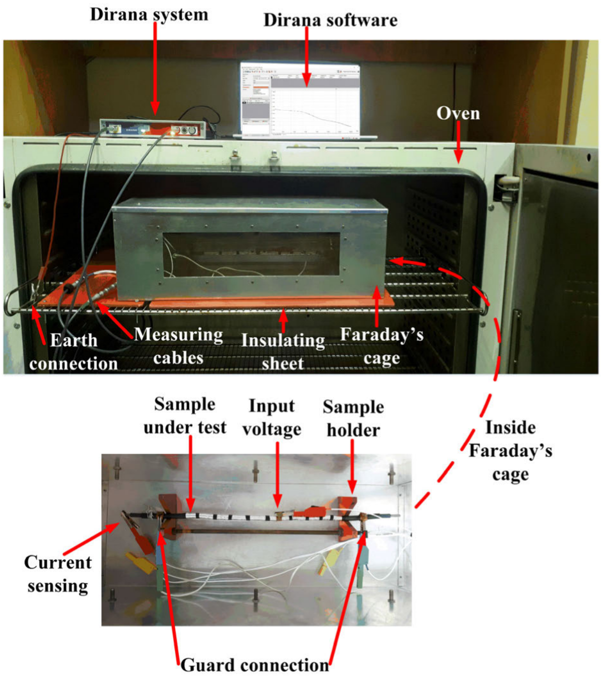


FIGURE 4. Experimental setup of Dirana system for dielectric response measurement over frequency range from 100 mHz to 1 kHz.

were carried out in Faraday's cage to restrain the random noise, Fig. 4 and Fig. 5.

D. TIME DOMAIN SPECTROSCOPY

One of the time domain diagnosis techniques is the Return Voltage (RV) measurement, which was introduced by Endre Németh in 1960's. The basic idea behind this technique is to investigate the slow polarization processes which have a time constant more than 1 sec. Out of this technique, two methods have been introduced, namely the Return Voltage Measurement (RVM) and the Voltage Response (VR) method. Recently, these two techniques gained the attention of the researchers because they are non-destructive tools, which can be used to assess the state of various insulation systems [25], [35]–[39]. The VR technique is successfully applied for condition monitoring of PVC insulated NPP cables [40]. This research was focused on the advanced version of the VR method called Extended Voltage Response (EVR) [26], [39].

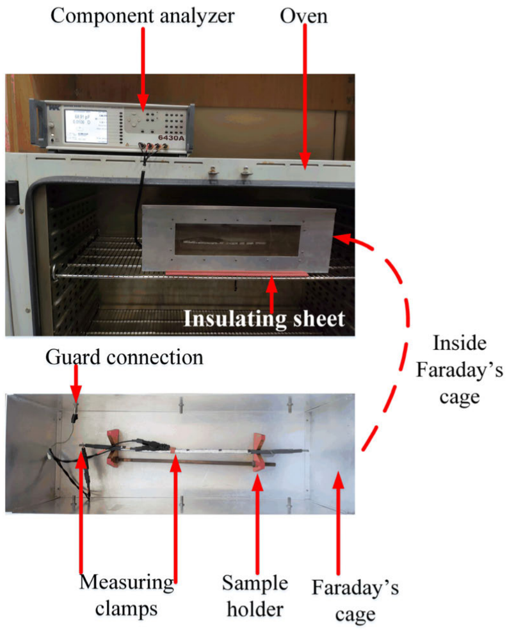


FIGURE 5. Experimental setup of Wayne Kerr component analyser for dielectric response measurement over frequency range from 2 kHz to 500 kHz.

EVR method involves the measurement of two voltage slopes, decay voltage slope (S_d) and return voltage slope (S_r) and both are given as:

$$S_d = \frac{V_{ch}}{\varepsilon_\infty}\gamma \tag{5}$$

$$S_r = \frac{V_{ch}}{\varepsilon_\infty}\beta \tag{6}$$

where V_{ch} is the charging DC voltage and ε_∞ is the relative permittivity due to instantaneous polarization processes.

