E-Journal of Advanced Maintenance Vol.7-1 (2015) 102-107
Japan Society of Maintenology

A Study on Insulation Degradation in Thermally Aged Ethylene Propylene Rubber Using Volume Resistivity Measurement

Tariq ALSHAKETHEEP[1,*], Kenta MURAKAMI[2] and Naoto SEKIMURA[1]

[1] *School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-Ku, Tokyo 113-8656, Japan*
[2] *Nuclear Professional School, The University of Tokyo, 2-22 Shirakata-Shirane, Tokai, Ibaraki 319-1188, Japan.*

ABSTRACT

This study presents electrical condition monitoring technique aiming at measuring volume resistivity (ρ) precisely for the tubular-shaped cables insulators. Tubular electrodes were designed to detect ρ for nuclear grade flame retardant ethylene propylene rubber (FR-EPR) insulated cables that underwent thermal accelerated ageing. FR-EPR insulated cables were heated at 125 °C for 5040 hours by two methods: with jacket and without jacket, while only FR-EPR cable with jacket was heated at 150 °C for 336 hours. ρ in insulators heated with jacket sharply decreased at ageing times 800-3480 hours and 300-336 hours during ageing at 125 °C and 150 °C respectively, hence obeying "induction-time" behavior as confirmed from elongation at break degradation curves at similar ageing conditions. Reduction of ρ in insulators heated at 125 °C without jacket is less significant compared to ageing with jacket.

KEYWORDS

Thermal ageing, cable insulator degradation, volume resistivity, elongation at break, and ethylene propylene rubber

ARTICLE INFORMATION

Article history:
Received 21 November 2014
Accepted 27 March 2015

1. Introduction

Nuclear power plants (NPPs) cables ageing is key concern that can affect plant operation and plant life management. The total length of a NPP cables can reach 2000 km [1], delivering power and signals to both safety-related and non-safety related equipment, hence their total replacement will be cost prohibitive [2].On the other hand, the cables that are installed in harsh environment conditions with high elevated temperature [3], will experience chemical reactions like oxidation, chain scission and cross linking [4,5] leading to altered electrical and mechanical properties with long term operation [6].

Mechanical properties such as elongation at break (EAB) showed excellent indications for cable insulator degradation [7]. EAB degradation behaviors at different ageing temperatures have been successfully utilized for predicting lifetimes of insulator materials at typical NPP environment temperatures [8-10]. On the other hand, electrical properties such as voltage withstand and insulator resistance (IR) are most vital parameters for insulator integrity and functionality [11]. Oxidation ageing stressors like temperature can alter insulator electrical conductivity or resistivity (ρ) by formed chain scission moieties [6]. Nevertheless, IR measurement is not counted for trending and monitoring insulator ageing by temperature, but only used as pass/fail test [12]. Ordinal IR measurement insensitivity to thermal induced ageing can be referred to uncertainties of measured IR which also contains leakage current over cable surface (i.e. surface resistivity) [13], in addition to other impacts like cable length, humidity, and surface contaminations [14].Hence, estimating behavior of insulators electrical properties and predicting lifetimes from corresponding degradation cannot be achieved due to the lower accuracy and reliability of estimating ρ compared to EAB.

Accordingly, the objective of this study is to precisely detect ρ behavior along thermal ageing through improved electrical condition monitoring (CM) technique. Accurate detection of IR and ρ can lead to better assessment of electrical property under accelerated ageing; hence lifetimes of insulators

---

[*] Corresponding author. TEL (Fax.): 0081-3-5841-6987
E-mail: benzeyad86@yahoo.com (T. ALSHAKETHEEP)

can be predicted from electrical properties degradation.

2. Accelerated ageing experimental settings

2.1. Cable materials

Ethylene propylene rubber (EPR) insulated cable was focused in this study due to its wide usage in operating NPPs, counting for about 75% of in-service control and power cables [15]. Nuclear grade 3 core low voltage (< 600 V) power/control cable was used for testing. Cable insulator material is flame-retardant (FR-EPR), while jacket material is polyvinyl chloride (PVC). Conductor size of each insulator is $3.5mm^2$. Insulator and jacket thicknesses are 1 mm and 2 mm respectively. All FR-EPR cables used in this study belong to the same lot.

