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Investigation of Aging Processes of Insulating Materials in Multi-Stress Environment

Investigation of Novel Electrical Aging Quantities: A Case of Low Voltage Cables

Ph.D. Thesis

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1. Introduction

The last couple of decades has seen an increase in the share of electrical energy generation by Nuclear Power Plants (NPPs) and Photovoltaic (PV) systems, which is expected to grow till 2050 by 17% and 25% respectively. Apart from other key components used in these power plants, low voltage (LV) power cables have high importance as not only they are used extensively but the safe and reliable operation of these plants depends on these cables. In the NPPs, the LV power cables account for only 15% of the total LV cables deployed in a typical NPP. 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. While in a PV system, the LV DC cables are used to connect the modules and inverters, where the DC cables cost is only 2% of the total PV project.

During the service period of these LV cables, they encounter different types of stresses, which result in irreversible changes to the polymeric materials of the cable, known as aging. Electrical, mechanical, the temperature is such type of stresses. But with the case of NPPs and PV systems, the environmental stress has gained due consideration as the γ-irradiation and temperature in NPPs and thermal stresses in PV systems are common stresses. Figure 1 (a) shows the main factors for aging while Figure 1 (b) shows the possible cause of temperature and radiation stress in the NPPs.

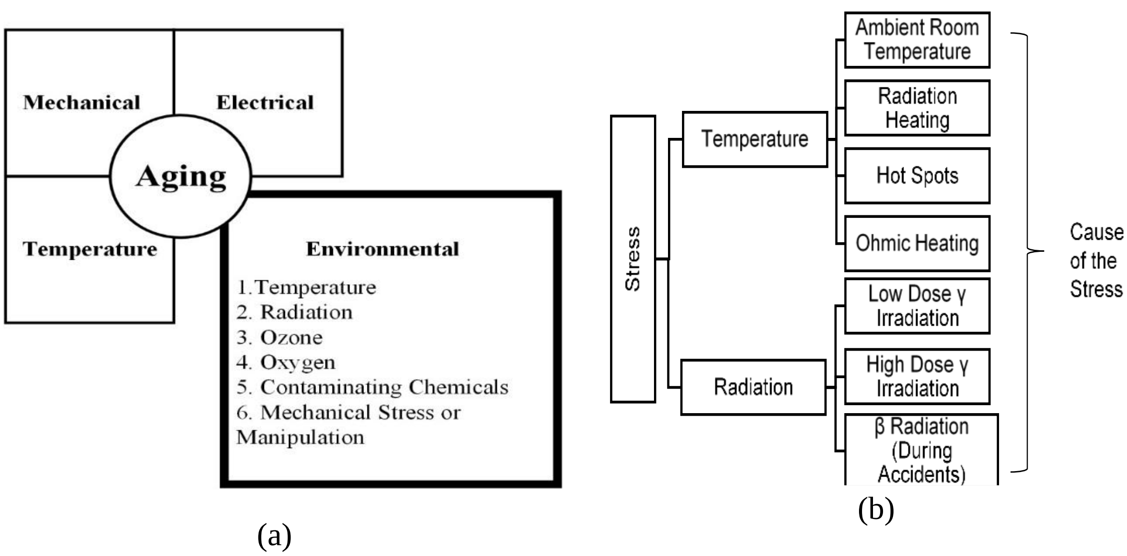
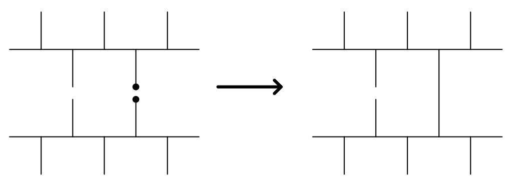
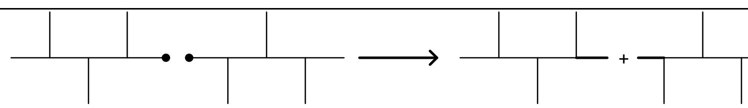
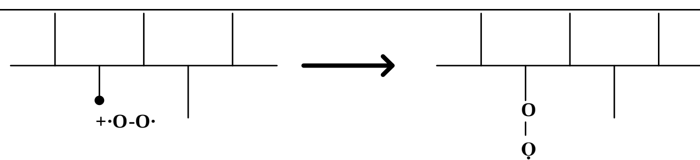


