Study of Electrical Integrity of Low Voltage Nuclear Power Cables in Case of Plant Life Extension

Ehtasham Mustafa[1,2](✉), Ramy S. A. Afia[2,3], Semih Bal[2], and Zoltán Ádám Tamus[2]

[1] Department of Electrical Engineering, Faculty of Engineering and Technology, Gomal University, Dera Ismail Khan 29050, Pakistan

[2] Department of Electric Power Engineering, Budapest University of Technology and Economics, P.O.B. 91, Budapest 1521, Hungary

{mustafa.ehtasham, bal.semih, tamus.adam}@vet.bme.hu

[3] Department of Electrical Power and Machines Engineering, Helwan University, 1 Sherif Street, Helwan, Cairo 11792, Egypt

ramysaad@h-eng.helwan.edu.eg

Abstract. During the last couple of decades, many nuclear power plant operators are seeking the life extension of the operating nuclear power plants. This makes the condition assessment of major components in the plant an important topic. One such component is low voltage power and instrumentation and control cables, which are more than 1000 km in length and makes their replacement a severe cost burden. Since these cables during service are under high thermal and radiation stress, hence making the condition assessment of them inevitable. The thermal stress as compared to other stresses results in the structural change and hence effecting the electrical integrity of the cable insulation. In this work, the complex permittivity of the XLPE/CSPE based low voltage nuclear power cable will be studied under thermal stress. The potential electrical aging markers from the measurement will help in calculating the expected lifetime of the cable for the case of life extension of the nuclear power plants.

Keywords: Nuclear power plant · Life extension · Thermal aging · Low voltage power cables · Complex permittivity · Elongation at break

1 Introduction

Nuclear power plants (NPPs) are credited for supplying reliable, low carbon and affordable electrical energy. The worldwide production of electrical energy has a considerable share of nuclear energy which is expected to be 17% by the year 2050 [1]. Since the NPPs are initially designed for 40 years but in the last decade, many of the plant operators are seeking the life extension of the NPPs as it is more economical than building a new one and helps in avoiding supply shortages and support the country in reducing carbon emission. The safe and reliable operation of the NPP depends not only

Published by Springer Nature Switzerland AG 2020
L. M. Camarinha-Matos et al. (Eds.): DoCEIS 2020, IFIP AICT 577, pp. 311–318, 2020.
https://doi.org/10.1007/978-3-030-45124-0_29

on its structure but also on the systems and components [2]. One such component is low voltage (LV) cables, which are used to deliver power and control signals for the systems; safety and non-safety related. This makes the cables to be reliable not only for the normal operation but also during the design-based events (DBEs). The cables in the NPP are vulnerable to a number of stresses such as temperature, radiation, mechanical, electrical, chemical, moisture and humidity [3]. The temperature being more effective as compared to others as it creates physio-chemical changes inside the cable insulation. As a result, the cable degrades and may result in the exposure of the metallic parts of the cable, resulting in the short circuit, open circuit and even cable breakdown, which eventually leads to probable plant shutdown or transients.

The long term operation and safety issues have increased the importance of cable management in the NPPs. This has led to intensive research work in this regard. For the evaluation of the state of the cable, condition monitoring (CM) techniques can help in this context. In recent times, a number of CMs techniques have been presented and are listed by IAEA in its report [4]. The desirable features of the CM techniques are to be non-destructive and non-intrusive. Even though the presence of diversity in the CM techniques, there is no single CM technique which can access the condition of the cable during service, since each cable passes through different manufacturing processes and have its own composition [5]. Therefore, a number of techniques are combined to evaluate the state of the cable.

One such technique is dielectric spectroscopy which is based on the measurement of complex permittivity of the insulation material, which is a polymer in nature. The technique has recently been adopted for the insulation CM of a number of LV shielded cables [6–8]. But still, its application to LV unshielded cables has not been reported, as it is difficult to monitor the state of the cable without separating the jacket, insulation and conductor. So, in this work, thermal aging of the whole LV unshielded NPP power cables is studied without separating the cable components. The power cables are subjected to four thermal aging cycles in the oven at 120 °C. The morphological changes happening inside the cable are studied using the complex permittivity for a range of frequency 20 Hz–500 kHz. The electrical aging markers are evaluated, investigated and a correlation between the markers and the elongation at break (EaB) which is a time-dependent degradation evaluation technique has been established. The results show that the evaluated electrical aging markers have the potential to be used for the investigation of the level of cable degradation in the context of the field conditions.

