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Abstract. Energy is the heart of any industry since each industry uses energy. One of the most critical sources for energy generation is the nuclear power plants. The plants building needs a lot of investments and a pivotal role from the financial services sector in providing the necessary finance for the capital works. Control, instrumentation and low voltage power cables have a vital role in the operation, reliability and lifetime of these plants. The performance of these cables has an effect on the energy industry and the industries which use this kind of energy source. During operation, these cables are subjected to different stresses such as thermal, environmental, electrical and mechanical stresses so, condition monitoring of these cables is a must. This paper discusses a combined aging mechanisms effect on the electrical parameters of these cables. The assessment was done by monitoring the capacitance and the loss factor of the cables.

Keywords: Nuclear Power Industry, Low Voltage Cables, Combined Stresses, Condition Monitoring, Capacitance, Loss Factor

1 Introduction

Nuclear Power Plants (NPPs) are one of the most important energy sources that overcome the dramatic increase in the power demand. Some parts in these plants have a particular concern such as nuclear reactors, heat exchangers, concrete structure in addition to hundreds of kilometers of instrumentation and control (I&C) and low voltage power cables [1- 5]. These cables have a vital role in the safety and operation of NPPs since they provide the link between the transducing, instrumentation and control systems that monitor these plants [1]. The functionality of these cables depends on its insulation integrity. Thanks to the harsh environmental conditions in NPPs characterized by elevated temperatures and gamma- radiations, the insulating materials of these cables must withstand these stresses and other stresses such as electrical and mechanical stresses to ensure their safety functions over the long-term normal operation and during the design basis events (DBE) such as loss of coolant accident (LOCA). The insulating material of the cables which are particularly related to NPPs is made of polymers such as ethylene propylene rubber (EPR), cross-linked polyethylene (XLPE) and ethylene propylene diene monomer (EPDM) [4, 6, 7]. The effect of the stresses on the polymeric materials related to the nuclear environments affects its physical, chemical and electrical properties causing progressive degradation since monitoring of these cables is a must. Monitoring of these cables can be done by different testing techniques such as visual, electrical, mechanical and chemical technique. The traditional method used for condition monitoring of these cables is the mechanical one which includes two types of testing, the 50% elongation at break (EaB) and the indenter modulus but these two tests are destructive [7, 8]. So, many types of research based on non-destructive condition monitoring has been published recently especially there is a desire to extend the lifetime of NPPs however they are 30 to 40 years old. One of the non-destructive methods such as electrical technique to evaluate these cables is measuring the capacitance and the loss factor. In this research work, low voltage NPP power cables have been subjected to accelerated thermal aging followed by mechanical bending stress. The effect of combined stresses on the capacitance and the loss factor as a function of frequency was studied. Further analysis was done by correlating the loss factor and EaB results for the same aging conditions carried out at Laborelec lab, Belgium under the IAEA project [9].

2 Relationship to Industrial and Service Systems

Around the globe, the backbone of the industrial world is the electric power industry since it supplies the essential energy to industrial, manufacturing, commercial and residential customers. The investments in the mature power markets of the developing countries are driven to the transition of fuel and energy sources, increased environmental legislation and an ever-aging generation fleet and transmission-distribution infrastructure. In contrast, the expansion in the power bases in the developing economies is a must to meet the growing demand for electricity, especially in starved regions. For these reasons, the electric power industry continues to have the largest investments. Electric power can be generated by either renewable or nonrenewable resources. The nonrenewable resources are coal, oil, natural gas and nuclear. Nuclear power plants (NPPs) are relatively cheap to run but in contrast, they are very expensive to be built. In many places, in comparison with fossil fuels, nuclear energy is competitive as a means of electricity generation because waste disposal and decommissioning costs are usually fully included in the operating costs. If the social, health and environmental costs of fossil fuels are also taken into account, the competitiveness of nuclear power is improved. The NPPs contain enormous kilometers of I&C as well as low voltage power cables. The harsh environmental conditions in NPPs has a serious effect on these cables because of the high radiation levels and elevated temperature. High radiation and temperature stresses may be accompanied by other stresses such as electrical and mechanical. The operation, reliability and lifetime of NPPs are affected greatly with the performance of I&C in addition to low voltage power cables so these cables should be conditionally monitored to ensure their functionality. To ensure the continuity of energy supplied by NPPs, non-destructive

Condition Monitoring (CM) techniques must be applied to these cables which are directly reflected in the industry and service systems.

