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INVESTIGATION OF AGING PROCESSES OF INSULATING MATERIALS IN MULTI-STRESS ENVIRONMENT:

THE ROLE OF THERMO-MECHANICAL AND RADIO-MECHANICAL STRESSES ON LOW-VOLTAGE NUCLEAR CABLES INSULATION

Ph.D. Dissertation Booklet

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1. Background

In accordance with the climate-energy package [1], the role of clean energy sources in the energy generation market increases day by day since there is an unwavering desire to de-carbonize energy sources. Nuclear fission applications, i.e., nuclear power plants (NPPs), are extensively introduced as clean energy sources among the various sustainable energy sources. Since nuclear energy is the world's second-largest source of low-carbon electricity after hydropower, also, they can secure a continuous service for long periods without interruptions. In November 2021, 442 nuclear power reactors were in operation worldwide, totaling a net electrical installed capacity of 394.467 GW. Besides, there were 51 reactors under construction, which will increase the net capacity by 53.870 GW [2]. Currently, NPPs supply around 10.3% of the world's electricity, and it is expected that by the year 2050, the share of NPPs will increase up to 17% [3].

Safe operation is one of the most important criteria for nuclear power plants. The concept of nuclear safety includes the "control of the radiation exposure of people and the release of radioactive materials to the environment, to restrict the likelihood of events that might lead to a loss of control over a nuclear reactor core, nuclear chain reaction, radioactive source or any other source of radiation, and to mitigate the consequences of such events if they were to occur" [4]. The items (structures, systems, and components) important to safety are those items whose "malfunction or failure could lead to radiation exposure of the site personnel or members of the public." These items can be classified into the groups of safety systems and safety-related items [5].

The operation of a typical NPP requires thousands of kilometers of cables. Low-voltage (LV) cables are extensively used for power transmission and to connect the various system components. A significant proportion of these cables are in the group of safety-related components. For instance, the link between the plant safety and control systems is provided by LV cables via signaling to control equipment, plant operators, and safety systems [5–7]. Considering their crucial role, the safety-related components have to be qualified. The qualification is the process of demonstrating that equipment will operate on demand, under specified operating conditions, and meets the performance requirements of the system [5]. Therefore, the functionality of safety-related cables has to be demonstrated during normal operation, accidents, and post-accident conditions. The qualification methods are type testing, analysis, use of operating experience, and a combination of these methods [9].

The qualification method of safety-related (Class 1E) cables is prescribed by the IEEE-383 standard [10]. The test procedure for type testing of cables includes the following steps:

1. The thermal and radiation aging for simulation of normal service;
2. Testing integrity of insulation and jacket (electrical tests on wounded and soaked samples);
3. Design-basis event (DBE) simulation: functionality test in DBE environment;
4. Post DBE simulation test: flexibility and electrical tests on soaked samples.

2. Motivation

Depending on the application and location of the LV cables, they are subjected to a wide range of environmental conditions and stresses, involving elevated temperature, high radiation doses, humidity, submergence, and mechanical bending. Fortunately, some cables are located in a mild environment, while others are located in the containment area where the environmental conditions become harsh. Figure 1 illustrates the various stresses and how they interact with each other.

