Insulation Resistance Measurements of Medium-Voltage Cross-Linked Polyethylene Cables under Thermal Stresses

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***Abstract*—The insulation of medium-voltage electrical cables is usually composed of polymers such as cross-linked polyethylene (XLPE) that excel in electrical dielectric properties and thermo-mechanical reliability. Thermal stress is one of the key factors that degrade the insulation performance of heavily loaded cables and eventually cause irreversible cable failures. To inform XLPE insulation resistance (IR) changes which measure cable insulation conditions under thermal stresses and assist in the development of related IR models, this paper presents IR measurements of 10 kV XLPE power cables which were thermally aged at around 100 ºC under an accelerated thermal ageing experiment. The yearlong IR observations exhibited two consecutive U-shape changes followed by a rough decline, which might reflect a joint effect of annealing and thermal ageing. The experiment results highlight the necessity of enhancing IR models to additionally consider the promotion of hopping conduction within insulation by the chemical components diffused from semicon layers under the annealing effects.**

Keywords—accelerated thermal ageing, annealing, cross-linked polyethylene, insulation resistance measurement, medium-voltage cable, thermal stress.

I. INTRODUCTION

Polymer materials such as cross-linked polyethylene (XLPE) are widely used as the insulation of electrical cables due to their robust dielectric properties and thermo-mechanical reliability [1]. Cable insulation performance will degrade over operating hours due to the exposure to various sources of stresses such as thermal, electrical, environmental and mechanical stresses [2], [3]. These stresses initiate ageing reactions under different mechanisms [4] and are considered as intrinsic ageing factors which interact with the physicochemical structure of insulation materials and change material properties [3]. In contrast to intrinsic ageing, extrinsic ageing evolves from insulation defects such as voids and cavities which are created unexpectedly during cable manufacturing, transportation, installation and operation [3]. Cable insulation ageing will increase cable failure rates and threaten the reliable supply of electricity. Therefore, it is necessary to understand the variations of insulation properties over the degradation process, providing cable asset managers with knowledge and basis for preventive maintenance or replacement of cables.

Cable condition monitoring techniques for the insulation degradation characterisation fall into four main categories: those based on measurements of partial discharge which indicates localised deterioration [5]; measurements of dielectric loss (also named as dissipation factor and tan δ) which reflects the overall cable insulation deterioration [6]; measurements of space charge accumulation which distorts local electric fields and accelerates insulation ageing [7]; and measurements of insulation resistance (IR) which is a DC diagnostic test [8]. IR is considered to most directly reflect on the overall insulation degradation among a range of monitoring techniques, though there is currently a lack of in-service IR monitoring techniques applicable to AC conditions [2]. Most research related to IR monitoring deals with insulation resistivity or conductivity measurements during the ageing process, especially under thermal stress which is considered one of the primary and common stresses accelerating the insulation ageing [9]. In this respect, the volumetric resistivity assessments of dumb-bell-shaped and circular XLPE probes were conducted in [10], finding that resistivity declined significantly with decreasing polymer viscosity during 5000-hours thermal ageing and exhibited a faster reduction at a higher ageing temperature. Resistivity reductions of XLPE insulation accelerated by higher ageing temperatures were also experimentally validated in [11] and [12]. Furthermore, the conductivity of XLPE insulation over an accelerated thermal ageing process was measured in [13], which initially dropped due to the evaporation of low molecular weight substances and then gradually increased due to the post-crosslinking and thermal decomposition reaction. However, the experiments conducted in [10]-[13] only considered the thermal ageing of insulation itself and neglected the interaction between insulation and contacting semicon layers within extruded power cables. Chemical components diffused from semicon layers into insulation layers of extruded power cable samples under the annealing effect were observed via infrared spectroscopy in [14], which promoted hopping conduction within insulation [15]. The cumulation and subsequent exhaustion of the chemical components during annealing resulted in the observation of a hump-shaped variation of XLPE insulation conductivity under isothermal conditions [14].