Equation (5) shows the relation between the return voltage slope and the insulation specific conductivity (γ) while the return voltage slope is related to the polarization conductivity (β) as in (6). The circuit representation of EVR measurement is shown in Fig. 6. With switch S_1 closed and S_2 open, 1000 V external charging DC voltage (V_{ch}) was connected between the cable conductor and the jacket for 4000 s charging

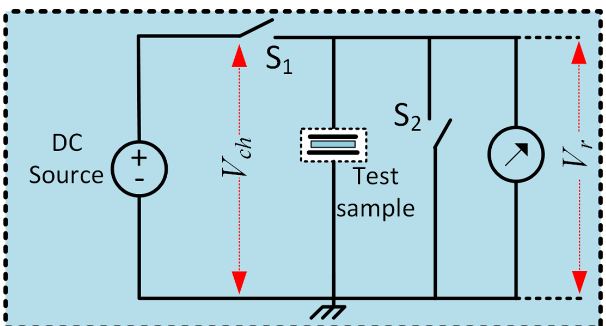


FIGURE 6. Circuit representation of EVR measurement.

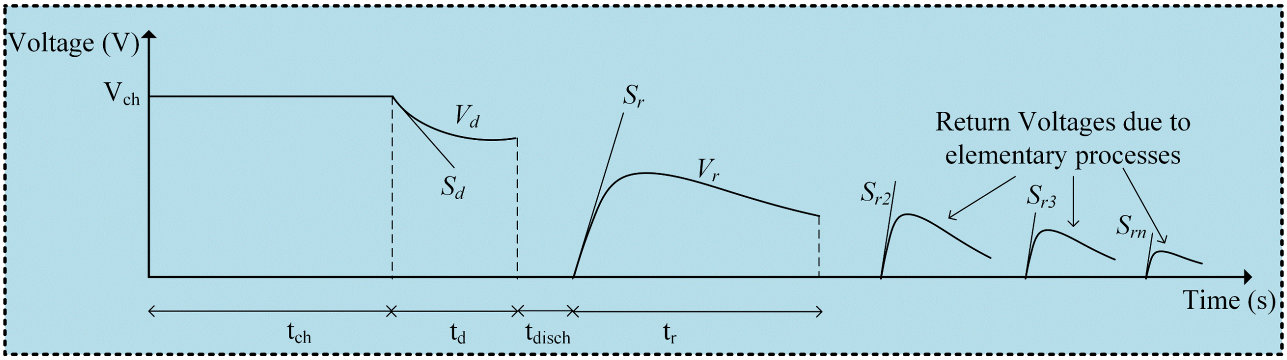


FIGURE 7. Timing diagram of EVR technique.

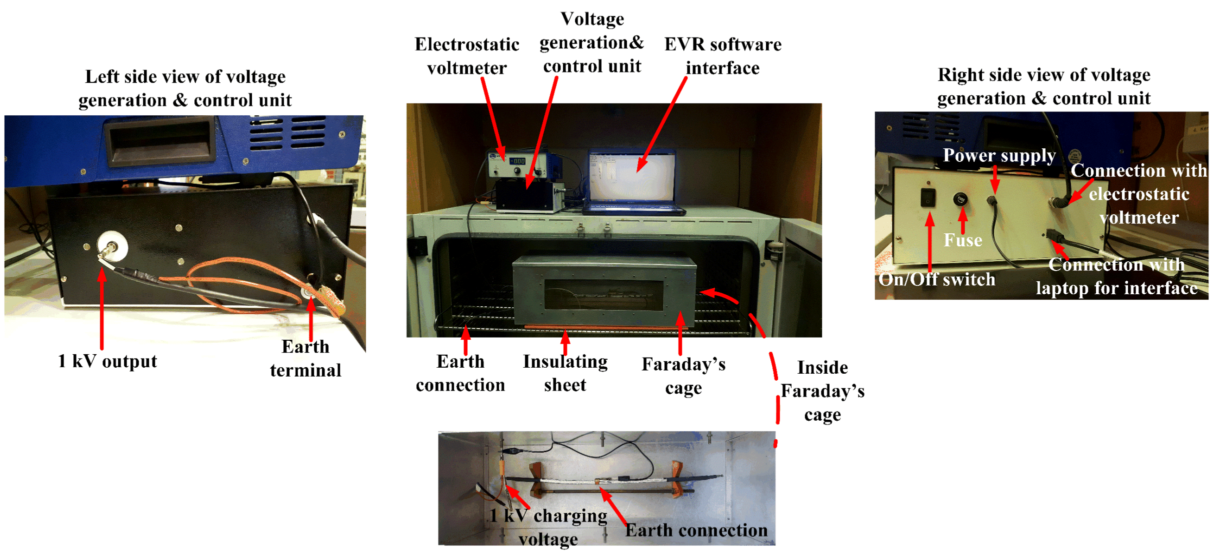


FIGURE 8. Experimental setup of EVR measurement.

period (t_{ch}). This allows the accumulated charge on the electrodes to discharge into the cable insulation then, both switches remained open for the measurement of S_d. For S_r measurement, switch S_1 opened and switch S_2 closed for multiple shortening periods lasted to 2000 s allowing the high time constant polarization processes to relax. Also, this gives the advantage of studying the polarization spectrum in a wide range. The EVR timing diagram is illustrated in Fig. 7 and the experimental setup is depicted in Fig. 8.

