Accelerated Aging Phenomena of 15 kV EPR Cable Energized by Elevated AC Voltage with Switching Impulses Superimposed

S. Grzybowski, L. Cao, A. Zanwar
High Voltage Laboratory
Electrical and Computer Engineering
Mississippi State University
Email: lc428@msstate.edu

Abstract: Aging of polymer insulated power cables is a significant subject of investigation during the last several decades. Extensive attention has been focused on aging phenomena of polymer power cables. Despite the great achievements in aging mechanism by single stress, much less is known about the aging phenomena of cables under multi-stress conditions. During service, the operation of power system will trigger overvoltages, which place the cable insulation under heavy electrical stress. In this study, the accelerated aging of 15 kV Ethylene Propylene Rubber (EPR) power cables was undertaken by elevated ac voltage (3V₀) with switching impulses superimposed. Rated ac current was supplied to simulate the thermal stress encountered in operation. The experiment aims at obtaining a comprehensive understanding of the accelerated aging phenomenon of EPR cable insulation and the impacts from different aging factors.

1 INTRODUCTION

Polymer-insulated power cables have been installed in distribution systems for more than several decades. Power cables will encounter electrical, mechanical, and thermal stress. All these stresses will initiate the deterioration of cable insulation materials. In addition to these stresses, surrounding environment will also affect the aging rate of power cables. In some cases, such as in marine condition, the influence of the moisture from surrounding environment will be of more significance [1-3].

Compared to the traditional paper oil-insulated cables, the merits of polymer-insulated cables are the excellent electric properties and moisture resistance, extremely low moisture vapour transmission, and high resistance to chemicals and solvents. The polymeric materials that have been used for power cable insulation include polyethylene (PE), cross-linked polyethylene (XLPE), and ethylene propylene rubber (EPR). Among all its features, the high short-term dielectric strength, high operating temperature, better moisture, and treeing resistance make EPR preferable to other polymeric materials as cable insulation [4-5].

One of the major concerns for utilities is the possible failure of polymer cable in operation. In the past, many studies have been focused on the aging mechanisms. Failure of polymer cable insulation under service conditions results from the combined effects of multiple factors, including the electrical, thermal, mechanical stress, and environmental conditions. The electric stress, from both operational ac voltages and abnormal overvoltages, as well as thermal stress from load current are treated as the most harmful aging factors. Thermal aging of cables will generate amorphous regions in insulation layer. Due to the treeing [6-7], partial discharges initiating in the amorphous regions will lead to degradation. If the insulation layer comes in contact with water or other chemicals, electrochemical trees will come into exist, further increasing the aging rate [8-9]. Moreover, factors such as electrical field and temperature have synergistic relation. For example, failure of insulation due to the interaction between these two factors is explained based on electric field concentration in inhomogeneous regions and micro-cracks [10-11]. Also, mechanical stresses resulting from thermal expansion, vibrations, and compressive forces lead to formation of initiation sites for insulation degradation [12].

Many studies accomplished in the past are exclusively focused on the aging phenomena induced by single aging factor. Life models or equations based on single aging factor are proposed, such as inverse power law, exponential model, and Arrhenius model [11]. Their validity is confirmed by the later research results. However, it is well known that single-stress aging does not reproduce the same results under multi-stress conditions. The actual aging is a product of synergetic effects of different aging factors [1]. Life models under multi-stress condition are developed as well. Those include the model developed by Simoni, Ramu [13], the Exponential model by Fallou [13], the probabilistic model by Montanari [14], and the physical model by J. P. Crine [15]. A common problem with those models is that they are based on the studies on general insulation materials rather than the full scale cable samples. The actual polymer cables contain not only insulation layer, but also semi conductive layer, copper shield, etc, as well as interface between those layers. All of them have impacts on the reliability and life time of polymer cables. Thus they must be applied with certain constrains.

This study helps to obtain new information on the aging of the 15 kV EPR cables under the multi-stress conditions.
2 EXPERIMENTAL SETUP

2.1 Sample description
All cable samples are made from commercially available EPR cable. The EPR cables are from the same manufacture as the previously tested EPR cable samples. The detail of the tested cable sample can be found in reference [16].

Three cable samples were tested in the experiment with switching impulses superimposed. The configuration of the prepared samples is shown in Fig. 1. The EPR cable samples were prepared into 5.5 m long segments. The active length was 4.2 m for the prepared sample. Proper terminations were introduced to reduce the local electric stress at the end of the cable samples. During the experiment, all cable samples were placed in individual PVC conduit that was filled with tap water. The filled tap water penetrates through LDPE jacket layer and contacts the insulation layer. The water level was checked and re-filled regularly during the aging process. The temperature for carried experiments was maintained at a room temperature (20° C).

Figure 1: Dimensions of tested cable samples

2.2 Experimental setup for aging
A 4 stage, 8 kJ impulse generator was used to generate switching impulses. AC voltage was supplied by a potential transformer. A 2 kVA current transformer was used to circulate the load current through the EPR cables. Before the aging of tested samples, all samples were preconditioned for 65 hours by the suggested condition defined in IEEE standard 1407-2007. The following Fig. 2 presents the scheme of experimental setup for aging. Sphere gap arrangement was used to isolate the capacitors of the impulse generator from being charged by the ac voltage.