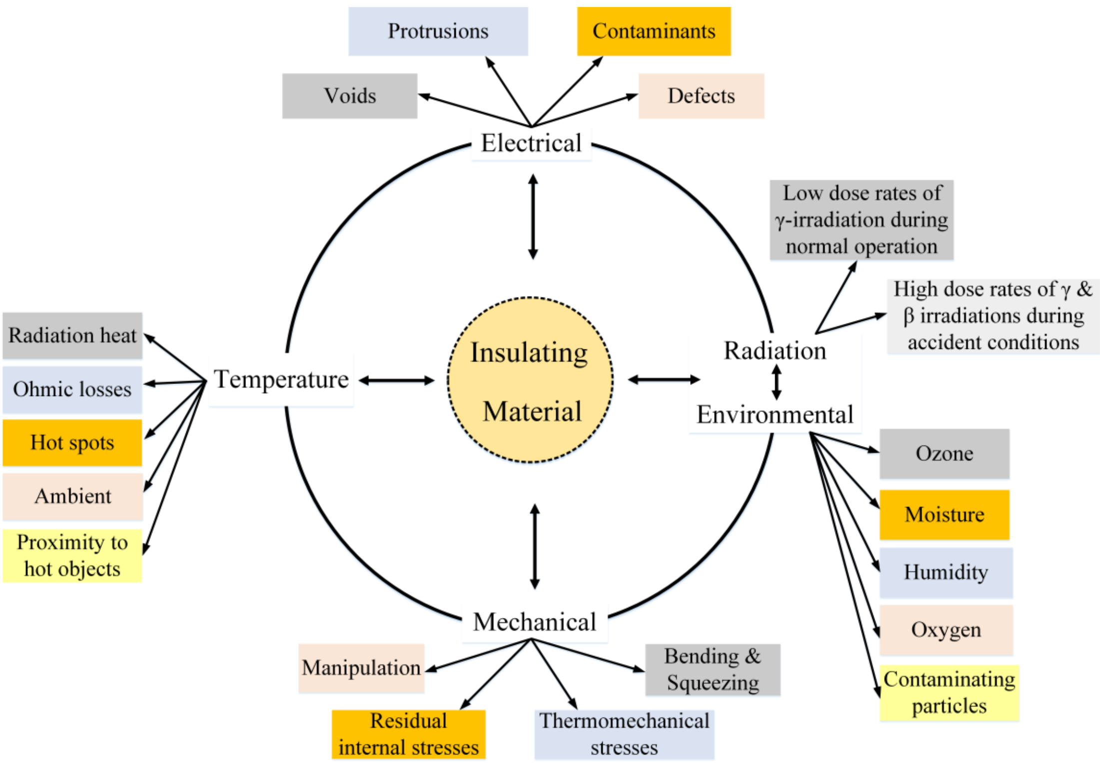

Figure 1: Aging stressors and multi-stress aging.

Each of electrical, thermal, and mechanical stresses represents one side. The radiation and environmental stresses are combined on the fourth side. Signifying that the majority of insulation systems endure electrical, thermal, and mechanical stresses, but the exposure to radiation and harsh environmental conditions is related to nuclear systems.

According to the IEEE standard, aging during regular operation is simulated by thermal and radiation stresses [10], while, as we have seen above, the cables are subjected to several other stresses. Moreover, the IAEA Specific Safety Guide 69 [9] prescribes considering the possible synergic effects, where they can lead to significant aging effects and degradation mechanisms. However, as reported, at some locations in NPPs, the bending radius may reach critical values, and the role of mechanical aging can be significant [11].

Cables polymeric insulation must face the challenge of mechanical stresses such as the externally applied forces when cables are sharply bent during installation [11], [12]. Depending on the cable diameter and the bending radius, if the bending radius is sufficiently small, the insulating material is elongated, and cracks are initiated. Thus, the jacket material excessively aged more than the underlying insulation [13], [14]. It is reported that when the PE material was subjected to tensile stress, macromolecular chain movement occurred easily, and the molecular chains were stretched along the direction of the tensile stress. Therefore, the attraction bonds between the molecular chains were fractured, leading to stress concentration on the polymeric material's main chain [15]. 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 microcavities that arise with the tensile stress are compressed, resulting in an apparent reduction in the free volume [15–17].

Mechanical strains and stresses affect the dielectric behavior of polymeric insulating materials, affecting the characteristics of breakdown strength [16]. Tanaka et al. reported the temperature dependence of mechanical properties affected the breakdown characteristics of the insulation [19]. As in [20], when XLPE insulation was exposed to a mechanical strain of 21%, the AC breakdown strength was reduced. Mita et al. studied the breakdown of PE under different mechanical strains. It showed a reduction in the breakdown field with strains up to 30% [21].