Figure 1. (a) Aging and Types of Stresses, (b) Cause of Temperature and Radiation Stresses

Under the temperature and radiation stress, physio-chemical changes happen inside the polymeric materials, which affect the integrity of the cable insulation. Table 1 describes the different structural changes inside the polymeric material. So, the assessment of the state of the cable (condition monitoring) either under normal operating conditions or design-based event (DBE) or even for the case of the life extension of NPPs, is very important. As any premature failure of the LV cables can cause the unavailability of the equipment or even plant shut down or transient situation.

Table 1 Structural Changes due to the Chemical Reactions and their Effect

Chemical Reactions	**Structural Changes**	**Effects**
Cross-Linking		• Stiffening of material • Increase in Tensile Strength and hardness • The decrease in Elongation at Break
Chain Scission		• Mechanically the material is weakened
Oxidation		• The decrease in mechanical strength • Increase in dielectric loss

In recent times a wide range of condition monitoring (CM) techniques has been developed and adopted, Figure 2 [1-6]. These CM techniques have focused on the measurements of electrical, mechanical properties, thermal analysis, and physicochemical properties, which are classified into destructive and non-destructive techniques.

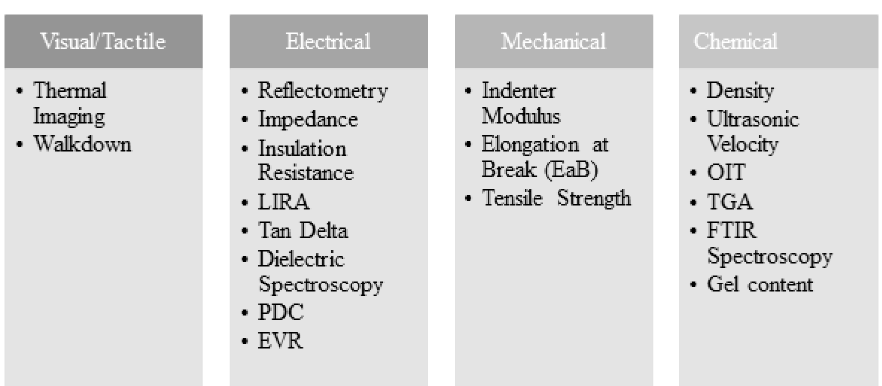


Figure 2. Condition Monitoring Techniques used in Recent Times [1]

While the electrical techniques are classified under the non-destructive techniques, even though with the electrical techniques the researchers have focused on the LV multi-conductor shielded cables. Where the aim had been to study the effect of aging on the insulation and jacket material separately since the integrity of both components is critical in maintaining the qualified conditions of cables. While the measurement of electrical properties of insulation can be easily executed by the different connections of the test equipment to the shielding and conductors of the 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 single conductor (1C) cables, such as power cables. Nevertheless, in the case of the unshielded 1C cables, the measurements of dielectric properties of the dielectric polymeric components, i.e., jacket and core insulation, is not a simple task as the insulation and jacket together form composite insulation. Since this kind of cable has only one conductive core, therefore connection of the test equipment is not obvious.

The main goal of this research work is to implement electrical techniques. 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 1C cable practicable.

Since the materials used in the cable insulation differ from each other in composition, geometry, and manufacturing processes, so it is difficult to decide on a single CM technique, even though a lot of research has been devoted to this. As a result, it is still a challenge for the researchers to determine the key indicators, obtained from the CM techniques, of cable aging that correlate with measurable changes in the polymer material properties. The main goal of this research work is to extend the application of the non-destructive electrical CM techniques to assess the degradation in the LV unshielded 1C single conductor power cables.