3 Experimental Work

3.1 Sample Description

The measurements were carried out on samples of low voltage NPP power cable. The technical specifications of this cable are listed in Table 1. The cable consists of three main parts tin-coated copper conductor, XLPE as main insulation and outer jacket made of chlorosulfonated polyethylene (CSPE) as seen in Figure 1.

Table 1. Cable Specifications.

Parameter	Value
Nominal voltage	0.6 kV
Insulation material	XLPE
Insulation thickness	1.143 mm
Jacket material	CSPE
Jacket thickness	0.762 mm
Continuous bending radius	38.1 mm
Overall diameter	8.636 mm
Max. conductor temperature	90^{o}C

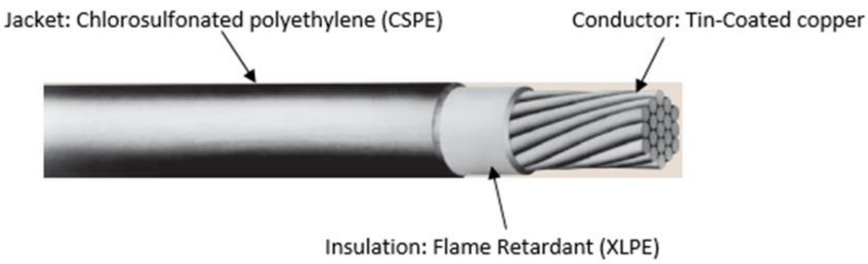

Fig. 1. Cable Construction.

3.2 Accelerated Aging Procedure

The samples have been thermally accelerated aged at a temperature of 120^{o}C for different periods to simulate different service aging times. Based on the Arrhenius equation, Table 2 shows the accelerated aging periods and the equivalent service aging time at the service temperature of 55^{o}C and activation energy (Ea) of 1.13. The NPP cables should be installed according to the manufacturer's recommendations but in some situations, this does not happen as seen in Figure 2 since exceeding the running bending radius makes the mechanical aging more significant [4, 10]. So, after the completion of the thermal accelerated aging, the samples have been subjected to mechanical bending stress. The samples were bent for two weeks with a bending radius of 50% (19.05 mm) lower than the nominal bending radius recommended by the cable manufacturer.

Table 2. Accelerated thermal aging and equivalent service aging time.

Cycle	Accelerated aging period (hours)	Equivalent service aging period (years)
1	176	15
2	342	29
3	516	44
4	793	67

Fig. 2. High mechanical bending stress on NPP power cable [4].

4 Results and Discussion

The measurements of the capacitance and tanδ have been carried out by precision component analyzer with a testing voltage of 5 V and a frequency range from 20 Hz to 500 kHz. Figures 3 and 4 shows the baseline measurements for the cable samples without aging. As shown in Figure 3, the capacitance have a higher values at lower frequencies while it decreases moving to the higher frequencies. The tanδ values of unaged cable samples are shown in Figure 4 since the higher values of tanδ shifts to the high-frequency range indicating how the leakage current dominates in the insulation [7].

The effect of each thermal aging cycle was investigated by measuring the capacitance and tanδ after each cycle. At all frequencies, the aged samples have higher capacitance than the unaged samples as shown in Figure 5. Also increasing the aging time decreases the capacitance since the insulating material loses its capacitive property.

The plot of the tan δ values of the unaged cable samples is shown in Figure 6. The same result was obtained since the higher values of tanδ shifted to the high-frequency range in addition at each frequency the aged samples have higher values compared to the unaged samples. Also, Figure 6 shows that the tanδ was increased with increasing the aging period, which means that the insulation leakage current has increased as reported in [7].