Based on all these, the main topic of this thesis is the study of the effect of mechanical stress on the insulation of nuclear power cables. This Ph.D. thesis work has been conducted as a part of the "Condition Based Maintenance Technology Development for Nuclear Control and Instrumentation (C&I) Cable via Korea-Hungary Joint Research" project (KNN 123672). Earlier phase in the project, the effects of separated irradiation and thermal aging were studied, and condition monitoring methods have been proposed to track the insulation degradation due to these stressors [22]. This Ph.D. thesis is based on the results of the next phase when the effect of thermo-mechanical and radio-mechanical aging stresses on the electrical and mechanical parameters of NPP LV cables was investigated. The main research aims can be stated as follow:

i. Investigating the role of mechanical stresses on the electrical and mechanical properties of the insulation of NPP LV cables via comparing the results of thermally and thermo-mechanically aged cables;
ii. Examination of applicability of the proposed condition monitoring methods on multifactor aging, i.e.:
   a. Thermo-mechanically and,
   b. Radio-mechanically aged

   The cable samples used in the first phase of the project were XLPE/CSPE insulated.
iii. Investigation of multi-stress aging on other insulating material (XLPO).

3. Thesis Outline

The Ph.D. thesis work has been formulated and presented in seven chapters. Each chapter has been arranged to give the reader clear and in-depth knowledge about the impact of multi-stress environments on single-core unshielded LV cables' degradation.

Chapter 1, Introduction, this chapter has been divided into four main parts. The first part presents a brief introduction to the NPPs and the role of LV cables on the safe and reliable operation of NPPs. Also, the qualification methods of NPP LV cables are addressed in this part. The motivation behind the Ph.D. thesis work is described in the second section. In the third section, the aim of the Ph.D. work is elaborated. The fourth part depicts the implemented CM techniques and their related literature review, dielectric spectroscopy, Extended Voltage Response (EVR), polarization-depolarization current (PDC), and indenter testing.

Chapter 2, Experimental Work, provides a detailed description of the LV cable samples used in this research and the measurement procedure. A complete illustration of the experimental setup of each evaluation technique, electrical and mechanical, has been presented.

The measurement results of the electrical and mechanical techniques have been presented in the subsequent three chapters. The results of LV NPP power cables under thermo-mechanical stresses have been demonstrated in Chapter 3, Results of NPP Cables Under Simultaneous Thermal-Mechanical Aging. While the results under radio-mechanical stresses have been presented in Chapter 4, Results of NPP Cables Under Simultaneous Radiation-Mechanical Aging. The results of the XLPO insulated LV PV DC cables under thermo-mechanical stresses have been introduced in Chapter 5, Results of PV Cables Under Simultaneous Thermal-Mechanical Aging.

Chapter 6, Discussion, is inscribed to the discussion on the obtained results of both NPP and PV cables. Electrical aging markers have been selected to emphasize the degradation cause. Afterward, correlations have been established to verify the applicability of the implemented techniques.

Chapter 7, Summary and Future Work, is the last chapter, where the executed research work has been summarized. The obtained scientific results were highlighted by categorizing as Thesis I, Thesis II, Thesis III, and Thesis IV. Finally, the future perspectives beyond this research work were proposed.

4. Theses

4.1 Thesis I

"The qualification tests of nuclear power plant cables do not involve mechanical stress in the simulation of operation aging. To investigate the effect of mechanical stress, XLPE insulated, CSPE jacketed, unshielded, low-voltage, single-conductor nuclear power plant cable samples were exposed to thermal and thermo-mechanical accelerating aging. Analyzing the results of the low-frequency dielectric spectrum and Shore D hardness measurements of thermally and thermo-mechanically aged samples, I have revealed that:

- *The central frequency of the imaginary part of permittivity of thermo-mechanically aged samples was higher than that of thermally aged ones by 0.5 mHz;*
- *On average, the Shore D hardness of thermo-mechanically aged samples was higher than that of thermally aged ones by 3.92%.*

These results show that mechanical stress substantially impacts the degradation of the polymeric materials of nuclear power plant cables in combination with the thermal stress. It is necessary for cables subjected to mechanical stress to include mechanical stress in the aging procedure of the qualification tests."

The research aimed to investigate whether the mechanical stresses during accelerated aging cause any additional change in the physical properties of cable insulation. The dielectric behavior in the low-frequency range and the Shore D hardness of thermally and thermo-mechanically (T-M) aged single-core XLPE/CSPE insulated LV NPP cables were compared. For the purpose of investigation, one group of cables was straightened, and the other one was coiled on a mandrel. Both groups were aged at 120 ºC for more than 1200 h. The dielectric spectrum in the 200 μHz-50 mHz frequency range and the Shore D hardness were measured on both groups to investigate the dielectric and mechanical properties of both groups. To evaluate the changes in the dielectric spectrum due to aging, derived quantities, namely the central real and imaginary parts of permittivity (CRP and CIP), and the real and imaginary permittivities' central frequencies (RPCF and IPCF), were introduced, similarly to [23]. The deducted quantities showed that the real part of permittivity of the T-M aged samples was higher by nearly 0.1 than that of thermally aged ones during the whole aging period in the investigated frequency range. At the same time, the RPCF curves decreased by 1 mHz due to thermal aging. A similar change was not observed in the case of T-M aged samples.