2. Research Objectives

Heeding the problem faced in the determination of aging in LV unshielded 1C cables, this Ph.D. thesis has been aimed to study the impact of thermal and radiation stress on the electrical/dielectric properties of LV cables. The study has been focused on unshielded single conductor LV cables used in NPPs and PV systems. The research goals are:

- **i.** Implementation of non-destructive electrical CM methods for aging in unshielded 1C cables.
- **ii.** Identification of electrical/dielectric aging markers through the estimation of electrical/dielectric parameters to understand the degradation in the overall cable's polymeric insulation and jacket.
- **iii.** Establish a correlation between the electrical/dielectric aging markers and the physical degradation of the different kinds of LV cable materials.
- **iv.** To establish the practicability of non-destructive techniques as viable techniques instead of destructive techniques.

The electrical/dielectric parameters of the cable jacket and insulation are evaluated with the help of dielectric spectroscopy in a wide frequency range, Extended Voltage Response (EVR), Polarization-Depolarization Current (PDC) while the mechanical properties are evaluated by Shore D hardness. As thermal and radiation aging result in cross-linking, chain scission, and oxidation, which affect the dielectric polymer properties such as conductivity and polarization. The electrical/dielectric properties such as complex permittivity, polarization, and depolarization current respond to these properties, so they would help achieve the objectives of the research work.

The above-stated electrical techniques have been implemented successfully on medium voltage (MV) and high voltage (HV) cables and on LV shielded cables, so it is expected that the effect of the thermal and radiation stresses on the LV unshielded 1C cable could be studied effectively. To analyze the internal morphological changes inside the polymer materials, a correlation between the electrical aging markers and mechanical property will be established to better understand the role of aging. With the selection of the electrical aging markers, it will not only help in the estimation of the residual life of the cable but will also help in the selection of cable for the newly constructed or planned NPPs and PV systems, and hence for an effective cable lifetime management [1].

3. Thesis Outline

The thesis has been organized as:

Chapter 1, Introduction, is a brief introduction about aging, the importance of low voltage cables in nuclear power plants and PV systems, the condition monitoring methods for aging detection, and their applications. At the end of the chapter research goals of the thesis have been stated.

Chapter 2, LV Cable, Degradation, and Condition Monitoring is about the role and construction of LV cables deployed in NPPs and PV systems. The stressors the cables face during their service life along with the degradation mechanisms in the cable polymeric materials and the CM methods used to ascertain this degradation have been discussed. The chapter also includes the aims of the Ph.D. work at the end.

Chapter 3, Experimental Setup, is dedicated to the cable samples used in this research work with the procedure used to carry out the work. The measurement setup for the detection of the electrical properties through the electrical techniques and the mechanical technique has also been outlined in this chapter.

The results of the measurement of electrical techniques for the thermally and irradiation aged LV NPP unshielded power cables are discussed in **Chapter 4, Results**. The chapter also contains the results of the thermally aged LV PV DC cables.

Chapter 5, Discussion, is inscribed to the discussion of the results of the preceding chapter. The electrical and mechanical properties results obtained through adapted measurement techniques are analyzed. The cause of the degradation is optimized with the selection of electrical aging markers. The electrical aging markers are then correlated with the mechanical property to establish the validity of the methods.

Chapter 6, **Summary and Future work**, the final chapter, summarizes the work done in this research work. Also, the important scientific results in this research work are highlighted by categorizing as Thesis I, Thesis II, Thesis III, and Thesis IV. The future directions beyond this research work are also proposed in this chapter.

4. Theses

4.1 Thesis I

"The dielectric measurement methods have not been implemented as condition monitoring techniques on low voltage unshielded single-conductor cables because this cable structure contains naturally only one electrode, the conductor. Covering the cable's outer surface with conductive foil, I have demonstrated that the dielectric measurements such as dielectric spectroscopy and extended voltage response methods can be applicable for condition

monitoring of low voltage unshielded single-conductor cables. This method enables tracking the general aging of the whole structure of the insulation and the jacket."