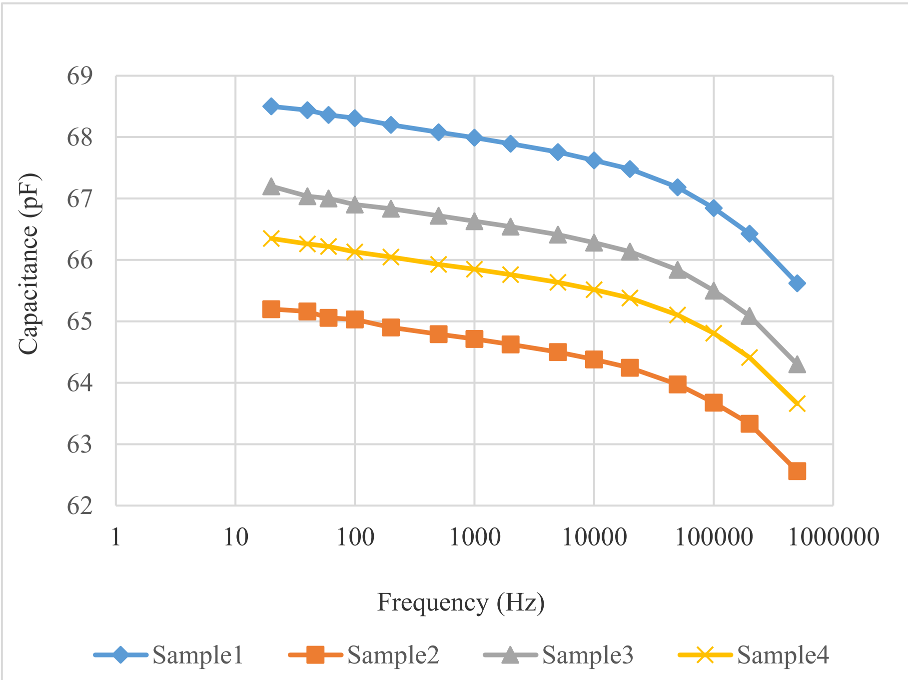

Fig. 3. The capacitance of unaged samples versus frequency.

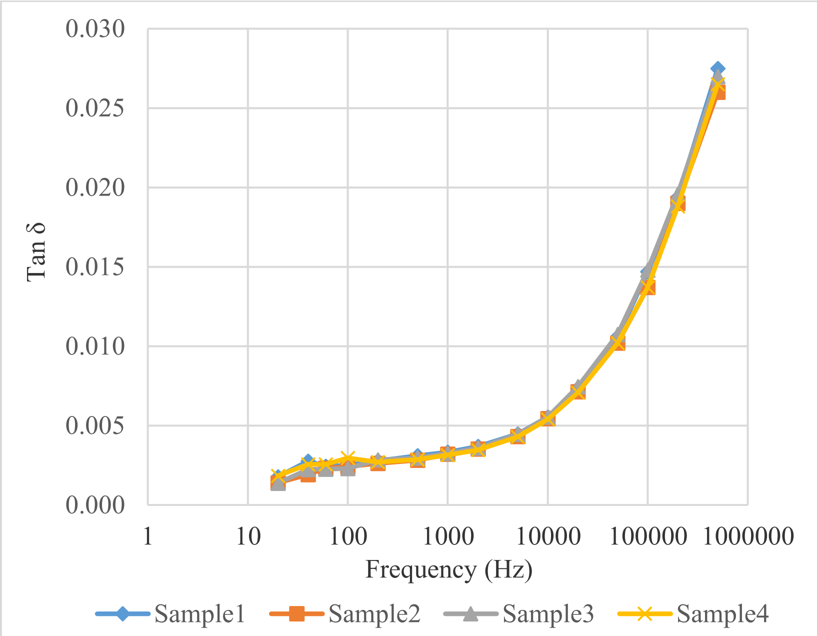

Fig. 4. Tanδ of unaged samples versus frequency.

After the fourth thermal aging cycle (67-year), the cable samples have been subjected to mechanical bending stress for two weeks. The effect of combined (thermal and mechanical) aging is plotted in Figures 7 and 8. As it is clearly shown in Figure 7, the mechanical stress increased the capacitance compared to the thermal stress only and the high difference in the capacitance between the two different aging mechanisms was observed at lower frequencies decreasing when shifting to the high-frequency range. Figure 8 shows the variation in tanδ under different stresses where the combined aging mechanisms increased the tanδ the in comparison with thermal aging only.

