Thermal Degradation and Condition Monitoring of Low Voltage Power Cables in Nuclear Power Industry

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Abstract. A strong electric power industry having diverse generation sources is a key for advances in the industry, agriculture, technology and standards of living for any nation. In the last few decades, the nuclear power industry has emerged as a strong competitor in the electric power production market due to its less carbon oxide emission, high capacity, and efficiency. The reliable operation of nuclear power plants is heavily dependent on the safe operation of the low voltage instrumentation and control and power cables, which are mostly installed in the containment area and are under thermal and radiation stresses which may decrease the expected life of the cable. In this research work, the behavior of Choloro-Sulfonated Polyethylene/Cross-Linked Polyethylene based low voltage nuclear power plant power cable samples under thermal stress have been studied with the help of non-destructive extended voltage response method. The effect of the thermal stress on the expected life of the cable are also discussed.

Keywords: Nuclear power industry · Condition monitoring · Low voltage cables · Thermal aging

1 Introduction

For any nation advancement in the industry, agriculture and technology and standards of living strongly depend on a strong electric power industry having a diverse generation sources. In the last few decades, out of the generation sources, nuclear power industry (NPI) has emerged as a strong competitor in the electric power production market due to its number of advantages such as less carbon oxide emission, high capacity, and efficiency. For any nuclear power plant (NPP) to operate reliably, it is important that the low voltage (LV) instrumentation and control (I&C) and power

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cables must operate safely. Since, most of the LV cables are installed in the containment area hence, they are under a number of stresses such as environmental, electrical, mechanical and thermal [1]. These stresses affect the polymer insulation of the cables, electrical and mechanical properties, and hence may decrease the expected life of the cable. Practically, the lifetime of the cable is evaluated by subjecting the cables specimen under accelerated aging tests and then the integrity of them are monitored through the condition monitoring (CM) techniques. These tests provide either the critical properties or diagnostic properties by destructive or non-destructive tests, respectively. The International Atomic Energy Agency (IAEA) has narrated the desirable features of the CM techniques in its report [2], on the other hand, the CM techniques used in the recent times are also discussed in number of literature [3–8]. In spite of these research, still there is a search of an effective CM technique as the research results in regard to the effect of aging on the integral property i.e., electrical is still not sufficient. The main purpose of this paper is to search the electrical aging markers like specific and polarization conductivities and then to assess the condition of the LV cable insulation.

Out of the diagnostics tests, Extended Voltage Response (EVR) method has been successfully adopted for the CM of many insulations used in electric power equipment with the background to study the slow polarization processes in the insulation. The main advantage of the technique is its non-destructive nature. In this research work, the performance of LV NPP power cables based on Choloro-Sulfonated Polyethylene (CSPE)/Cross-Linked Polyethylene (XLPE) insulation under the thermal stress has been analyzed by the EVR method.

2 Relationship to Industrial and Service Systems

Electrical energy can be harvested either by burning energy sources such as natural gas, oil, coal (thermal energy) and nuclear or by taking advantage of renewable sources such as hydro, solar, wind and biomass. Out of the thermal energy sources, the NPI has an advantage of low operating cost with the drawback of high capital cost. The initial design of an NPP is 40 years but its reliable and safe operation is highly dependent on the services, structures, and components. In the NPP, there is about 1,000 km of long LV cables, which are exposed to thermal, radiation, mechanical and electrical stresses. With these stresses, the integrity of the cables decreases with the passage of time, aging. It is important to study the aging behavior of the cable during the operation. Also, in the case of extension in the service life of NPP, these cables must be capable of safe operation as the cable-replacement is cost-prohibitive and impractical [9]. Even though a substantial amount of effort has been expended on the degradation mechanism in the cable polymer insulation and the CM techniques, but with the challenge that each polymer has its own composition, geometry and passes through different design and fabrication processes, it is difficult to state the real cause of the cable aging in any particular polymer. Also, the effort to standardize the CM techniques is still an interesting task. Keeping in view the challenges, this research is focused on one such CM technique, EVR used to diagnose the thermally aged CSPE/XLPE based LV NPP power cable.

3 Extended Voltage Response

The electrical aging markers, stating the condition of an insulation can be obtained either by time domain analysis or frequency domain analysis. In the time domain analysis, measurement of return voltage is one such technique, with the main idea behind the technique to study the slow dielectric polarization processes, possessing high time constants, higher than 1 s [10]. Two new techniques emerged from this idea, Voltage Response (VR) and Return Voltage Measurement (RVM) method [11]. Both the methods have been adopted successfully for the condition monitoring of a wide range of the insulating materials. An advanced version of the VR method, EVR has been introduced in recent times with more charging time, 4000 s instead of 100–1000 s and discharging times to study a wide range of polarization spectrum. The method has shown its applicability on diverse high and low complex insulations materials [10, 12–14].