However, no significant change was observed between the two groups in terms of the CIP, the IPCF of T-M aged samples was higher than the thermally aged ones by 0.5 mHz. Indicating a higher conductivity in the case of T-M aging, which can be the result of the annealing effect [24]. The Shore D hardness was also higher on the T-M aged samples than the thermally aged ones during the aging. At the end of aging, the hardness of the T-M was 34% higher than the initial value, while that of thermally aged samples was only 30% higher.

Based on the results, it can be concluded that mechanical stress has a strong role in the degradation of NPP LV cables insulation.

This thesis has been published in [J3, J6, J8, J9, J12, J13, J16, J17, J18, C4, C6, C9, C12, C13].

4.2 Thesis II

"I have implemented the dielectric spectroscopy over a wide frequency band, and the extended voltage response techniques on thermo-mechanically aged XLPE insulated, CSPE jacketed, unshielded low-voltage, single-conductor nuclear power plant power cable samples. I have revealed that:

- *The real part of permittivity at 10 Hz and the initial slope of return voltage declined in the initial stages of thermal-mechanical aging, then both parameters increased, indicating the severe damage of the insulation;*
- *The imaginary part of permittivity at 10 Hz and the initial slope of decay voltage monotonically increased with aging;*
- *The behavior of the initial slope of decay voltage and the imaginary part of permittivity at 10 Hz strongly correlates with the Shore D hardness data.*

The obtained results elaborate the applicability of these parameters as non-destructive aging markers for thermally-mechanically aged XLPE insulated, CSPE jacketed, unshielded low-voltage nuclear power plant power cable samples."

The thesis's main purpose is to seek such aging markers that could explore the interaction between the aging stressors and the polymeric insulation of NPP cables under combined thermal-mechanical stresses. With the cable samples being subjected to eight aging cycles at 120 °C, the applicability of two potential-based electrical non-destructive techniques for assessing the XLPE/CSPE cable samples was evaluated and confirmed. These techniques involve dielectric spectroscopy with frequency swapping from 200 µHz to 500 kHz and the extended voltage response.

The real part of permittivity and the return voltage slope showed a downward trend after the first six aging cycles, which may be attributed to the cross-linking of the XLPE & CSPE and the dehydrochlorination of the CSPE. Moreover, the opposite effect of tensile-compressive forces. After that, the real permittivity and the return voltage slope increased. That was due to the cracks and insulation damage as the insulation became more brittle. This indicates that the chemical and physical changes in the mechanical properties influenced the dielectric response of the cable insulation.

The decay voltage slope, associated with insulation conductivity, has increased with aging. However, the imaginary part of permittivity presented a non-monotonic trend with aging due to the presence of several reactions; a good agreement was observed between the decay voltage slope and the imaginary permittivity at 10 Hz.

The established correlations reflect the effectiveness of the conducted techniques and confirm their applicability to be used as non-destructive aging indicators for thermally-mechanically aged XLPE/CSPE unshielded LV NPP power cable samples.

This thesis has been published in [J3, J6, J9, J13, J16, J18, C2, C6, C9, C12, C13].

4.3 Thesis III

"I have implemented the dielectric spectroscopy over a wide frequency band, and the extended voltage response techniques on irradiated-mechanically aged XLPE insulated, CSPE jacketed, unshielded low-voltage, single-conductor nuclear power plant power cable samples. I have revealed that:

- *The real part of permittivity at 1 Hz and the imaginary part of permittivity at 1 kHz have increased monotonically with the absorbed irradiation dose;*
- *The initial decay and return voltage slopes have increased with the absorbed irradiation dose;*
- *The monatomic increasing fashion of these parameters presented a strong correlation with the Shore D hardness measurements.*

These findings demonstrate the applicability of the implemented techniques as non-destructive condition monitoring techniques for XLPE insulated, CSPE jacketed low-voltage unshielded, single-conductor nuclear power plant cables exposed to simultaneous radiation-mechanical aging."