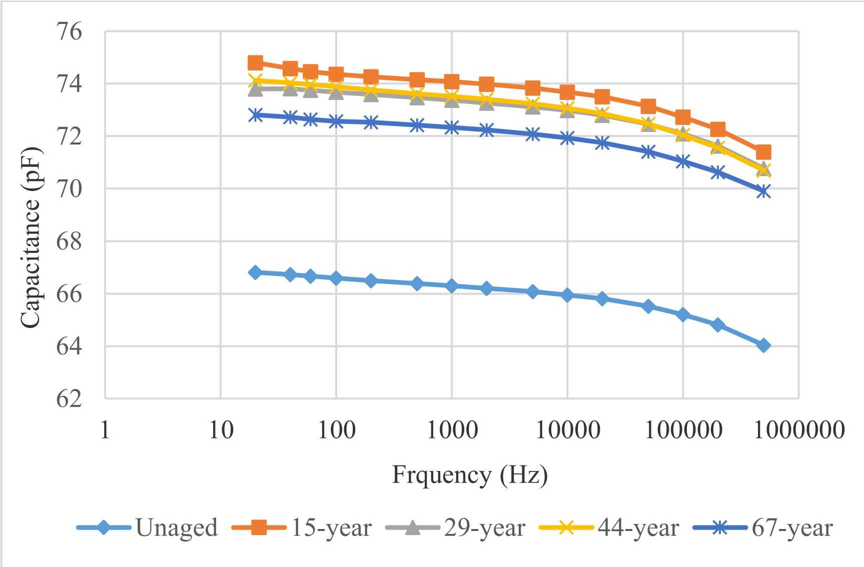

Fig. 5. Variation in the capacitance of aged samples versus frequency.

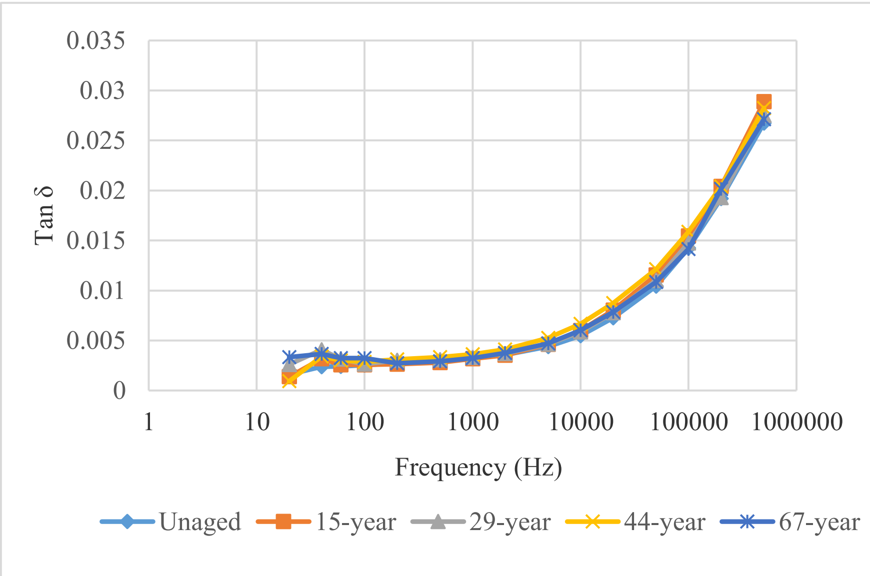

Fig. 6. Variation in the tanδ of aged samples versus frequency.

High difference between the two aging mechanisms was observed at lower frequencies so, at lower frequencies with combined stress, the insulating material greatly lost its capacitive property since the high increase in the capacitance was observed also the increase in the tanδ means high leakage current drawn by the insulating material.

Laborelec Lab, Belgium created the EaB tests for the same cable samples under the same thermal aging conditions [9]. Correlating the electrical tests, tanδ values and the mechanical tests, EaB values is given in Figure 9 showing that increasing the aging time decreases the EaB, which shows that the cable samples lost their mechanical properties while the higher values of the tanδ with the increase in the aging time shows that the insulation started to lose its electrical properties.

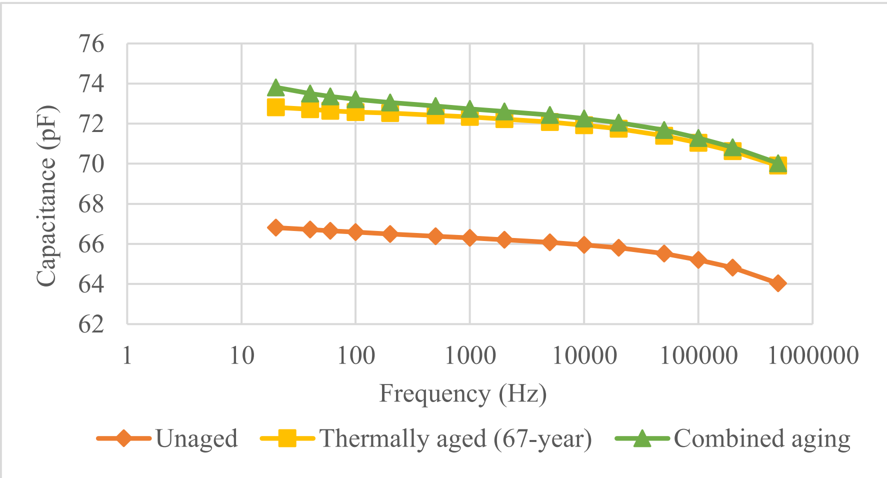

Fig. 7. Variation in capacitance under different aging mechanisms.