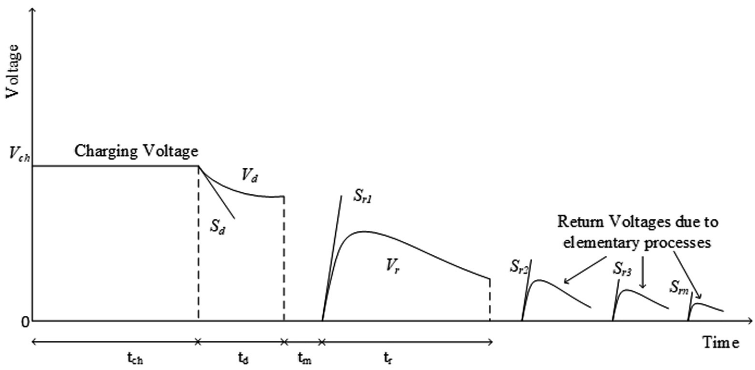

Fig. 1. Extended voltage response timing diagram.

In the EVR method, Fig. 1, the insulation is charged through a DC voltage, V_{ch} for a period, T_C. After a shortening period, the return voltage is measured across the insulation, representing the depolarization or relaxation processes inside the insulation material which did not relax during the short circuit period. Two tangents of both the decay voltage (S_d) and return voltage (S_r) are measured, showing the relationship between the specific conductivity (γ) of the insulation, Eq. (1) and the polarization conductivity (β) of the insulation, Eq. (2), respectively.

$$S_d = \left({}^{V_{ch}}/_{\in_o} \right) \gamma \tag{1}$$

$$S_r = \left({}^{V_{ch}}/_{\in_o} \right) \beta \tag{2}$$

Since there are a number of relaxation times in the insulation owing to the inhomogeneity of the material, so each relaxation time has its own time constant and correspondingly showing different return voltages [15] of the elementary processes.

4 Experimental Work

4.1 LV NPP Cable Specimen and Thermal Aging

The LV NPP power cable consists of the conductor, primary insulation of XLPE and outer insulation (jacket) of CSPE. Figure 2 shows the cross-sectional view of the cable sample.

Fig. 2. Cross-sectional view of the cable sample.

The CSPE is a special elastomer which is produced by the modification and functionalization of the polyethylene through simultaneous actions of chlorine (Cl) and Sulphur dioxide (SO_2) on PE dissolved in the CCl_4 in the presence of the radical initiators. The specification of the cable is given in Table 1.

Table 1. Specification of the cable.

Parameters	Values
Conductor	Stranded tin coated copper
Outer insulation/Jacket	CSPE
Outer insulation/Jacket thickness	0.762 mm
Primary insulation	XLPE
Primary insulation thickness	1.143 mm

The accelerated thermal aging of four cable samples was carried out in the oxygen controlled oven. The accelerated aging hours were calculated using the Arrhenius model. The model relates the degradation rate to temperature [3, 16] and is widely used for the thermal aging evaluation of the polymers in nuclear-qualified cables, it addition it is helpful in determining different ambient temperature influencing the polymer insulation of the cables. Table 2 shows the thermal exposure time (hours) of cable in the oven to the equivalent service time (years).

Table 2. Oven time (hours) and service time (years) for CSPE/XLPE cable samples.

Input aging parameters	Service time (years)	Oven time @120 °C (hours)
Service temperature: 60 °C	8	176
Oven temperature: 120 °C	16	342
Activation energy of CSPE/XLPE,	24	516
$E_a = 1.13\,\text{eV}$	36	793

4.2 EVR Measurements

For the EVR measurements, the cable sample was covered at the center by an aluminum foil and was connected to the ground terminal and the cable end was connected to the supply terminal, 1000 VDC. The equipment has connection with a static voltmeter and a computer for recording the charging, discharging times and the slope values. The S_r versus the shorting times for the unaged cable samples is shown in Fig. 3. The return voltages at the longer discharging times are a sign that there are intensive higher time constant polarizations in the insulation. Figure 4 shows the S_r for the samples after each thermal aging cycles. It is interesting to note that the values of S_r decreased as the thermal cycle time increased showing that the relaxation process has decreased.

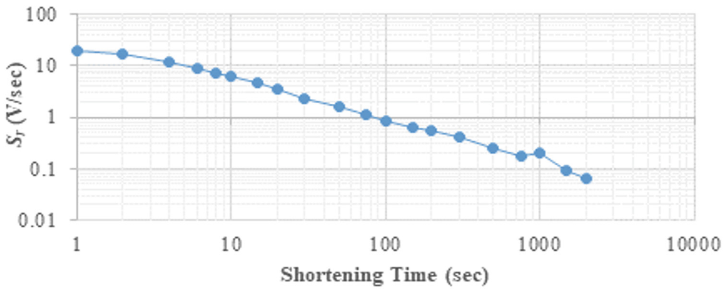

Fig. 3. S_r for unaged samples, existence of slow polarization process.

While the conductivity inside the material has been shown by the S_d plot, Fig. 5. The values of S_d first decreased then increased sharply and the end of the fourth thermal cycle the slope decreased.