Both frequency and time domain spectroscopy measurements were carried out at temperature of 50 °C (in oven) and relative humidity of 12% as the mobility of polymer chains and charge carriers increase at higher temperatures. Moreover, at the temperature of 50 °C, the contact between the dielectric material and the conductor is improved since the insulating material becomes softer so as to obtain an enhanced response from the polymeric material [27], [33]. Also, all the grounding connections was done via single-point grounding to avoid any circulating current, which may arise in the grounding circuit in case of multi-point grounding [41]. Besides, the Faraday's cage was isolated from the oven shelf to restrain any noise as in Figs 4, 5, and 8.

E. MECHANICAL TESTING

Generally, the Shore D hardness technique is applied to measure the polymeric material resistance to indentation. Shore D hardness value refers to the depth of an indentation formed by a given force on a specified indenting foot. In this research, Shore D hardness tester type HPE II by Bareiss with the flat base was used to measure the hardness of the cable samples. The evaluation was based on the average of 10 measured points along the cable length [42]. The hardness measurement was carried out at temperature 25 °C ± 0.5°C.

III. RESULTS

A. COMPLEX PERMITTIVITY WITH FREQUENCY SWAPPING

The data of the real and imaginary parts of permittivity as a function of frequency for different aging periods is presented

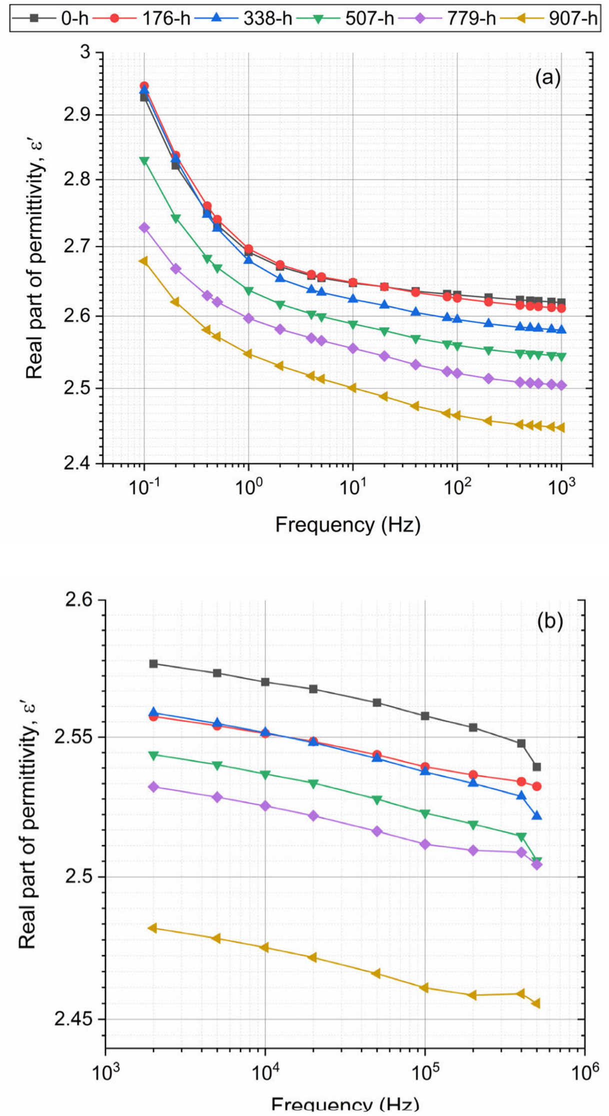


FIGURE 9. **The real part of permittivity over frequency range (a) 100 mHz to 1 kHz (b) 2 kHz to 500 kHz.**