2 Contribution to Life Improvement

Nowadays the economic development of any country is heavily dependent on a reliable and adequate supply of electrical energy. This also adds to the uplift of the social life of the country [9]. Although having high capital cost; the predictable, reliable and clean nature of nuclear energy has made it an attractive option, which is reflected by the increase in the number of NPPs in the last couple of years not only in developed countries but also in developing countries [10]. With more urbanization, nuclear energy can be used as a baseload provider, urban transport systems and non-electric applications such as district heating, industrial processes and water desalination, which are essential components of the life improvement of the people of a country. It is important that the NPP must work safely, efficiently and reliably during its service and life extension case, which is highly acknowledged for the socio-economic improvement of a country but also for the operators. This all depends on the safe operation of all the components of the power plant which are under multiple stresses during service. The CM of these components especially the LV cables is of utmost importance as it has to ensure the supply of power and signals to the equipment which have to operate during all sorts of conditions and operations. An effective CM technique can ensure the safe and efficient operation of the NPP which will have a profound impact on the socio-economy of the country.

3 Experimental Work

3.1 Low Voltage Cable

The cross-sectional view of LV NPP power cable under consideration is shown in Fig. 1. The outer jacket consisted of Choloro-sulfonated polyethylene (CSPE), a thickness of 0.762 mm, and the inner insulation was Cross-linked polyethylene (XLPE) with a thickness of 1.143 mm. A stranded tin-coated copper material was used as a conductor.

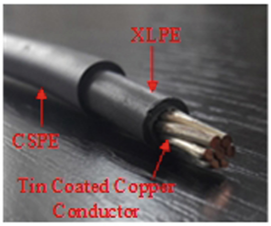

Fig. 1. The cross-sectional view of the cable sample under consideration.

3.2 Thermal Aging

The XLPE/CSPE based cable samples were exposed to thermal stress in an oxygen controlled oven at 120 °C. The accelerated aging period was calculated using the Arrhenius relationship and was 176, 342, 516 and 793 h.

3.3 Measurement of Dielectric Properties

The electrical properties, complex permittivity, of the cables were studied using the precision component analyzer. The technique is based on the phenomenon of conduction and polarization in the materials. Since there are a number of polarization phenomenon in operation in the material which have their own frequency response and can be separated on the basis of that. The atomic and ionic polarization operate at a very high frequency while the dipole orientation operates at a lower frequency. While the DC conduction and orientation polarization are significant at very low frequencies.

The range of frequency was chosen as 20 Hz to 500 kHz at 5 V_{rms}, where the dipolar orientation and interfacial polarization can be observed. The cable samples were kept in the Faraday cage to reduce any pickup noise during the measurement. The test temperature was kept at 25 °C ± 2%.

4 Experimental Results

The real part of permittivity (ε') against the frequency range is shown in Fig. 2. The ε' values decreased with the increase of frequency irrespective of the aging. After the first thermal cycle, a prominent increase in the values of the real part of permittivity was observed at all frequencies. But after the subsequent cycles, a very slight change was observed. The overall impact of aging was an increase in the values of ε' irrespective of the frequencies.

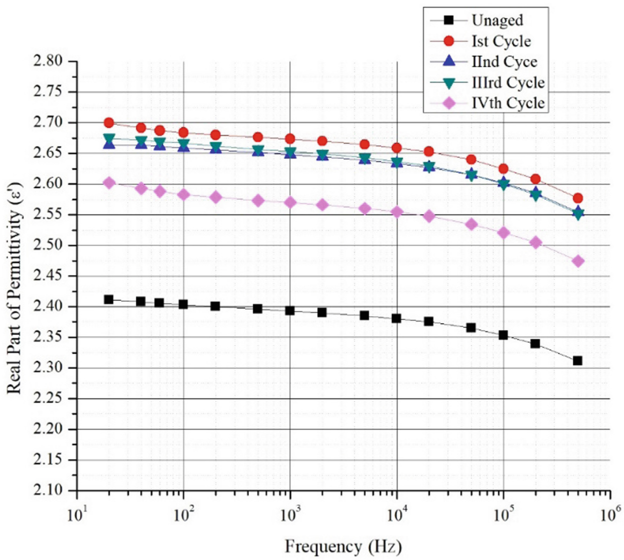

Fig. 2. The real part of permittivity (ε') vs. frequency for different aging times.