LV NPP cables placed in the containment area are exposed to high levels of gamma irradiations during their normal operation and accident conditions. Thus, it is believed that radiation stress is one of the dominant stresses that the NPP LV cables encounter. At the same time, less attention has been paid to the role of mechanical stresses and their impact on the insulation integrity of NPP LV cables. This thesis targeted investigating the effect of parallel radiation-mechanical accelerated aging tests on XLPE/CSPE insulation-based single-conductor unshielded LV NPP cable samples.

The cable samples underwent combined radiation-mechanical aging with a constant bending radius while exposed to five gamma irradiation doses with a total absorbed dose of 400 kGy at a 500 Gy/hr dose rate. Dielectric spectroscopy over a frequency band of 200 μHz-500 kHz and the EVR have been implemented as non-destructive CM techniques to assess the insulation state.

The regular increase of the real permittivity at 1 Hz revealed the intensity of the interfacial polarization process. This hypothesis has been confirmed by the rise of the return voltage slope, which is related to the polarization conductivity. Also, the monotonic increment of the imaginary permittivity at 1 kHz reflects the dipolar polarization's intensity and the insulation resistivity reduction. This is also agreed with the rise of the decay voltage slope, which is associated with the insulation conductivity. Furthermore, the cable insulation hardness has increased with aging.

Based on the strong agreement (liner fitting) between the insulation electrical parameters and the Shore D hardness, it can be stated that the real permittivity at 1 Hz, the imaginary permittivity at 1 kHz, the decay and return voltage slopes are applicable as non-destructive aging markers for XLPE/CSPE, unshielded LV, single-conductor NPP cables.

This thesis has been published in [J1, J4, J16, C12, C13].

4.4 Thesis IV

"*I have implemented the dielectric spectroscopy over a wide frequency band, and the extended voltage response techniques on thermo-mechanically aged XLPO insulated, XLPO jacketed, unshielded low-voltage, single-conductor photovoltaic cable samples. I have revealed that:*

- *The real part of permittivity at 0.1 Hz and the imaginary part of permittivity at 1 Hz initially increased, while they declined with the aging time increased;*
- *The non-monotonic trend of the real part of permittivity at 0.1 Hz and the imaginary part of permittivity at 1 Hz agrees with the Shore D hardness measurements;*
- *The initial decay voltage slope presented a strong correlation with the imaginary part of permittivity at 1 Hz;*
- *The deducted central imaginary permittivity showed a solid agreement with the initial slope of decay voltage.*

The results prove that the dielectric spectroscopy and the extended voltage response techniques can be used as non-destructive condition monitoring techniques for thermo-mechanically aged XLPO insulated, XLPO jacketed, unshielded low-voltage, single-conductor photovoltaic cable."

In thesis IV, the behavior of LV PV cable samples under the effect of simultaneous thermo-mechanical stresses has been studied. The XLPO insulation-based PV cable samples have been subjected to eight aging cycles lasting 1120 hours. Electrical and mechanical dielectric assessment techniques have been conducted to investigate the changes in the XLPO material. The evaluation involved a dielectric response with frequency swapping between 200 μHz and 500 kHz and extended voltage response. While, as a mechanical property, the Shore D hardness measurement has been applied.

The change of the real permittivity at frequencies higher than 1 Hz was rarely where the values almost remained unchanged. At the same time, a slight change was observed at 1 Hz and less, which was more evident at 50 mHz, 100 mHz, and 1 Hz. In contrast to the real permittivity, the change of the imaginary permittivity was more noticeable between 200 μHz and 1 kHz. For instance, at 1 Hz, the imaginary permittivity change increased monotonically with aging till the fourth aging cycle, 396 aging hours. Afterward, it decreased until reaching the last aging cycle, 1120 hours.

The return voltage slope initially dropped, while after the subsequent cycles, the role of the thermal-mechanical stresses on the return voltage values was not significant as slight changes were observed. After the fourth aging cycle, the decay voltage slope decreased monotonically. With the aging period increased, the hardness of the XLPO material surprisingly decreased, showing that the XLPO became softer.