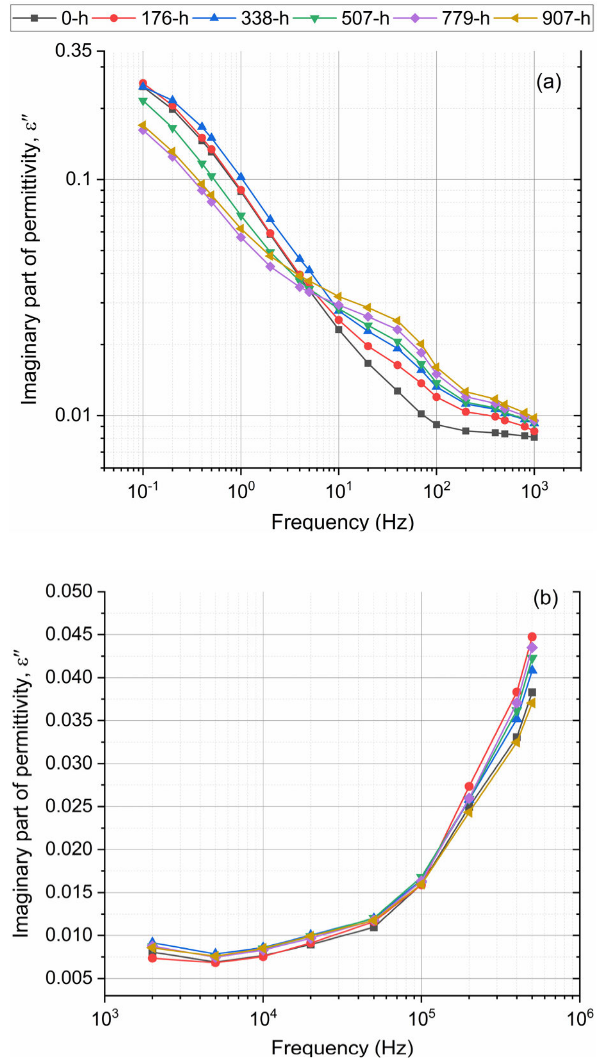


FIGURE 10. **The imaginary part of permittivity over frequency range (a) 100 mHz to 1 kHz (b) 2 kHz to 500 kHz.**

in Fig. 9 and Fig. 10, respectively. The real part is illustrated in Fig. 9 (a) and Fig. 9 (b) for frequency range 100 mHz to 1 kHz and from 2 kHz to 500 kHz, respectively. While the imaginary part is shown in Fig. 10 (a) and Fig. 10(b).

The real part of permittivity showed a pronounced decrease with aging over the whole frequency range (100 mHz to 500 kHz) except after an aging period of 176-hours, a very slight increase was obtained at frequencies from 100 mHz to 10 Hz.

With the aging level increase, the imaginary part of permittivity increased over frequency range 10 Hz to 1 kHz while it decreased at frequencies below 10 Hz to 100 mHz. Moreover, the trend was not uniform in case of higher frequencies (2 kHz to 500 kHz) since, after aging period of 176 hours, the imaginary part of permittivity increased at frequencies ranged from 20 kHz to 500 kHz while it decreased between 2 kHz – 10 kHz. After the second aging cycle, it increased over frequency band from 2 kHz to 100 kHz. However, the samples showed a very slight change after the third and fourth cycles but ε'' increased at frequencies higher than 100 kHz. Reaching the final aging step, the imaginary part of permittivity went up from 5 kHz to 20 kHz and decreased at frequencies above 20 kHz.

B. EXTENDED VOLTAGE RESPONSE

The return voltage slope, S_r versus the discharging time at different aging periods is illustrated in Fig. 11, while the decay voltage slope, S_d versus the aging period is presented in Fig. 12. It can be seen that the return voltage slope which is related to the polarization process has decreased as the cable samples were more aged. In contrast, the decay voltage slope which is connected to the insulation conductivity showed an upward trend with aging.