The imaginary part of permittivity (ε'') profile is shown in Fig. 3(a). The ε'' started with high value at 500 kHz and then decreased with the decrease of frequency. It reached a minimum value and then started to increase. This profile of ε'' was the same for all the aging periods. With the thermal stress, it was observed that the ε'' increased at all frequencies. But the change in the values of ε'' was more prominent at the low frequencies than at the high frequencies. Figure 3 (b) shows the imaginary part of permittivity at four different frequencies; 100 Hz, 500 Hz, 10 kHz, and 20 kHz.

A sharp increase in the values was observed at 100 Hz after the end of the fourth thermal cycle, where the values have increased twofold.

5 Discussion

The primary insulation of the cable is composed of XLPE while the jacket material is based on CSPE. Through the modification of the backbone of polyethylene both the materials are produced and are classified as semi-crystalline [11, 12]. CSPE is formed through the process of chlorination and chlorosulfonation of polyethylene, on the other hand through the cross-linking the chains of polyethylene result in the formation of XLPE. Due to polar nature, any change in the material structure will affect the real and imaginary part of permittivity.

The increase in the values of ε' and ε'' for all thermal cycles shows that the stress has strongly effected the morphological structure of the polymers. This phenomenon can be explained due to the polarization phenomenon and the losses; conduction and polarization, happening inside the material. The polarization has a strong relationship with ε', while the ε'' correlates with the losses.

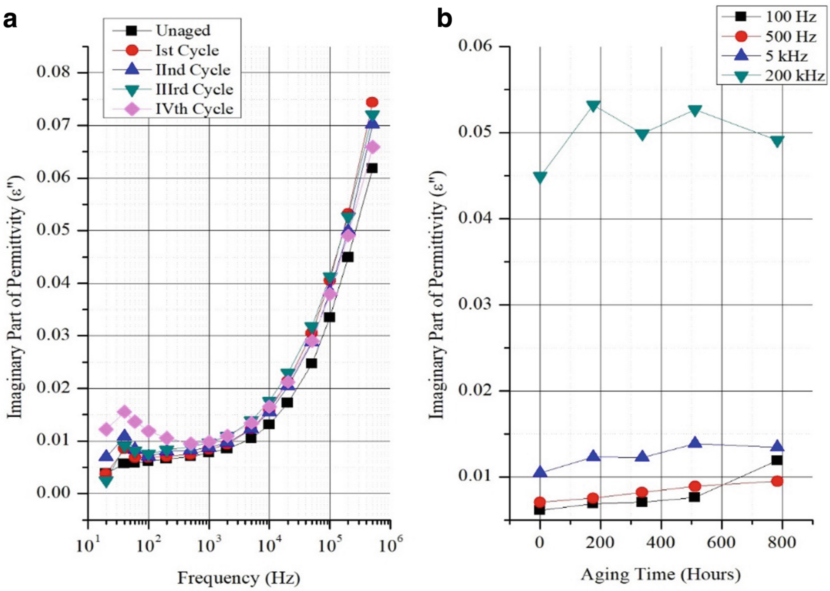

Fig. 3. (a) Imaginary part of permittivity (ε'') vs. frequency for different aging times. (b) ε'' vs. aging time at 100 Hz, 500 Hz, 5 kHz, and 200 kHz.

As it was observed that the ε' showed no discrepancy in relation to the frequency either for unaged or aged cable samples, this made ε' independent of the frequency. As an increase in the values of ε' has been observed with each thermal stress cycle, this has resulted in the generation of dipolar species. These dipoles are adding to the polarization of the material and hence to the ε'.