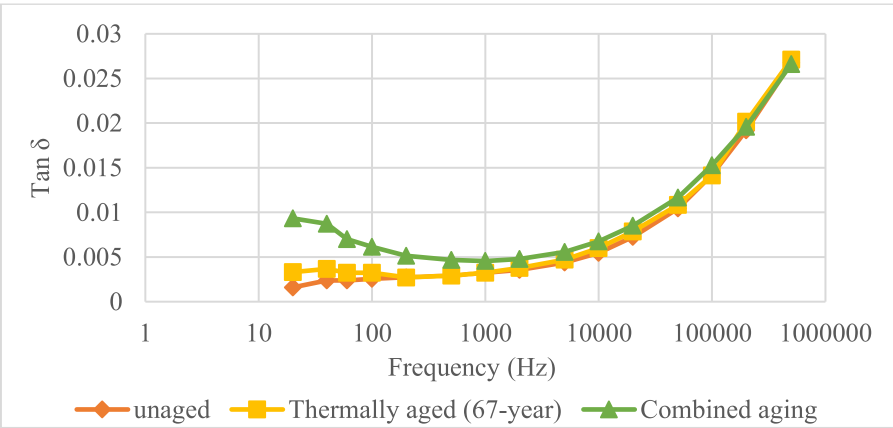

Fig. 8. Variation in tanδ under different aging mechanisms.

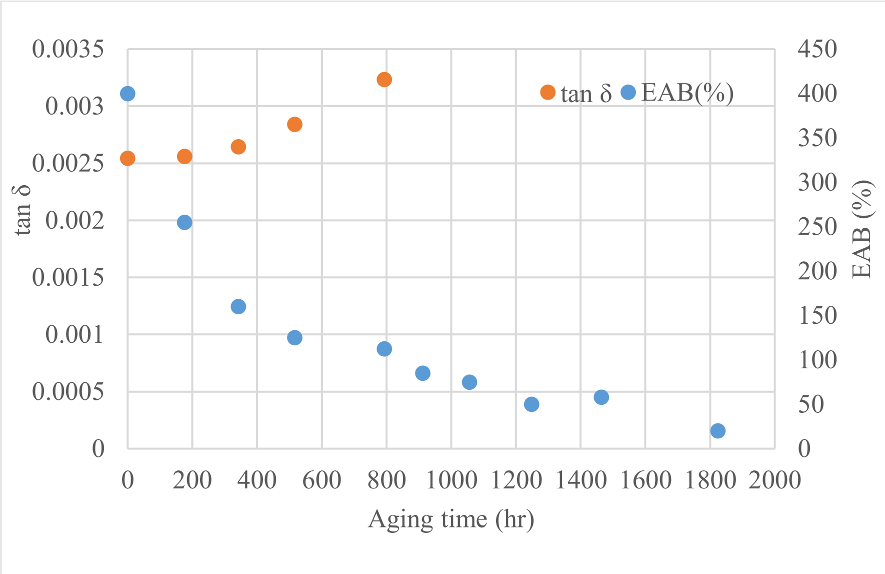

Fig. 9. Correlation between electrical and mechanical monitoring tests.

5 Conclusion

In this research work, low voltage NPP power cable samples were thermally aged under 120°C for four different thermal cycles. The effect of each thermal cycle on the insulation integrity was done by investigating the capacitance and tanδ over a frequency range from 20 Hz to 500 kHz. It was observed that with increasing the aging time and frequency, the capacitance was decreased and tanδ was increased. Also, the cable samples were subjected to mechanical bending stress after the thermal aging and it was found that the capacitance and tanδ were increased compared to the thermally aged samples and a large difference was observed at lower frequencies showing that the insulation materials lost their capacitive function.

The correlations between tanδ values and the EaB values for the same cable samples at the same thermal aging conditions show that the cables EaB decreased while the tanδ increased with increasing aging time. Further chemical investigations are needed to better understand the presented behavior of tanδ.

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