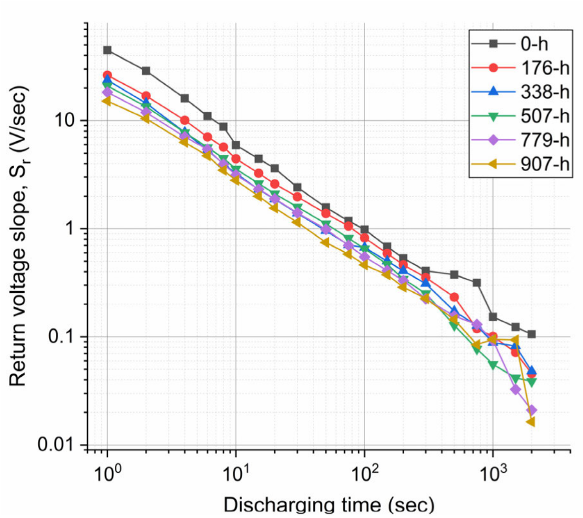


FIGURE 11. **Return voltage slope, S_r versus the discharging time.**

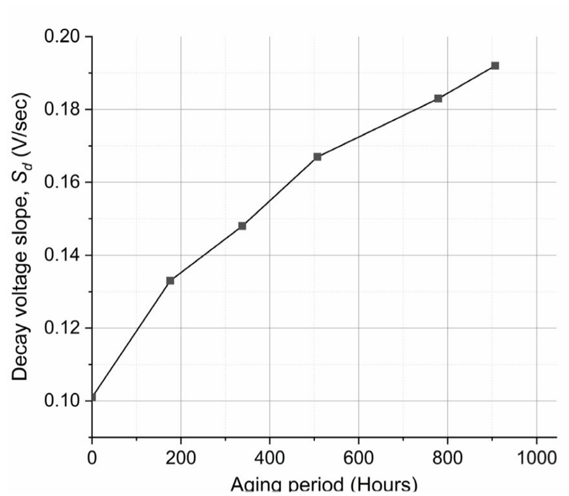


FIGURE 12. **Decay voltage slope, S_d versus the aging period.**

C. SHORE D HARDNESS

The average of 10 replicates Shore D hardness measurements against the aging time is given in Fig. 13. As observed, the cable insulation hardness has increased with aging.

IV. DISCUSSION

A. DIELECTRIC SPECTRA

As previously mentioned in section II.B, the cable samples suffered combined aging; thermal and mechanical. During the normal operation of NPPs, cables polymeric insulation may endure thermal oxidation as a consequence of long-term thermal aging. As a result, two opposite reactions may occur simultaneously, namely cross-linking and chain-scission. Chain-scission causes backbone degradation which is opposed by inter-chain cross-linking. It is believed that the cross-linking results in a reduction in the permittivity while the chain-scission contribute to increase the permittivity [9].

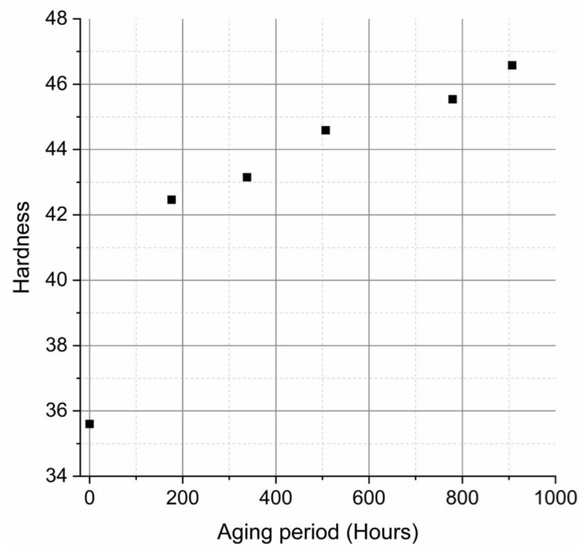


FIGURE 13. **Cable insulation hardness versus the aging period.**

Also, the mechanical bending stress involves two different stresses, compression and tension stresses. When the polymer material subjected to tensile stress, macromolecular chain movement occurs easily, and the molecular chains are stretched along the direction of the tensile stress. Therefore, the attraction bonds between the molecular chains is fractured leading to stress concentration on the main chain of the polymeric material [43]. In contrast, due to the nature of the compressive stress, it generates more attraction bonds as the distance between the molecular chains becomes smaller. Moreover, the micro cavities which arise with the presence of the tensile stress are compressed resulting in apparent reduction in the free volume [44]–[46]. In case of multi-factor aging, one mechanism could be more dominant than the others.

The change in the real and imaginary parts of permittivity (ratio of aged to the pristine case) which are associated with the polarization process and the losses inside the insulating material are displayed at different reference frequencies, Fig. 14 and Fig. 15, respectively. The change in the real permittivity is less at lower frequencies; 0.1 Hz, 10 Hz, 100 Hz, and 1 kHz in comparison with higher frequencies 10, 100, and 500 kHz as there was no much variation observed at these frequencies.

The change in the imaginary part of permittivity showed an increase with aging at frequencies 10 and 100 Hz while no significant change was obtained at higher frequencies. As reported in [11], free radicals are generated when the polymers are subjected to elevated temperatures and they contribute to the conductivity of the material.