Figure 2: Scheme of experimental setup

All the 15 kV EPR cable samples were stressed at 26 kV ac voltage (3V-). Rated ac current (226 A) was applied to simulate the maximum load current of the EPR cable samples without exceeding their ampacity. A 250/2500 µs switching impulse with a magnitude of 62 kV was applied to the cable samples. The magnitude of the applied impulses was determined so that each impulse will result in the occurrence of partial discharge (PD), even if the impulses were applied at a negative half cycle. The number of the applied switching impulses during every 100 hours ac voltage application was 1000. For switching impulses application, the impulses were applied at the rate of 2 per minute.

2.3 Measurement setup
PD parameters were recorded during the aging study. The PD inception voltages and PD extinction voltages were measured. The ac breakdown voltages measurement was conducted immediately after the completion of 1300 hrs of aging. It is believed that the PD measurement can reveal the minor changes of cable samples, while the ac breakdown voltage measurement is able to assess the overall status of the cables [17].

3 EXPERIMENTAL RESULTS

3.1 Measurement results for partial discharge parameters
Partial discharge parameters such as the partial discharge inception voltages and the extinction voltages were measured during the experiment. They served as a monitoring tool. Measurements were taken after 100, 200, 350, 500, 650, 800, 950, 1100, and 1300 aging hours. The number of switching impulses applied was 1000, 2000, 3500, 5000, 6500, 8000, 9,500, 11,000, and 13,000 accordingly.

Figure 3a: PD inception voltage of the EPR cable samples aged by elevated ac voltage with switching impulses superimposed

Fig. 3a shows the changes in the PD inception voltage and Fig. 3b shows the changes of the PD extinction voltage with respect to the aging time. A decrease of the partial discharge inception and the
extinction voltages is observed after the first 150 hours of aging. Then the inception and extinction voltages start to increase. A similar trend is shown for PD measurements of cable samples aged by switching impulses [18-19] and by rated ac voltage with switching impulses superimposed [2]. The PD inception and extinction voltages slightly increase between the aging time 150 to 350 hrs. After 350 hrs ac application, the PD inception and extinction voltage decreases. The fluctuation of PD inception and extinction voltages appears again at the aging time between 650 and 800 hrs. As more switching impulses are applied and longer time samples are aged, a very significant drop of PD inception voltage presents.

3.2 Measurement results for ac breakdown voltages

The ac breakdown voltages of all the EPR cable samples were determined after 1300 hrs of aging by ac voltage and 13,000 switching impulses. A stepped measurement technique was used while performing the breakdown voltages measurement. For each measurement, the ac voltage was quickly increased to 45 kV. Then the voltage was kept constant for 3 minutes; if no breakdown occurred during the 3 minute period, the voltage was further increased by a step of 4.5 kV. The voltage was kept for 3 minutes for each step. The ac breakdown voltages measurement is essential to estimate the dielectric strength of cable samples.

Table 1: ac breakdown voltages (kV) of the EPR cable samples aged by elevated ac voltage with switching impulses superimposed

<table>
<thead>
<tr>
<th>Sample</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakdown voltage (kV)</td>
<td>87.8</td>
<td>87.8</td>
<td>57.2</td>
<td>77.0</td>
</tr>
</tbody>
</table>

Average ac breakdown voltage of 77 kV is obtained for the samples aged by elevated ac voltage with switching impulses superimposed.

3.3 Effects of different aging conditions on PD inception voltages and ac breakdown voltages

In the past, we have aged EPR cables under many different conditions. Table 2 summarizes the aging conditions and the reduction of partial discharge inception voltages after aging. The percentage reduction of the partial discharge inception voltage is calculated using average values with respect to the values before aging.

Table 2: Percentage reduction of PD inception voltage (PDIV) for 15 kV EPR cables aged under different conditions

<table>
<thead>
<tr>
<th>Aging conditions for 15 kV EPR cable samples</th>
<th>Percentage reduction of PDIV</th>
</tr>
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<tbody>
<tr>
<td>650 hrs of aging with elevated ac voltage (3V°) [16]</td>
<td>0</td>
</tr>
<tr>
<td>650 hrs of aging with elevated ac voltage (3V°) with rated current [16]</td>
<td>26.87%</td>
</tr>
<tr>
<td>1300 hrs of aging at rated ac voltage and current, impulses superimposed</td>
<td>31.57%</td>
</tr>
<tr>
<td>1300 hrs of aging at elevated ac voltage and current, impulse superimposed</td>
<td>44.04%</td>
</tr>
</tbody>
</table>

Cable samples aged with elevated ac voltage (3V°) do not show any significant change in PD inception voltage after 650 hrs of aging. Similar results are
observed in [20], when no significant aging is found on the EPR cable samples aged by 3 times rated ac voltage. Samples aged with elevated ac voltage and rated current shows a drop of 26.87%. Also, cable samples aged by rated ac voltage (V₀) with switching impulses superimposed presents a reduction of 31.57% in PD inception voltage. The EPR cable samples aged in this experiment reaches a 44.04% decrease after aging. Through the above comparison, the impact of switching impulses along with thermal stress can easily be identified.