The low voltage (LV) unshielded single-conductor (1C) cables are used extensively in nuclear power plants (NPPs) and PV systems. Till now, the determination of the cable jacket and electrical insulation degradation has been limited to mechanical tests, which are destructive and require the separation of the jacket and insulation from the cable. Since this type of cable has only one conductor, hence the absence of a well-defined ground path makes the application of the electrical tests as condition monitoring challenging. Although, in recent times techniques such as interdigital capacitive sensor [7] have been developed for the evaluation of the condition of the cable, but the methods have only been limited to the ac test techniques.

In this thesis, it was shown that while covering the outer surface of the unshielded 1C cable with a conductive layer, the application of non-destructive dielectric measurements can be implemented for the condition assessment of the cable. Several measurements were carried out on the unshielded 1C cable by using dielectric spectroscopy and extended voltage response (EVR) methods to prove the applicability of the measuring solution to this type of cable. It was also proved that the technique is useful for the detection of global aging of the cable jacket and electrical insulation, however, it cannot detect the localized problems such as hot spots.

This thesis has been published in [J2, J4, J6, J8, J9, J10, J11, C2, C4, C5, C6, C9, C10, C11, C12].

4.2 Thesis II

"I have applied the developed electrode system with dielectric spectroscopy method on thermally and irradiation aged XLPE insulated, CSPE jacketed low voltage unshielded, single-conductor nuclear power plant cable samples. I have revealed the monotonic increase of permittivity at 0.1 Hz and 100 Hz frequencies. The monotonic increase of these parameters shows a strong correlation with the results of Shore D hardness measurement. These findings prove that the applicability of the dielectric spectroscopy technique as a non-destructive condition monitoring method for XLPE insulated and CSPE jacketed low voltage unshielded single-conductor nuclear power plant cable."

The thermal and radiation stresses in NPP are the stresses which the LV cables have to encounter during their service period due to their location. In this thesis, the impact of thermal stress and radiation stress on the XLPE/CSPE single conductor unshielded 1C power cable was studied. The whole cable samples were exposed to 120°C accelerated temperature for 10 different periods and 500 Gy/hr dose rate for 5 different periods. The dielectric spectroscopy in two frequency ranges: 100 mHz to 1kHz and 2 kHz to 500 kHz, was then implemented as a non-destructive electrical CM technique. Due to the absence of fix ground reference in the unshielded 1C cable, the application of the technique is not obvious. With the connection of the surface electrode and the conductive conductor, the dielectric spectroscopy technique was implemented, as the jacket and insulation behaved as composite insulation.

Under the thermal stress, an increase in the real part of permittivity at 0.1 Hz and the imaginary part of permittivity at 100 Hz was observed, which is associated with the interfacial polarization. The increase of permittivity with thermal stress showed that the morphological changes happened inside the insulation under thermal stress. With exposure to the thermal stress and presence of oxygen intensifies the degradation process in the cable jacket and insulation and which resulted in the increase of the dipolar species and hence, an increase in the interfacial polarization was observed.

The monotonic increase of the permittivity at 0.1 Hz and 100 Hz for the irradiated samples also revealed the intensity of interfacial polarization. While the hardness of the cable insulation increased under both stresses. The linear variation of the selected electrical aging markers: real part of permittivity at 0.1 Hz and imaginary part of permittivity at 100 Hz, with aging showed the implementation of the CM techniques to the LV unshielded 1C cable in case of NPP environment.

This thesis has been published in [J2, J4, J6, J10, J12, C2, C4, C10, C11, C12].

4.3 Thesis III

"I have applied the developed electrode system with extended voltage response method on thermally aged and irradiated XLPE insulated, CSPE jacketed low voltage unshielded single-conductor nuclear power plant cable samples. I have revealed that:

- *The initial slope of decay voltage increases with the time of thermal aging,*

- *The initial slope of decay voltage increases with the absorbed dose and,*
- *The initial slope of return voltage increases with the absorbed dose in case of radiation aging.*

These results prove that the decay voltage and return voltage slopes can be used as electrical aging markers for XLPE insulated and CSPE jacketed low voltage unshielded single-conductor nuclear power plant cable."