The real part of permittivity has decreased in both investigated frequency ranges with aging (Fig. 9.). According to the imaginary part of permittivity curves (Fig. 10. a), the rearrangement of polarization processes can be observed in the 100 mHz-1 kHz range. It is clearly seen the intensity of

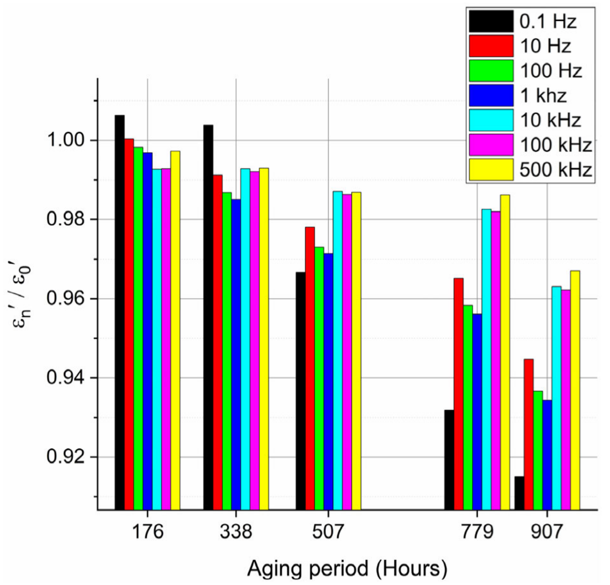


FIGURE 14. Change (ratio of aged to pristine) in the real part of permittivity (ε') versus the aging time at frequencies 0.1 Hz, 10 Hz, 100 Hz, 1 kHz, 100 kHz, and 500 kHz.

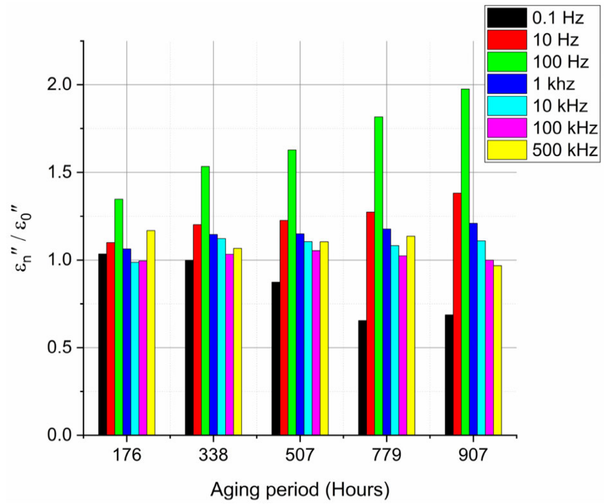


FIGURE 15. Change (ratio of aged to pristine) in the imaginary part of permittivity (ε'') versus the aging time at frequencies 0.1 Hz, 10 Hz, 100 Hz, 1 kHz, 100 kHz, and 500 kHz.

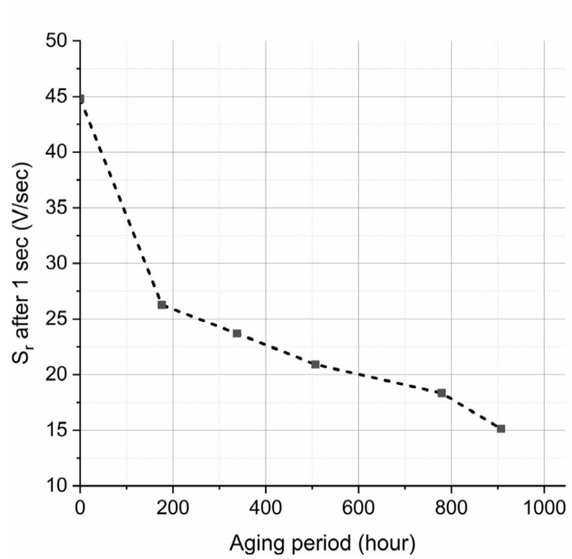


FIGURE 16. Return voltage slope after 1 sec discharging.