Although the EPR cable samples aged by elevated ac voltage with switching impulses superimposed shows maximum drop of PDIV, the aging rate during experiment is not the same for the cable samples tested under different conditions.

Table 3: Reduction of ac breakdown voltages (ACBD) for 15 kV EPR cables aged under different conditions

<table>
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<th>Aging conditions for 15 kV EPR cable samples</th>
<th>Reduction of ACBD</th>
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<tr>
<td>650 hrs of aging with elevated ac voltage (3V₀) [16]</td>
<td>0</td>
</tr>
<tr>
<td>650 hrs of aging with elevated ac voltage (3V₀) with rated current [16]</td>
<td>7 kV</td>
</tr>
<tr>
<td>1300 hrs of aging at rated ac voltage and current, impulses superimposed</td>
<td>12 kV</td>
</tr>
<tr>
<td>1300 hrs of aging at elevated ac voltage and current, impulse superimposed</td>
<td>8 kV</td>
</tr>
</tbody>
</table>

No reduction of ac breakdown voltages is found for the EPR samples aged by elevated ac voltage, which is in agreement with the partial discharge parameters measurements. Cable samples aged by rated ac voltage with switching impulses superimposed have the maximum drop after aging. The EPR cables aged in this experiments show a reduction of 8 kV. The 4 kV difference in breakdown voltages exists between the EPR samples aged under the two different conditions, which accounts for less than one step in measurement.

4 ANALYSIS OF MEASUREMENT RESULTS

The trend of decrease of inception voltage is noticed for the EPR samples aged under different conditions. Assuming the cables’ life come to an end when their PDIV drop to less than 9.57 kV (1.1 V₀), the remaining life of the tested EPR cables is estimated from the extrapolation curve of PDIV measurement results.

As observed from Fig. 4, for cable samples aged by rated ac voltage and current with switching impulses superimposed, the reduction of PDIV is 27.2% after the first 650 hrs of aging; while the EPR cable samples aged by elevated ac voltage with switching impulses superimposed only show 17.9% decrease of PDIV after 650 hrs of aging. The cable samples aged by rated ac voltage with switching impulses have a fast aging rate at the beginning of aging. However, the aging will reduce to a slower rate after some specific time, as drop in PDIV is only 4% between 650 hrs and 1300 hrs of aging. The EPR cable samples aged by elevated ac voltage with switching impulses superimposed show a steady aging rate even after 1300 hrs of aging, which is proven by the 25% drop of PDIV.

Similar comparison is achieved through the ac breakdown voltages measurement. Following table 3 presented the ac breakdown voltages for the EPR cable samples aged under different conditions. The reduction of ac breakdown voltages is calculated with respect to the average ac breakdown voltage of the new EPR cable samples, which is 85 kV.
For cable samples aged by rated ac voltage with switching impulses superimposed, the remaining life will be 1925 hrs, with 19250 switching impulses left. For cable samples aged by elevated ac voltage with switching impulses superimposed, the remaining life is only 201 hrs, with 2010 switching impulses superimposed. Yet it is important to note that the above assumption is an empirical calculation derived from the measurement results, which should only be applied to the cable samples aged under the above mentioned conditions.

5 CONCLUSION

In this paper study, the EPR cable samples were aged by elevated ac voltage with switching impulses superimposed. The maximum ac current was applied to the EPR samples. A total number of 13,000 switching impulses were applied during 1300 hrs of aging study. The partial discharge parameters were recorded during aging process as monitoring tool. The ac breakdown voltages of the EPR cable samples were measured after aging to determine the remaining dielectric strength. The ac breakdown voltages measurement was taken immediately after aging. The measurement results for the EPR cables aged under different conditions were compared as well. We can arrive at the following conclusions based on the measurement results and the analysis obtained.

1. After 1300 hrs of aging by elevated ac voltage with switching impulses superimposed, deterioration was observed on the EPR cable samples.
2. Measurement results of the partial discharge inception and the extinction voltage showed the clear evidence that degradation has taken place.
3. The comparison of partial discharge inception voltages of cable samples aged under different conditions revealed the contribution of switching impulses and thermal stress to the aging of the EPR cables.
4. Observation confirmed that the synergic effects of different aging factors showed enhancement of the aging of the EPR cables.
5. The decrease of the ac breakdown voltages after 13,000 switching impulses and 1300 hrs of elevated ac aging was a result of accelerated aging.
6. Compared with the ac breakdown voltage measurement, the partial discharge parameters measurement had better sensitivities to monitor the changes in the EPR cables during aging.
7. Additional work of EPR cables aged by higher stress levels, such as higher ac voltage and higher magnitude of switching impulse, should be taken into consideration for the investigation of a thorough aging model and better life prediction.

6 ACKNOWLEDGMENTS

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7 REFERENCES