The EVR method is based on the determination of the insulation condition through conductivity and polarization processes, after the charging and discharging phase, respectively. In the past, the technique has only been implemented either HV and MV equipment and in LV case, to only multiconductor shielded cables. Its application to the NPP scenario has not been explored. To extend the application of the technique to the NPP case, thermally and irradiated stressed XLPE/CSPE unshielded single-conductor cable samples were analyzed with the EVR technique in this thesis.

The decay voltage slope associated with conductivity increased with aging for both stress types, which showed the increase of conductivity with aging. While for the thermal aging, the return voltage slope decreased initially and then increased in the later aging periods. The behavior showed the initial decrease and then increase of the interfacial polarization. Whereas the interfacial polarization phenomenon increased in the case of radiation stress, where an increasing trend was observed with absorbed dose. These results were in-line and supported the results of the dielectric spectroscopy, and hence showing the degradation of the cable insulation and jacket.

The correlation values for the decay voltage and return voltage slopes with aging and hardness showed the application capability of the EVR technique to the cable type and the NPP environment.

This thesis has been published in [J2, J4, J10, J11, C8, C12].

4.4 Thesis IV

"I have applied the developed electrode system with dielectric spectroscopy and extended voltage response methods on thermally aged XLPO insulated, XLPO jacketed low voltage unshielded single-conductor photovoltaic cable samples. It was revealed that:

- *The real part of permittivity at 10 mHz and the imaginary part of permittivity at 100 mHz show a good correlation with the result of the Shore D hardness measurement.*
- *The slope of return voltage decreases in the initial stages of thermal aging then it starts to increase indicating the severe damage of the insulation. This trend has been proved by Shore D hardness measurement.*

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

Thesis IV was aimed to study the effect of the thermal stress on LV DC cables deployed in PV systems by the application of dielectric spectroscopy, EVR, and Shore D hardness as the CM techniques. The thermal stress during the service period of PV cables is an important concern. The XLPO/XLPO PV cable with different chemical composition and size in comparison to the NPP cable was exposed to 120°C temperature for 12 aging periods.

Below 100 mHz, the change in the real part of permittivity and the imaginary part of permittivity with each thermal period was noticeable as the real part of permittivity for most of the frequency range was either decreased or remained unchanged. On the other hand, the imaginary part of permittivity increased in a very low-frequency region, i.e., 200 µHz and 1 mHz. For most of the aging time, the return voltage slope decreased while it increased after eight thermal periods. The cross-linking-based reactions in XLPO were suggested as an explanation for the decrease in the permittivity and return voltage slope which resulted in the optimization of the crystallinity, a phenomenon associated with XLPO.

Under thermal stress, the bulk polarization phenomenon was also observed as at very low frequencies the losses due to the polarization were reflected in the increase of the imaginary part of permittivity. Shifting of the maximum value of the imaginary part of permittivity to lower frequency and minimum value to lower frequency was also observed. The re-crosslinking-based chemical reaction in the amorphous region was considered as the cause of degradation in the polymeric materials, a phenomenon associated with XLPO material.

With aging, the cable became harder as shown by the Shore D hardness measurement, which supported the observations of the electrical measurements of EVR, as the S_r values increased in the latter part of the aging period while observing a decreasing trend in the initial stages of the aging periods. The increasing trend of the S_r and the hardness values in the latter stages of the aging period shows that the cable was damaged.

Correlation between the real part of permittivity at 10 mHz and the imaginary part of permittivity at 100 mHz with hardness was established. The latter showed a higher R^2 value as compared to the former, but the correlation was not so good. A similar weak correlation between the decay voltage slope and return voltage slope at 1sec and hardness was observed.

This thesis has been published in [J5, J8, J9, C6, C9].

The results obtained through the electrical and mechanical measurements in this research work showed the effectiveness of the techniques to be used as the non-destructive CM techniques for the unshielded 1C LV power cables with different construction and composition and under different stresses. The selected electrical aging markers also showed a good trend with aging.