In contrast to ε', the variation of ε'' values with frequency and aging period show how the ε'' is dependent on both variables. Since the values of ε'' changed more at the low frequencies as compared to high frequencies, resulting in the generation of conduction particles. These particles are adding to the losses and hence an increase in the ε'' has been observed. Due to thermal stress in the case of XLPE and CSPE, there is a generation of alkyl radicals. These radicals add to the ionic leakage or conduction current and are reflected in the prominent change of ε'', which has also been reported in the literature [11] (Fig. 4).

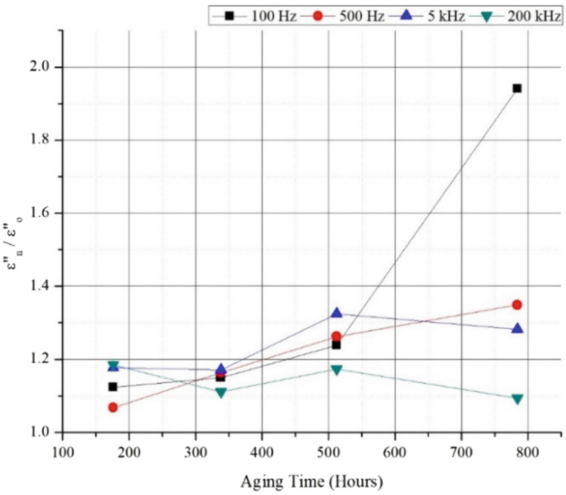

Fig. 4. Change of ε'' with unaged values vs. aging time (hours) at 100 Hz, 500 Hz, 5 kHz, and 200 kHz.

It was also observed that the minimum value of ε'' has shifted to higher frequency; from 20 Hz for unaged to 500 Hz, Fig. 5, which shows that how the thermal stress affected the polymer matrix and resulted in the generation of dipolar ionic conduction particles.

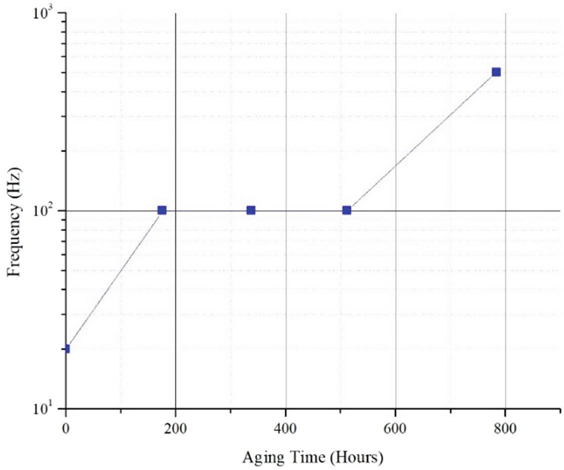

Fig. 5. Shifting of minimum value of ε″, corresponding frequency vs. aging time (hours).

The data of EaB as a function of aging time helps in validating the results of complex permittivity. The EaB values have been taken from the Laborelec Lab, Belgium, where the cable samples were thermally aged under the same conditions and EaB was measured. The EaB values decreased with aging time as reported in Fig. 6.

Since ε″ at 100 Hz has shown more variation with aging, hence it has been chosen as an electrical aging marker. A correlation between ε″ at 100 Hz and EaB has been established, Fig. 6. The decrease in the values of EaB and the increase in the values of ε″ shows that the thermal stress has effected the cable and has cause noteworthy embrittlement and also effected the dielectric property.