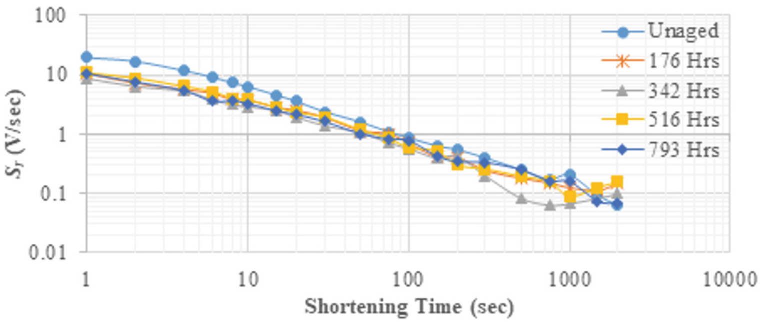

Fig. 4. S_r for aged and unaged cable samples.

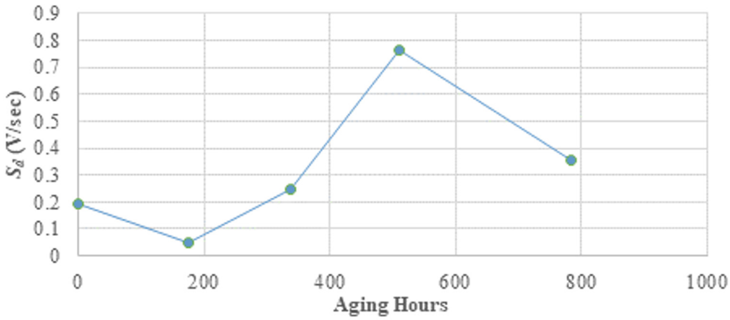

Fig. 5. S_d versus aging hours.

5 Results and Discussion

It is known that when a DC voltage is applied to an insulation material, three types of currents are generated in the material; leakage current due to the insulation resistance, absorption and charging current due to the capacitance of the insulation [17]. The leakage and absorption currents are more prominent in the case the AC voltage is applied while the charging current is more prominent under the DC voltage. Due to this charging current, there is the phenomenon of dielectric relaxation, which is related to the number of dipoles and their mobility. In CSPE, the dipoles are due to the C-Cl bond which is broken during the thermal aging and releases the chlorine, dehydrochlorination [18]. This, in turn, reduces the number of dipoles and hence the dielectric relaxation. In addition to this, since CSPE is a thermoset polymer, so due to the thermal aging there is a phenomenon of cross-linking, increasing with aging, which also affects the relaxation process. So, dehydrochlorination and cross-linking could be the reasons for the decrease values of S_r with aging, Fig. 6.

The profile of the S_d, Fig. 5, could be due to the presence of fillers, which are used in the polymer composites to increase the electrical and mechanical properties and hence effecting the conductivity of the material [19]. As shown in the Fig. 5, the

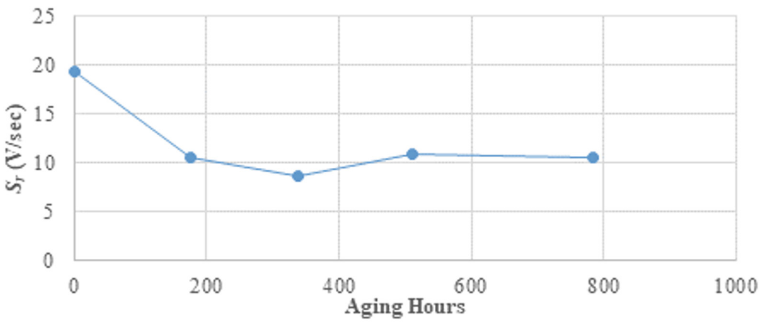

Fig. 6. S_r versus aging hours cable samples.

conductivity, S_d, decreased after the first thermal cycle, this could be attributed due to the polymer-filler interaction or the interface, which acts as the barrier to the conduction of the charge carrier in the conductor-polymer system. As the thermal stress increased, there is an increase in the electric charge which may affect the polarization of the fillers in the polymer matrix. This may result in the excess negative charge and is shown as a sharp increase in the value of S_d. After the fourth cycle, the conductivity decreased which may be due to the creation of the cross-links and dehydrochlorination, and evaporation or the reduction of the polar molecules. A further chemical investigation could be helpful in this regard [20, 21].

6 Conclusion

In this research work, CSPE/XLPE based LV NPP power cables were thermally aged under 120 °C for four different thermal cycles. The change in the polarization processes in the polymer insulation has been studied using the diagnostic method, EVR. It was observed that due to the formation of cross-linking and breakage of the C-Cl bond, resulting in a decrease of the number and mobility of dipoles the values of S_r decreased as the aging stress increased. While the values of S_d for the first cycle decreased owing to the formation of the filler-polymer bond, which may act resistive path to the charge carriers. While for the next two cycles the slope increased which may be attributed to the polarization of the filler matrix. The decreased in the slope at the end of the fourth cycle may be due to the decrease in the charge carriers and the formation of the cross-links.

From the curves of S_d and S_r, it could be concluded that in CSPE due to the thermal aging, the leakage and absorption current are more dominant as compared to the charging current as the number and mobility of the dipoles are reduced. A good chemical investigations will be helpful in backing these results.

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