5. Conclusion and Future Directions

Understanding the aging of polymeric materials in LV cables has been a topic of high interest for researchers in recent times. This has led to the search for suitable CM techniques which can fulfill the task. But due to the complex composition of the materials and complex aging, a lot of new findings still has to be unearthed. This Ph.D. research work is also a step forward in the search of CM techniques where the adopted ones have the advantages of being simple, non-destructive, and compatible especially for the case of unshielded 1C single conductor cables.

The results obtained through the electrical and mechanical measurements in this research work showed the effectiveness of the techniques to be used as the non-destructive CM techniques for the unshielded 1C LV power cables, where different cables having different construction and composition and the cables being exposed to different stresses. Keeping in view the objectives of the research work, suitable electrical aging markers were also selected. The strong correlation and good trend with aging proved the authenticity of the aging markers.

However, it is still considered that there are emerging research problems that can be addressed, which are:

i. The results obtained in this work can be validated through chemical tests such as OIT, gel content, and FTIR, which will give a more in-depth understanding.

ii. The mechanical tests such as EaB of the LV unshielded 1C cables will also help in validating the findings of the electrical measurements.

iii. The estimation of remaining life has also been a topic of interest for the researchers. The aging markers selected in this work can be used for the remaining life estimation of the cables.

iv. Since aging is a multi-factor phenomenon, where different stresses are acting simultaneously. Hence investigating the behavior of the LV unshielded 1C cables under a multi-stress environment by using the adapted methods can further help in understanding the degradation happening and making the methods more reliable.

v. Since the work was carried out in laboratory conditions, the application of these methods in field conditions will be helpful for practical applications.

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

Journal Publications

[J1] Afia, R. S. A., **Mustafa**, **E.** and Tamus, Á. Z., “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, 4531-4541, 2021. **(IF = 3.745, Q1, Indexed: WoS, Scopus, SCIE)**

[J2] **Mustafa**, **E.,** Afia, R. S. A. and Tamus, Á. Z., “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. **(IF = 1.18, Q2, Indexed: WoS, Scopus, SCIE, SCI)**

[J3] Afia, R. S. A., **Mustafa**, **E.** and Tamus, Á. Z., “ Dielectric Spectroscopy of Low Voltage Nuclear Power Plant Power Cables Under Simultaneous Thermal and Mechanical Stresses,” Energy Reports, vol.6 (9), 662-667, 2020. **(IF = 3.595, Q1, Indexed: WoS, Scopus, SCIE)**

[J4] **Mustafa**, **E.,** Afia, R. S. A. and Tamus, Á. Z., “ Application of Non-Destructive Condition Monitoring Techniques on Irradiated Low Voltage Unshielded Nuclear Power Cables,” IEEE Access, vol.8, 166024-166033,2020. **(IF = 3.745, Q1, Indexed: WoS, Scopus, SCIE)**

[J5] **Mustafa**, **E.,** Afia, R. S. A. and Tamus, Á. Z., “Condition Assessment of Low Voltage Photovoltaic DC Cables under Thermal Stress using Non-Destructive Electrical Techniques,” Transactions on Electrical and Electronic Materials, vol. 21 (5), 503-512, 2020. **(Q3, Indexed: WoS, Scopus, ESCI)**

[J6] **Mustafa**, **E.,** Afia, R. S. A. and Tamus, Á. Z., " 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, 2020. **(WoS, Scopus)**

[J7] Afia, R. S. A., **Mustafa**, **E.** and Tamus, Á. Z., " Investigating the Complex Permittivity of Low Voltage Power Cables Under Different Stresses," IFIP Advances in Information and Communication Technology, vol. 577, 2020. **(WoS, Scopus)**

[J8] **Mustafa**, **E.,** Afia, R. S. A. and Tamus, Á. Z., " Investigation of Complex Permittivity in XLPO based Photovoltaic DC Cables due to Thermal Aging," Lecture Notes in Electrical Engineering, vol. 598 (1), 2019.