2.2. Heating test and measurement environmental conditions

Thermal ageing was performed inside air circulated fan oven equipped with thermocouples distributed near samples. Samples were vertically hanged inside the oven and isolated from each other. Heating was performed at two temperatures; 125 °C and 150 °C. The cables were cut into 100 mm length and were hung in the oven vertically. In order to observe the effect of insulator environment, PCV jacket of some cables were stripped when it were heated at 125 °C. Deviation of testing temperature is affected by the number of the specimen stored in the oven, but was not more than ±4 °C. Heating test at 125 °C and 150 °C were continued up to 5040 hours and 336 hours, respectively.

3. Volume resistivity measurement

Samples removal for ρ measurements were performed periodically up to end of ageing times. The jacket was stripped and the surface of each insulator was cleaned by ethanol. ρ measurements were performed at same session after 10 days from last sampling at ageing conditions 125 °C x5040 hours. Measurements conditions were 20-21 °C and 25%-46% relative humidity. IR measurements were performed on FR-EPR insulators after removing jacket by tubular-electrode design shown in Fi.g. 1. The tubular-electrode was made for the three colored insulators (white, red and black) at each ageing time.

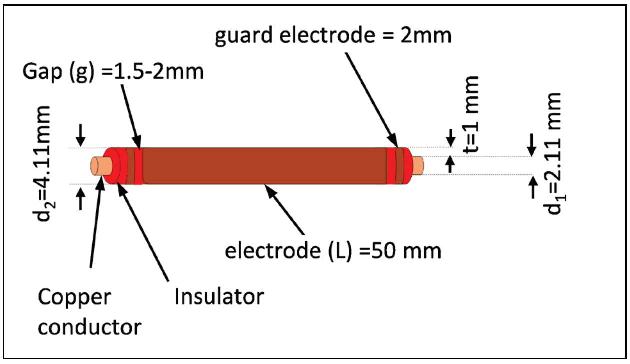

Fig. 1.Tubular electrode for FR-EPR red insulator

In Fig. 1, the total current passing from copper conductor to insulator outer surface includes capacitive charging current, dielectric absorption current and resistive leakage current. [16]. The first two currents will vanish within few seconds and the total current is represented by resistive leakage current that is converted into meaningful volume resistivity value expressing electrical property status through insulator thickness. The electrode and guard electrode were made from copper foil with conductive tape having a thickness of 39 μm and resistance of $0.02\Omega/cm^2$. The electrode that has a resistance (Rx) was electrically connected with 500V dc power source through Wheatstone bridge configuration as shown in Fig. 2. Analog Pico-ammeter was used for the purpose of detecting the small leakage current through cable insulator. Wheatstone bridge circuit had two constant resistors (R_B and R_N) and variable potentiometer (R_A) for balancing the bridge (zeroing the Pico-ammeter) where Rx is calculated as (R_B R_N / R_A) at balance condition. At each ageing time, the circuit was balanced and Rx was calculated after 60 seconds from activating the electrical circuit.

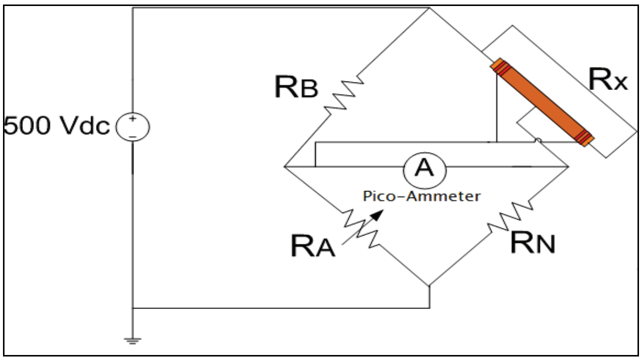

Fig. 2. Electric circuit schematic diagram for IR and ρ measurement by Wheatstone bridge configuration

In Fig. 2, the guard electrode is used in order to reduce the errors from fringing and stray currents [17]. The electrode is used for Rx detection, which is corresponding to the volume in between copper conductor, electrode length (L) as well as current lines fringing on both electrode ends. Thus, volume resistivity (ρ) is correlated with Rx by equation 1:

$$\rho = 2\pi(L + 2(g/2 - \delta))Rx/\ln(d_2/d_1) \quad (1)$$

Where L is the length of electrode (mm), g is gap width between electrode and guard electrode (mm), d_2 and d_1 are insulator outer diameter and conductor diameter (mm) respectively. δ is a constant depending on both insulator thickness (t) and gap (g) as described by equation 2:

$$\delta = t(2/\pi)\ln\cosh[(\pi/4)(g/t)] \quad (2)$$

In equation 1, the term [L+2(g/2-δ)] is the actual effective length that is a summation of electrode length (L) and increment from current lines fringing on both electrode ends (2(g/2-δ)) [18]. By designing gap width (g) within 1.5-2 mm (Fig. 1), an average value of effective length is (L+0.5g), and volume resistivity (ρ) can be calculated from measured Rx by: ρ [Ωm]=0.49Rx [Ω].