polarization processes have decreased below 5 Hz, while they have increased above 5 Hz. The shape of the curves suggests the polarization peek can be found below 100 mHz, which shifted towards lower frequencies. This behavior of dielectric spectrum suggests decreasing of conductivity because the imaginary part of permittivity at very low frequency is affected by the dc conductivity. The situation is more complicated, as the increase of slope of decay voltage indicates the increase of conductivity (Fig. 12). Nevertheless, the slope of return voltage has decreased with aging (Fig. 16.), which shows the radical decrease of the intensity of polarization processes below 1 Hz (time constant range higher than 1 s). Since the ratio of conductivity increase is lower than the ratio of the intensity decrease of the polarization process, these contrary trends result in the moving of polarization peaks towards lower frequency range. In the higher frequency range (2 kHz-500 kHz), the real part of permittivity has decreased with aging. In this frequency range, the dipole polarization is the dominant polarization process in polymers. However, the thermo-oxidative degradation process produces dipole molecular groups in polymers (e.g. in CSPE), probably the cross-linking is the dominant reaction in the XLPE, which result in permittivity decrease. From the point of view of the dielectric measurements, the XLPE insulation and the CSPE jacket can be considered as layered insulation, therefore the resultant of the dielectric properties can be measured only. Since the thickness of the XLPE layer is higher, the properties of XLPE will be dominant in the measurement results.

B. EVR

Since the polarization process is affected by the number and mobility of dipoles, the generation of dipoles was limited by the cross-linking reaction. Besides, it is observed that the cable jacketing material, CSPE undergo dehydrochlorination when exposed to higher temperatures. As a result, the dielectric relaxation phenomena which is proportional to the number and mobility of C-Cl dipoles of the vinyl chloride groups decreased [9], [47]. Therefore, the return voltage slope has decreased, Fig. 16.

The behavior of both the real permittivity at 0.1, 10, and 100 Hz and return voltage slope show a reduction in the interfacial polarization which may occur at the interface between two different materials (core insulation and jacket).

C. SHORE D HARDNESS

For semicrystalline polymers such as XLPE and CSPE, the stiffness of the material is associated with the hardness of

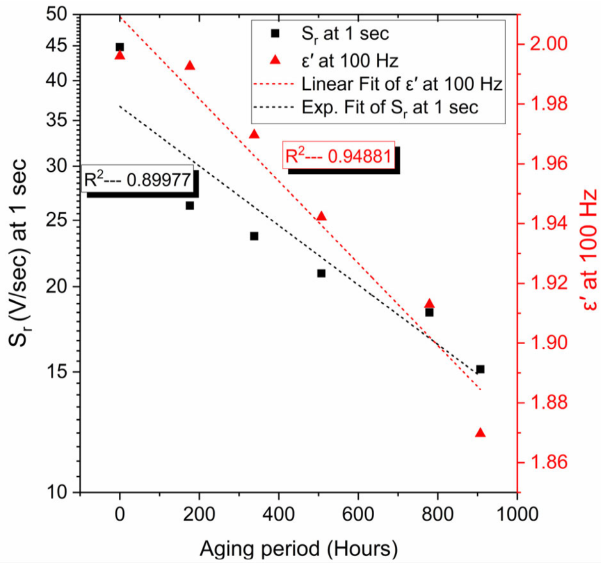


FIGURE 17. Correlation between S_r at 1 sec and ε' at 100 Hz.

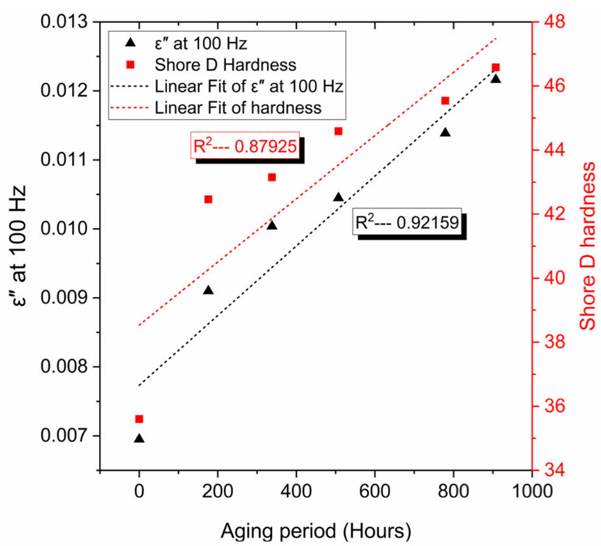


FIGURE 18. Correlation between ε'' at 100 Hz and hardness.

both the amorphous and crystalline regions. It was observed that the tensile elongation of both XLPE and CSPE tends to decrease with thermal degradation [48]. As presented in Fig. 13, the cable insulation hardness showed an increasing fashion. The changing of mechanical properties implies the intensive degradation of the insulation and the jacket material, due to cross-linking, dehydrochlorination, and oxidation processes [47], [48].