At the initial aging periods, the increase in permittivity and the decay voltage slope were attributed to the chain-scission-based reaction where localized sites with low energy fields are generated. As a result, the XLPO backbone has degraded, which was evident with the increase of the permittivity, decay voltage slope, and hardness. The electrical and mechanical parameters declined with more aging, suggesting cross-linking-based reaction domination. Moreover, with the chain-scission dominant reaction, the maximum value of the imaginary permittivity has been obtained at 40 mHz. While at higher aging periods where the cross-linking is more prevalent, the imaginary permittivity maximum value shifted back to 20 mHz, the same as the pristine case. It can be noticed that after 1120 aging hours, the XLPO material showed high durability against the combined thermal-mechanical stresses. The obtained results show the ability of the XLPO material to retain its electrical and mechanical properties while being exposed to long-term aging at a higher temperature.

This thesis has been published in [J2, C1, C5, C12, C13].

5. Summary and Future Work

The results of thermal and thermomechanical aging studies have shown that the effect of combined aging can be significant on the dielectric and mechanical properties of cable insulation. An extension of cable qualification standards in this direction should certainly be considered.

Another significant result is that the proposed non-destructive tests can monitor the effects of such multifactor aging. Emerging research problems that come from this research include the following:

i. The results of the electrical measurements can be validated by mechanical tests such as EaB;
ii. Also, involving chemical investigations such as FTIR, OIT, and density will provide a deep understanding of the aging effects and give a good explanation of the chemical and physical changes in the dielectric materials;
iii. Estimating the remaining useful life (RUL) is a topic that is receiving much interest. The obtained results and the selected aging markers can be used in the RUL estimation of single-conductor NPP LV cables;
iv. Since the entire work was based on laboratory testing (ex-situ), conducting the implemented techniques in fields (in-situ) will help to improve the applicability of these techniques for the in-situ assessment of NPP LV cables

6. List of Publications by the Author (Related to Ph.D. Work)

<u>International Journal Articles</u>

[J1] **Afia, R. S. A.**, Mustafa, E., and Tamus, Z. Á., "Ageing Assessment of XLPE/CSPE LV Nuclear Power Cables Under Simultaneous Radiation-Mechanical Stresses," Energy Reports, vol. (8) 1, pp. 1028-1037, 2022. **(IF = 6.87, Q1, Indexed: WoS, Scopus)**

[J2] **Afia, R. S. A.**, Mustafa, E., and Tamus, Z. Á., "Condition Monitoring of Photovoltaic Cables Based Cross-Linked Polyolefin Insulation Under Combined Accelerated Aging Stresses: Electrical and Mechanical Assessment," Energy Reports, vol. (8) 1, pp. 1038-1049, 2022. **(IF = 6.87, Q1, Indexed: WoS, Scopus)**

[J3] **Afia, R. S. A.**, Mustafa, E., and Tamus, Z. Á., "Comparison of Mechanical and Low-Frequency Dielectric Properties of Thermally and Thermo-Mechanically Aged Low Voltage CSPE/XLPE Nuclear Power Plant Cables," Electronics, vol. (10) 22, 2728, 2021. **(IF = 2.397, Q2, Indexed: WoS, Scopus)**

[J4] **Afia, R. S. A.**, Mustafa, E., and Tamus, Z. Á., "Aging Mechanisms and Non-Destructive Aging Indicators of XLPE/CSPE Unshielded LV Nuclear Power Cables Subjected to Simultaneous Radiation-Mechanical Aging," Polymers, vol. (13) 18, 3033, 2021. **(IF = 4.329, Q1, Indexed: WoS, Scopus)**

[J5] Mustafa, E., **Afia, R. S. A.**, Oumaima Nouini, and Tamus, Z. Á., "Implementation of Non-Destructive Electrical Condition Monitoring Techniques on Low-Voltage Nuclear Cables: I. Irradiation Aging of EPR/CSPE Cables," Energies, vol. 14 (16), 5139, 2021. **(IF = 3.004, Q2, Indexed: WoS, Scopus)**