4. Mechanical and electrical properties degradation curves for thermally aged FR-EPR insulator

Fig. 3 shows volume resistivity (ρ) in FR-EPR insulators thermally aged with PVC jacket at 125 °C and 150 °C. During heating at 125 °C, ρ in all insulators of three colors varies in similar trend and witnesses a large decrement to order level of 10^{10} Ωm at ageing time 800-3480 hours. Before it rises back to order level of 10^{12} Ωm at ageing time 5040 hours. This increment of ρ is due the significant ageing involved by embrittlment and volume shrinkage that overlaps ρ detection. The large reduction of electrical property is observed in specimens thermally aged at 150 °C for 300-336 hours where ρ in white and black insulators abruptly falls down to order levels of 10^{10} Ωm and 10^{9} Ωm respectively, while ρ in red insulator remains at order level of 10^{13} Ωm. That is due to the difference of colorant pigments between colored insulators [19]. Thus, the pigments in red colorant caused mechanism kinetics that delayed resistivity sharp reduction.

The sharp reduction of EPR insulator properties undergoing thermal ageing has been well-known for mechanical parameters, in particular elongation at break (EAB) which usually decreases by slow rate until certain time when abrupt rapid decrement occurs due to the large consumption of antioxidant amount at that point, and hence following the so called "induction-time" behavior [9,20].

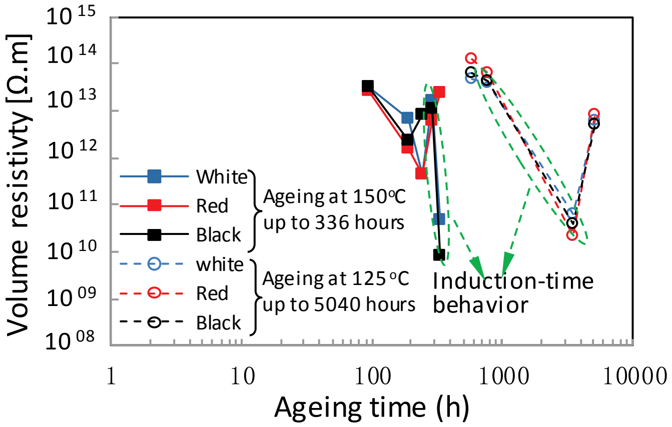

Fig. 3. Volume resistivity versus ageing time for FR-EPR insulator aged with PVC jacket at 125 °C and 150 °C

Accordingly, in order to confirm whether the mechanical properties follow induction-time behavior, EAB tensile testing was performed for same FR-EPR cable specimens that underwent identical ageing conditions at 125 °C and 150 °C. The tensile samples type is tubular type with end tabs and inserts made according to IEC-62582-3[21].Tensile testing machine was SHIMADZU Autograph and strain rate was 50 mm/min. EAB results confirm that the mechanical properties in specimens follow induction-time behavior as can be seen in Fig. 4, where EAB sharply decreases after around 300-336 hours and 800-2208 hours heating at 150 °C and 125 °C respectively. EAB decrement exceeds its half initial value (0.5 EAB_0) that is considered an acceptance criterion for cable end-of-lifetime [11]. Besides, the observed induction-time of 300-336 hours from EAB degradation curves is identical to ageing time of ρ sharp decrement when heating at 150 °C, hence induction-time behavior of electrical property degradation is confirmed when correlating with EAB degradation curves. However, for heating at 125 °C, EAB sharply decreases between 800-2208 hours of ageing times. The observed induction-time of 800-2208 hours is a little less than that observed during ρ measurement. Therefore, degradation rate of mechanical properties precedes the electrical properties.