[J9] Afia, R. S. A., **Mustafa**, **E.** and Tamus, Á. Z., " Thermal Aging of Photovoltaic Cables based Cross-Linked Polyolefin (XLPO) Insulation," Lecture Notes in Electrical Engineering, vol. 598 (1), 2019.

[J10] **Mustafa**, **E.,** Afia, R. S. A. and Tamus, Á. Z., "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, Scopus)**

[J11] **Mustafa, E.**, Tamus, Á. Z., Afia, R. S. A. and Asipuela, A., "Thermal Degradation and Condition Monitoring of Low Voltage Power Cables in Nuclear Power Industry," IFIP Advances in Information and Communication Technology, vol. 553, 2019. **(WoS, Scopus)**

[J12] Afia, R. S. A., Tamus, Á. Z. 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, 2019. **(WoS, Scopus)**

Conference Papers

(Peer-Reviewed)

[C1] **Mustafa**, **E.,** Afia, R. S. A., and Tamus, Á. Z., "Impact of Thermal and Mechanical Stresses on the Degradation of XLPE/CSPE Nuclear Power Plant Cable: Analysis of the Dielectric Response at Very Low-Frequency Range," in *The 4th International Conference on Electrical Engineering and Green Energy, CEEGE'21,* Munich, Germany, June 10-13, 2021. (Under Review)

[C2] **Mustafa**, **E.,** Afia, R. S. A., and Tamus, Á. Z., "Application of Novel Electrical Aging Markers for Irradiated Low Voltage Nuclear Power Plant Power Cables," in *International IEEE Conference AND Workshop in Obuda on Electrical and Power Engineering, CANDO-EPE '20*, Budapest, Hungary, Nov. 18-19, 2020.

[C3] Afia, R. S. A., **Mustafa**, **E.,** and Tamus, Á. Z., "Time-Domain Spectroscopy of Low Voltage Nuclear Power Cables under Simultaneous Thermal and Mechanical Aging," in *International IEEE Conference AND Workshop in Obuda on Electrical and Power*

Engineering, CANDO-EPE '20, Budapest, Hungary, Nov. 18-19, 2020.

[C4] **Mustafa**, **E.,** Afia, R. S. A., and Tamus, Á. Z., "Investigation of Electrical and Mechanical Properties of Low Voltage Power Cables under Thermal Stress," in *IEEE International Conference on Diagnostics in Electrical Engineering (Diagnostika'20)*, Pilsen, Czech Republic, Sep. 1-4, 2020.

[C5] Afia, R. S. A., **Mustafa**, **E.,** and Tamus, Á. Z., "Assessment of XLPO Insulated Photovoltaic Cables Based on Polarisation/Depolarisation Current," in *IEEE International Conference on Diagnostics in Electrical Engineering (Diagnostika'20)*, Pilsen, Czech Republic, Sep. 1-4, 2020.

[C6] **Mustafa**, **E.,** Afia, R. S. A., and Tamus, Á. Z., "Investigation of Photovoltaic DC Cable Insulation Integrity under Thermal Stress," in *IEEE 3rd International Conference on Dielectrics, ICD'20*, Valencia, Spain, July 5-9, 2020.

[C7] Afia, R. S. A., **Mustafa**, **E.,** and Tamus, Á. Z., "Assessment of Nuclear Power Plant Power Cables Under Thermal and Mechanical Stresses," in *IEEE 3rd International Conference on Dielectrics, ICD'20*, Valencia, Spain, July 5-9, 2020.

[C8] Afia, R. S. A., **Mustafa**, **E.** and Tamus, Á. Z., " Evaluation of Thermally Aged Nuclear Power Plant Power Cables Based on Electrical Condition Monitoring and Regression Analysis," in *International IEEE Conference AND Workshop in Obuda on Electrical and Power Engineering, CANDO-EPE '19*, Budapest, Hungary, Nov. 20-21, 2019.