[J6] **Afia, R. S. A.**, Mustafa, E., and Tamus, Z. Á., "Electrical and Mechanical Condition Assessment of Low Voltage Unshielded Nuclear Power Cables Under Simultaneous Thermal and Mechanical Stresses: Application of Non-Destructive

Test Techniques," IEEE Access, vol. 9, pp. 4531-4541, 2021. **(IF = 3.745, Q1, Indexed: WoS, Scopus)**

[J7] Mustafa, E., Németh, R. M., **Afia, R. S. A.**, and Tamus, Z. Á., "Parameterization of Debye Model for Dielectrics Using Voltage Response Measurements and a Benchmark Problem," Periodica Polytechnica Electrical Engineering and Computer Science, vol. 65 (2), pp. 138-145, 2021. **(Q3, Indexed: Scopus)**

[J8] Mustafa, E., **Afia, R. S. A.**, and Tamus, Z. Á., "Dielectric Loss and Extended Voltage Response Measurements for Low Voltage Power Cables Used in Nuclear Power Plant: Potential Methods for Aging Detection due to Thermal Stress," Journal of Electrical Engineering, vol. 103, pp. 899-908, 2020. **(IF = 1.18, Q2, Indexed: WoS, Scopus)**

[J9] **Afia, R. S. A.**, Mustafa, E., and Tamus, Z. Á., "Dielectric Spectroscopy of Low Voltage Nuclear Power Plant Power Cables Under Simultaneous Thermal and Mechanical Stresses," Energy Reports, vol. 6 (9), pp. 662-667, 2020. **(IF = 3.595, Q1, Indexed: WoS, Scopus)**

[J10] Mustafa, E., **Afia, R. S. A.**, and Tamus, Z. Á., "Application of Non-Destructive Condition Monitoring Techniques on Irradiated Low Voltage Unshielded Nuclear Power Cables," IEEE Access, vol. 8, pp. 166024-166033, 2020. **(IF = 3.745, Q1, Indexed: WoS, Scopus)**

[J11] Mustafa, E., **Afia, R. S. A.**, and Tamus, Z. Á., "Condition Assessment of Low Voltage Photovoltaic DC Cables under Thermal Stresses Using Non-Destructive Electrical Techniques," Transactions on Electrical and Electronic Materials, vol. 21 (5), pp. 503-512, 2020. **(Q3, Indexed: WoS, Scopus)**

[J12] Mustafa, E., **Afia, R. S. A.**, and Tamus, Z. Á., "Study of Electrical Integrity of Low Voltage Nuclear Power Cables in Case of Plant Life Extension," IFIP Advances in Information and Communication Technology, vol. 577, pp. 311-318, 2020. **(Indexed: WoS, Scopus)**

[J13] **Afia, R. S. A.**, Mustafa, E., Bal, S., and Tamus, Z. Á., "Investigating the Complex Permittivity of Low Voltage Power Cables Under Different Stresses," IFIP Advances in Information and Communication Technology, vol. 577, pp. 319-327, 2020. **(Indexed: WoS, Scopus)**

[J14] Mustafa, E., **Afia, R. S. A.**, and Tamus, Z. Á., "Investigation of Complex Permittivity of XLPO Insulated Photovoltaic DC Cables Due to Thermal Stress," Lecture Notes in Electrical Engineering, vol. 598 (1), pp. 261-269, 2020. **(Indexed: Scopus, EI)**

[J15] **Afia, R. S. A.**, Mustafa, E., and Tamus, Z. Á., "Thermal Aging of Photovoltaic Cables Based Cross-Linked Polyolefin (XLPO) Insulation," Lecture Notes in Electrical Engineering, vol. 598 (1), pp. 253-260, 2020. **(Indexed: Scopus, EI)**

[J16] Mustafa, E., **Afia, R. S. A.**, and Tamus, Z. Á., "Condition Monitoring Uncertainties and Thermal-Radiation Multistress Accelerated Aging Tests for Nuclear Power

Plant Cables: A Review," Periodica Polytechnica Electrical Engineering and Computer Science, vol. 64 (1), 2019, pp. 20-32. **(Q3, Indexed: Scopus)**

[J17] Mustafa, E., Tamus, Z. Á., **Afia, R. S. A.**, and Asipuela A., "Thermal Degradation and Condition Monitoring of Low Voltage Cables in Nuclear Power Industry," IFIP Advances in Information and Communication Technology, vol. 553, pp. 405-413, 2019. **(Indexed: WoS, Scopus)**