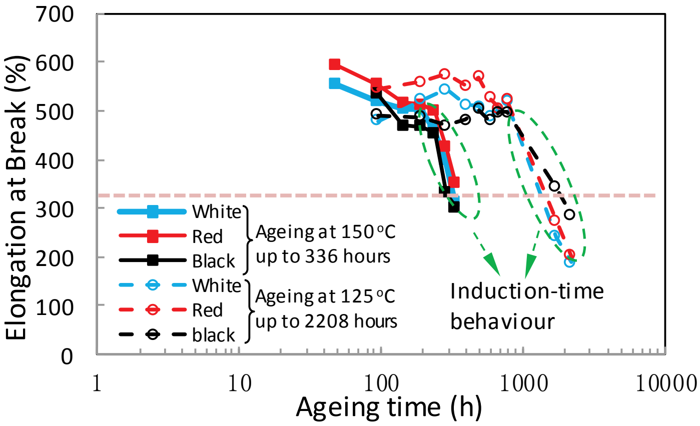

Fig. 4. Elongation at break versus ageing time for FR-EPR insulator aged with PVC jacket at 125 °C and 150 °C

5. Effect of thermal ageing method on FR-EPR insulator resistivity-time behavior

Fig. 5 shows volume resistivity (ρ) in FR-EPR insulators aged at 125 °C with and without PVC jacket. Starting from order level of 10^{14} Ωm, ρ in all insulators containing different coloring additives varies in similar trend up to ageing time of 800 hours. Shortly afterwards, ρ in FR-EPR insulators heated with jacket largely decreases by three orders of magnitude between ageing times 800-3480 hours, through induction-time behavior. On the other hand, ρ maintains slow rate decrement behavior for FR-EPR aged with no jacket reaching order level of 10^{13} Ωm at end of annealing time of 5040 hours without passing by induction-time behavior as in ageing with jacket. Therefore, the effect of thermal ageing method for FR-EPR insulators when heating solely or as full cable causes different injection rates of charged ions into insulator, that is higher when insulator environment is jacket. The source of charged ions is either chain-scission moieties or induced particles from insulator reactions with jacket environment. Nevertheless, ρ degradation for all FR-EPR colors is still not significant when compared with IAEA insulator function acceptance criterion limit of 1×10^{8} Ωm [11].

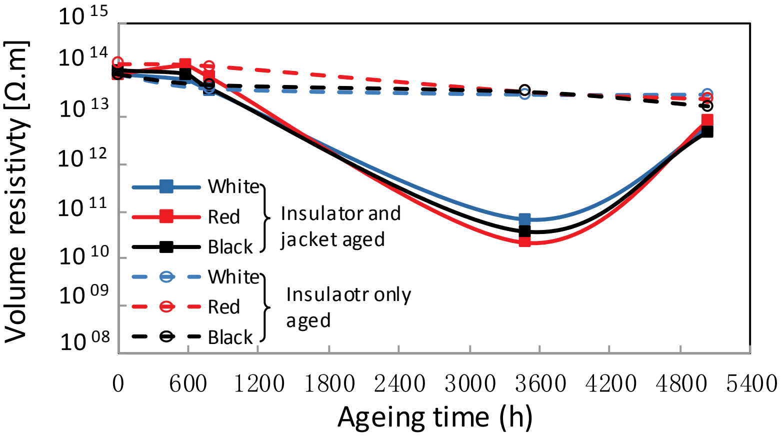

Fig. 5. Volume resistivity versus ageing time for FR-EPR insulator aged at 125 °C with and without PVC jacket

6. Conclusion

This study introduced an electrical CM technique that tracked ρ variance of FR-EPR insulators under accelerated thermal ageing. The specifically designed tubular electrodes for limited-dimensional portions of FR-EPR cables insulators succeeded to detect ρ up to order level of 10^{14} Ωm. Thermal degradation curves of ρ sharply decreased at times 300-336 hours and 800-3480 hours for heating at 150 °C and125 °C respectively, and hence following induction-time behavior when correlating with EAB degradation curves of same aged specimens. In addition, effect of annealing method on electrical property behavior with ageing time was different, and heating only insulator did not largely degrade ρ.

The continuous detection of IR and ρ from various accelerated thermal ageing conditions will lead to better estimation of electrical properties behavior and better prediction of insulator lifetimes as derived from their corresponding degradation curves.