V. CORRELATION BETWEEN ELECTRICAL AND MECHANICAL PROPERTIES

Relationships were established between the dielectric response ($\varepsilon', \varepsilon''$), the return voltage slope (S_r), and the mechanical properties (Shore D hardness). The correlation between the real part of permittivity at 100 Hz and the return

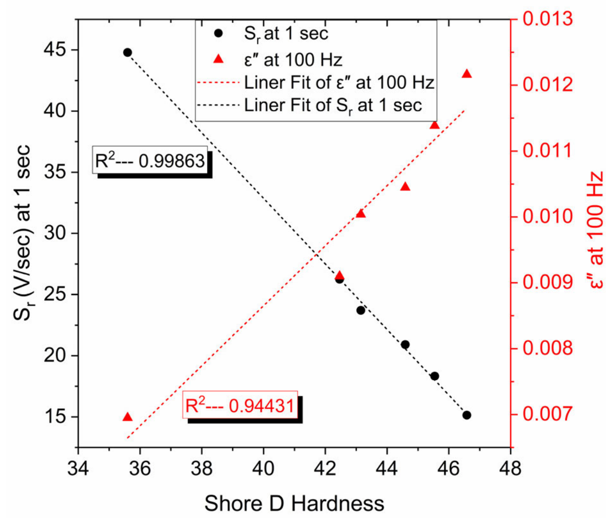


FIGURE 19. Correlation between S_r at 1 sec ε'' at 100 Hz, and hardness.

voltage slope after a shortening time of 1 sec is demonstrated in Fig. 17 while the imaginary part of permittivity at 100 Hz was correlated with the Shore D hardness, Fig. 18. In addition, the correlation between the return voltage slope after 1 sec, the imaginary part of complex permittivity at 100 Hz, and the Shore D hardness is given in Fig. 19. Based on the linear regression fitting, the results showed a strong correlation with each other with a high value of R^2. This reveals the applicability of the presented techniques to assess the degradation intensity of unshielded low voltage nuclear power cables.

VI. CONCLUSION

Multi-factor aging of the polymeric insulation of nuclear power plant cables is a complex phenomenon, but the pursuit of a predictive understanding of the effects of combined simultaneous exposure to thermal and mechanical stresses on the insulation integrity of nuclear power plant cables is of utmost importance for the nuclear safety and management decisions. This research evaluated and confirmed the applicability of three potential non-destructive techniques for assessing the degradation of unshielded low voltage XLPE/CSPE insulation-based power cables used in nuclear facilities. These techniques involve the dielectric spectroscopy with frequency swapping from 100 mHz to 500 kHz, measurement of the return and decay voltage slopes, in addition to, the Shore D hardness. The real part of permittivity showed a decreasing trend with aging over the whole frequency band. That was more prominent at lower frequencies; 0.1, 10, and 100 Hz which is correlated with the return voltage trend. Besides, an increase in the imaginary part of permittivity was observed at 100 Hz while there was no significant effect at other frequencies. Based on the linear fitting and the higher values of R^2, the established correlations between the return voltage slope after discharging time of 1 sec, the real and imaginary parts of permittivity at 100 Hz, and the hardness proves the applicability of using these parameters as aging indicators.

A further step towards the validation of the presented data is comparing the results with simple thermal aging in addition involving other test methods such as elongation at break as a mechanical testing technique in addition to chemical investigations for instance, Fourier Transform Infrared (FTIR) spectroscopy, the Oxidation Induction Tim (OIT), and density. This will provide more data and gives a good explanation for the chemical and physical changes in the dielectric.

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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.

Since 2010, he has been working as a Teaching Assistant with the Department of Electrical Power and Machines Engineering, Faculty of Engineering, Helwan University. He was promoted as an Assistant Lecturer with the Department of Electrical Power and Machines Engineering, in March 2015. 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.

MUSTAFA EHTASHAM was born in Dera Ismail Khan, Khyber Pakhtunkhwa, 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 papers in well-reputed journals and conferences. His research interests include study of insulation diagnostics, non-destructive diagnosis techniques for insulation materials, and insulation degradation with aging.

ZOLTÁN ÁDÁM TAMUS (Member, IEEE) received the M.Sc., Ph.D., and the Habilitation degrees in electrical engineering 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, where he has been working as an Associate Professor. He has more than 90 research articles to his name. His research interests include electrical insulation technology, insulation diagnostics, electrical characterization, electrical breakdown, and health effects of electromagnetic fields.