[J18] **Afia, R. S. A.**, Tamus, Z. Á., and Mustafa, E., "Effect of Combined Stresses on the Electrical Properties of Low Voltage Nuclear Power Plant Cables," IFIP Advances in Information and Communication Technology, vol. 553, pp. 395-404, 2019. **(Indexed: WoS, Scopus)**

Peer-Reviewed Conference Papers

[C1] **Afia, R. S. A.**, Mustafa, E., and Tamus, Z. Á., "Thermal-Mechanical Accelerated Aging Tests of XLPO Insulation Based Photovoltaic Cables: Inverse Aging Behavior," *4th International IEEE Conference and Workshop in Óbuda on Electrical and Power Engineering (CANDO-EPE 2021)*, Budapest, Hungary, pp. 31-36, Nov. 17-18, 2021.

[C2] **Afia, R. S. A.**, Mustafa, E., and Tamus, Z. Á., "Extended Voltage Response Measurement of Low Voltage Nuclear Power Cables Under Simultaneous Thermal and Mechanical Aging," *2020 IEEE 3rd International Conference and Workshop in Óbuda on Electrical and Power Engineering (CANDO-EPE 2020)*, Budapest, Hungary, pp. 213-216, Nov. 18-19, 2020.

[C3] Mustafa, E., **Afia, R. S. A.**, and Tamus, Z. Á., "Application of Novel Electrical Aging Markers for Irradiated Low Voltage Nuclear Power Plant Power Cables," *2020 IEEE 3rd International Conference and Workshop in Óbuda on Electrical and Power Engineering (CANDO-EPE 2020)*, Budapest, Hungary, pp. 69-72, Nov. 18-19, 2020.

[C4] Mustafa, E., **Afia, R. S. A.**, and Tamus, Z. Á., "Investigation of Electrical and Mechanical Properties of Low Voltage Power Cables under Thermal Stress," *2020 International Conference on Diagnostics in Electrical Engineering (Diagnostika)*, Pilsen, Czech Republic, Sep. 1-4, 2020.

[C5] **Afia, R. S. A.**, Mustafa, E., and Tamus, Z. Á., " Condition Assessment of XLPO Insulated Photovoltaic Cables Based on Polarisation/Depolarisation Current," *2020 International Conference on Diagnostics in Electrical Engineering (Diagnostika)*, Pilsen, Czech Republic, Sep. 1-4, 2020.

[C6] **Afia, R. S. A.**, Mustafa, E., and Tamus, Z. Á., "Assessment of Nuclear Power Plant Power Cables Under Thermal and Mechanical Stresses," *2020 IEEE 3rd International Conference on Dielectrics (ICD)*, Valencia, Spain, pp. 41-44, July 5-9, 2020.

[C7] Mustafa, E., **Afia, R. S. A.**, and Tamus, Z. Á., "Investigation of Photovoltaic DC Cable Insulation Integrity under Thermal Stress," *2020 IEEE 3rd International Conference on Dielectrics (ICD)*, Valencia, Spain, pp. 13-16, July 5-9, 2020.

[C8] **Afia, R. S. A.**, Mustafa, E., and Tamus, Z. Á., "Evaluation of Thermally Aged Nuclear Power Plant Power Cables Based on Electrical Condition Monitoring and Regression Analysis," *2019 International IEEE Conference and Workshop in Óbuda on Electrical and Power Engineering (CANDO-EPE 2019)*, Budapest, Hungary, pp. 203-206, Nov. 20-21, 2019.

[C9] **Afia, R. S. A.**, Mustafa, E., and Tamus, Z. Á., "Non-Destructive Condition Monitoring of Nuclear Power Plant Power Cables," *2019 7th International Youth Conference on Energy (IYCE)*, Bled, Slovenia, July 3-6, 2019.

[C10] Mustafa, E., **Afia, R. S. A.**, and Tamus, Z. Á., "Electrical Integrity Tests and Analysis of Low Voltage Photovoltaic Cable Insulation under Thermal Stress," *2019 7th International Youth Conference on Energy (IYCE)*, Bled, Slovenia, July 3-6, 2019.

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