References

[1] Y. Ohki, N. Hirai: “Location Feasibility of Degradation in Cable through Fourier Transform Analysis of Broadband Impedance Spectra”, Electrical Engineering in Japan, vol. 183, No. 1, pp. 1-8 (2013).
[2] G.J. Toman, A. Manty: “Cable System Ageing Management for Nuclear Power Plants”, Proceedings of 2012 IEEE International Symposium on Electrical Insulation, San Juan, PR, pp. 315-318 (2012).
[3] L. Verardi, et al.: "Electrical ageing markers for EPR-based low voltage cable insulation wiring of NPPs" Radiation Physics and Chemistry, vol. 94, pp. 166-170 (2014).
[4] T. Seguchi, et al.: “Degradation mechanisms of cable insulation materials during radiation-thermal ageing in radiation environment”, Radiation Physics and Chemistry, vol. 80, pp. 268-273 (2011).
[5] Anandakumaran A, Batonieek B, Bora JS, et al.: “Assessment and management of ageing of major nuclear power plant components important to safety: In-containment instrumentation and control cables”, vol.1,

IAEA-TECDOC-1188, International Atomic Energy Agency, Austria (2000).
[6] Simmons KL, et al.: “Determining remaining useful life of ageing cables in nuclear power plants”, PNNL-22812, Pacific Northwest National Laboratory, USA (2013).
[7] Kim IY, et al.: “A study of validation of condition monitoring method of NPPs cable through volume electrical resistivity” Proceedings of International Conference on High Voltage Engineering and Application, Shanghai, China, Sept., pp.17-20 (2012).
[8] J. Wise, et al.: “An ultrasensitive technique for testing the Arrhenius extrapolation assumption for thermally aged elastomers”, Polymer Degradation and Stability, vol.49, pp. 403–418. (1995).
[9] K.T. Gillen, et al.: “Lifetime predictions for semi-crystalline cable insulation materials: I. Mechanical properties and oxygen consumption measurements on EPR materials”, Polymer Degradation and Stability, , vol.91, pp. 2146-2156 (2006).
[10] T. Yamamoto, T. Minakawa: “Assessment of cable ageing for nuclear power plants”, JNES-SS-0903, Nuclear Energy Safety Organization, Japan (2009).
[11] J. Alonso, et al.: “Assessing and managing cable ageing in nuclear power plants”, IAEA No. NP-T-3.6, International Atomic Energy Agency, Austria (2012).
[12] Y.T. Hsu, et al.: “Monitoring the moisture-related degradation of ethylene propylene rubber cable by electrical and SEM methods”, Polymer Degradation and Stability, vol. 91, pp. 2357-2364 (2006).
[13] H.M. Hashemian: “Materials Ageing and Degradation in Light Water Reactors”, “Ageing of Electric Cables in Light Water Reactors” Woodhead Publishing, UK, pp.284-311, ISBN 978-0-85709-745-3 (2013).
[14] M. Villaran, R. Lofardo: “Essential elements of an electric cable condition monitoring program”, NUREG/CR-7000, United States Nuclear Regularity Commission, USA (2010).
[15] N. Sekimura, et al.: “Technical basis for commendable practices on ageing management-SCC and cable ageing project (SCAP)”, NEA/CSNI/R (2010)15, Nuclear Energy Agency, France (2011).
[16] P.K. Ramteke, et al.: “Thermal ageing predictions of polymeric insulation cables from Arrhenius plot using short-term test values”, Proceedings of 2nd International Conference on Reliability, Safety and Hazard (ICRESH-2010), India, Dec., pp.325-328 (2010).
[17] T. Ghaffari: “Characterization and Failure Analysis of Plastics: Electrical Testing and Characterization”. American Society of Metals, USA, pp. 164-176, ISBN: 0-87170-789-6 (2003).
[18] The American Society for Testing and Materials (ASTM): “Standard test methods for DC resistance or conductance of insulating materials”, ASTM- D257-07, USA (2007).
[19] V. Placek, T. Kohout:”Comparison of cable ageing”, Radiation Physics and Chemistry, vol. 79, pp. 371-374 (2010).
[20] K. Anandakumaran, D.J. Stonkus: “Assessment of oxidative thermal degradation of crosslinked polyethylene and ethylene propylene rubber cable insulation”, Polymer Engineering and Science, vol. 32, pp.1386-1393(1992).
[21] The International Electrotechnical Commission (IEC): “Nuclear power plants –Instrumentation and control important to safety-Electrical equipment condition monitoring methods-Part 3: Elongation at break”, IEC-625823, Switzerland (2012).