[C9] **Mustafa**, **E.,** Afia, R. S. A. and Tamus, Á. Z., "Electrical Integrity Tests and Analysis of Low Voltage Photovoltaic Cable Insulation under Thermal Stress," in *IEEE 7th International Youth Conference on Energy, IYCE'19*, Bled, Slovenia, July 3-6, 2019.

[C10] Afia, R. S. A., **Mustafa**, **E.,** Asipuela, A. and Tamus, Á. Z., "Non –Destructive Condition Monitoring of Nuclear Plant Power Cables," in *IEEE 7th International Youth Conference on Energy, IYCE'19*, Bled, Slovenia, July 3-6, 2019.

[C11] Asipuela, A., **Mustafa, E.**, Afia, R.S.A., Tamus, Á. Z., and Khan, M.Y.A., "Electrical Condition Monitoring of Low Voltage Nuclear Power Plant Cables: tanδ and Capacitance," *Proceedings of IEEE 4th International Conference on Power Generation Systems and Renewable Energy Technologies (PGSRET'18)*, Islamabad, Pakistan, Sep. 10-12, 2018, PAPERID-138, pp. 503-509.

[C12] **Mustafa, E.**, Afia, R.S.A., and Tamus, Á. Z., "A Review of Methods and Associated Models used in Return Voltage Measurement," *Proceedings of IEEE International*

Conference on Diagnostics in Electrical Engineering (Diagnostika'18), Pilsen, Czech Republic, Sep. 4-7, 2018, PAPERID-275, pp. 69-72.

[C13] Afia, R.S.A., **Mustafa, E.**, and Tamus, Á. Z., "Mechanical Stresses on Polymer Insulation Materials," Proceedings of IEEE International Conference on Diagnostics in Electrical Engineering (Diagnostika'18), Pilsen, Czech Republic, Sep. 4-7, 2018, PAPERID-276, pp. 170-173.

Other Publications by the Author (Not related to Ph.D. Work)

Book

[B1] **Mustafa, E.**, Analytical Efficiency Evaluation of Modular Multilevel Converter (MMC) for High Voltage Direct Current System, Germany: *GRIN Publishing*, 2016. ISBN: 3668160538.

Journal Publications

[J1] Khan, M. Y. A., **Mustafa, E.**, Nawaz, A, Saleem, N. and Illahi, U., "Sensor-Fusion Based Navigation for Mobile Robot in Outdoor Environment," *Mehran University Research Journal of Engineering & Technology*, vol. 38, no. 1, 2019, pp. 113-128.

[J2] Nawaz, A., **Mustafa, E.**, Saleem, N., Khattak, M.I., Shafi, M., and Malik, A., "Solving Convex & Non-Convex Static and Dynamic Economic Dispatch Problems Using Hybrid Particle Swarm Optimization," *Tehnick Vjesnik- Technical Gazette*, vol. 24, no. 4, 2017, pp. 1095-1102.

[J3] Nawaz, A., Saleem, N., **Mustafa, E**., and Khan, U.A., "An efficient global technique for solving network constrained static and dynamic Economic Dispatch Problem," *Turkish Journal of Electrical Engineering and Computer Science*, vol. 25, 2017, pp. 73-82.

[J4] Khan, M., Yong, W., and **Mustafa, E.**, "Design and Simulation of Control Technique for Permanent Magnet Synchronous Motor Using Space Vector Pulse Width Modulation," *IOP Conference Series: Materials Science and Engineering*, pp. 1-6, 2017.

[J5] **Mustafa, E.**, Saad, M.M., Mustafa, B., Khan, M.S. and Nouman, M., "Arduino based Condition Monitoring of Different Parameters of Distribution Transformer," *The New Horizon*, vol. 88-90, 2015-2016, pp. 39-42.

[J6] Saleem, N., Shafi, M, **Mustafa, E.** and Nawaz, A., "A Novel Binary Mask Estimation based on Spectral Subtraction Gain-Induced Distortions for Improved Speech Intelligibility and Quality," *Technical Journal*, vol. 20, no. 4, 2015.

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