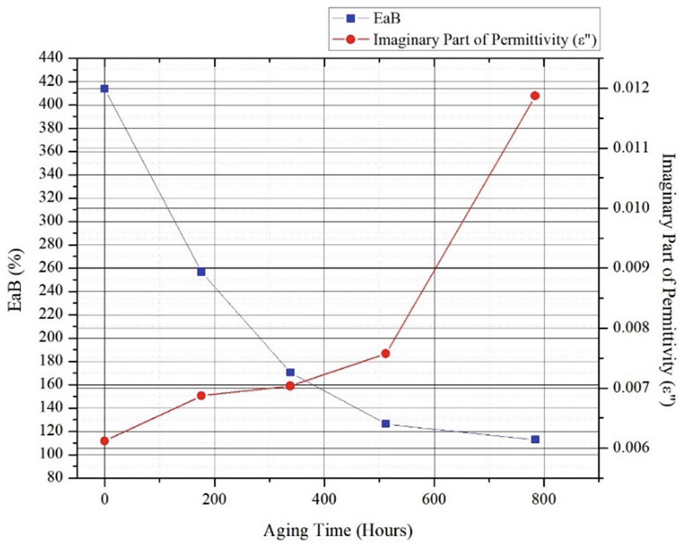

Fig. 6. Elongation at Break (EaB) and ε″ at 100 Hz vs. aging time (hours) correlation.

6 Conclusion

When it comes to the life extension of NPP, it is important to know the state of the insulation of LV cables. This could be achieved with the help of reliable CM techniques. In the lifetime of a cable, thermal stress is more severe as compared to other stresses in the power plants. Keeping in view the importance, in this research work LV NPP power cables are subjected to the thermal stress for four aging periods. The complex permittivity is measured for the aged samples. It was observed that both the real part (ε') and imaginary part of permittivity (ε'') increased with each aging cycle. The ε'' at 100 Hz showed more trend of aging, and was chosen as an aging marker. The ε'' developed a strong correlation with EaB, showing the effect of aging. This shows that the complex permittivity can be used to detect the aging in LV NPP cables without any destruction to the cable, which could be a future aspect for the online condition monitoring purpose.

Acknowledgments. This research work has been implemented under Project No. 123672 with the support provided from the National Research, Development and Innovation Fund of Hungary, financed under the KNN_16 funding scheme.

References

1. Rising, A.: World Nuclear Performance Report 2019 (2019)
2. Chang, Y.S., Mosleh, A.: Probabilistic model of degradation of cable insulations in nuclear power plants. Proc. Inst. Mech. Eng. Part O J. Risk Reliab. **233**, 803–814 (2019)
3. Mustafa, E., Afia, R.S.A., Tamus, Z.Á.: Condition monitoring uncertainties and thermal - radiation multistress accelerated aging tests for nuclear power plant cables: a review. period. Polytech. Electr. Eng. Comput. Sci. **64**, 1–13 (2019)
4. IT Series: Benchmark analysis for condition monitoring test techniques of aged low voltage cables in nuclear power plants, Vienna, Austria (2017)
5. Mustafa, E., Ádám, T.Z., Afia, R.S.A., Asipuela, A.: Thermal degradation and condition monitoring of low voltage power cables in nuclear power industry. In: Camarinha-Matos, L. M., Almeida, R., Oliveira, J. (eds.) DoCEIS 2019. IAICT, vol. 553, pp. 405–413. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-17771-3_35
6. Verardi, L., Fabiani, D., Montanari, G.C.: Electrical aging markers for EPR-based low-voltage cable insulation wiring of nuclear power plants. Radiat. Phys. Chem. **94**, 166–170 (2014)
7. Linde, E., Verardi, L., Fabiani, D., Gedde, U.W.: Dielectric spectroscopy as a condition monitoring technique for cable insulation based on crosslinked polyethylene. Polym. Test. **44**, 135–142 (2015)
8. Linde, E., Verardi, L., Pourmand, P., Fabiani, D., Gedde, U.W.: Non-destructive condition monitoring of aged ethylene-propylene copolymer cable insulation samples using dielectric spectroscopy and NMR spectroscopy. Polym. Test. **46**, 72–78 (2015)
9. Society and Nuclear Energy: Towards a Better Understanding. France, Paris (2003)
10. Nuclear power and sustainable development, Vienna, Austria (2016)
11. Chang, Y.-S., Mosleh, A.: Physics-based probabilistic model of the effects of ionizing radiation on polymeric insulators of electric cables used in nuclear power plants, California, USA (2019)
12. Lee, J.H., et al.: A study on the properties of CSPE according to accelerated thermal aging years. J. Electr. Eng. Technol. **9**, 643–648 (2014)