The contributions of the paper are to deal with experimental IR measurements of XLPE insulated cable samples subject to thermal stresses and present yearlong IR variations under non-isothermal conditions. Four XLPE insulated cable samples were thermally degraded at around 100 ºC in an accelerated thermal ageing experiment where heat sources came from the Joule heat generated in core conductors of energised cable samples. The dissipation of the Joule heat to ambient environment through the insulation induced temperature gradients along insulation radius. The 1-min and 10-min IRs of the cable samples were measured at room temperature of ~20 ºC by applying a voltage of 10 kV after different numbers of thermal ageing cycles, forming a yearlong pattern of IR variations under the combined effects of annealing and thermal ageing.

The paper is structured as follows. Section II describes the accelerated thermal ageing experiment of XLPE insulated cable samples; Section III presents insulation property measurements and discusses potential reasons behind the IR changing patterns; and Section IV gives conclusions and future work.

II. ACCELERATED THERMAL AGEING EXPERIMENT

A. XLPE Insulated Cable Sample

LSXHIOE 1x185/35 6,35/11 kV XLPE insulated cables were employed in the experiment. Their cross-section schematic and dimensional characteristics are shown in Fig. 1 and Table I, respectively [16]. Both terminals of 3.3m cable samples were specially processed (see Fig. 2) to facilitate the connection of the cable cores to the power supply and allow the copper wire shield to act as the grounding connection for IR measurements. A thin layer of polymer material was used to cover the terminal to keep the exposed insulation from moisture and potential impurities in ambient environment. The cable samples were pre-conditioned at room temperature of ~20 ºC for 500 days so as to reduce the presence of by-products in insulation to a negligible level [17].

B. Accelerated Thermal Ageing Experiment

To replicate the realistic operating condition of cables, four specially prepared cable samples were placed in parallel within a 2.5m aluminium chamber which was encapsulated into 20mm thick polystyrene materials for heat insulation, as shown in Fig. 3(a). The horizontal distances between adjacent cable samples and from outer cable samples to the chamber's lateral walls were 100 mm and 50 mm, respectively. The chamber's upper and lower walls were vertically separated from the cable samples by 100 mm. The parts of the 3.3m cable samples that extended out of the 2.5m chamber were used to link the terminals of adjacent cable samples in series and connect the terminals of outer cable samples to a current transformer for power supply. The chamber was elevated above the ground by four horse trestles to mitigate heat transfer to ground, as shown in Fig. 3(b).

Referring to IEEE Std. 1407 [18], the temperatures of cable samples during a 24-hour thermal ageing cycle were adjusted to simulate potential daily variations in practice by controlling the current transformer output. Each ageing cycle comprised (i) a 2-hour heating phase where cable surface temperatures rose from 20 ºC to around 100 ºC, (ii) a 6-hour high-temperature phase that kept cable surface temperatures at around 100 ºC, and (iii) a 16-hour cooling phase where the current transformer was turned off to allow sample temperatures to gradually fall towards 20 ºC.

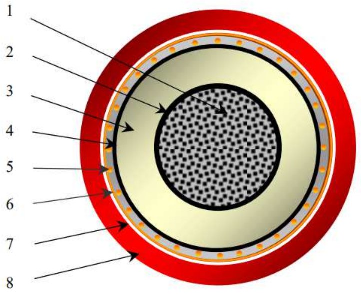


Fig. 1. The cross-secontion schematic of XLPE insulated cable samples [16].

TABLE I. DIMENSIONS OF XLPE INSULATED CABLES [16]

Index	Component	Characteristic	Value	Unit
1	Solid Aluminium Conductor	Nominal Area	185	mm^2
		Diameter	15.2	mm
2	Conductor Screen (Semicon)	Minimum Thickness	0.3	mm
3	XLPE Insulation	Average Thickness	3.4	mm
		Outside Diameter	23.2	mm
4	Insulation Screen (Semicon)	Minimum Thickness	0.3	mm
5, 6	Metallic Shield (Wires + Tape)	Cross-Sectional Area	35	mm^2
7	Waterblocking Tape	–	–	–
8	Outer Sheath	Average Thickness	1.9	mm

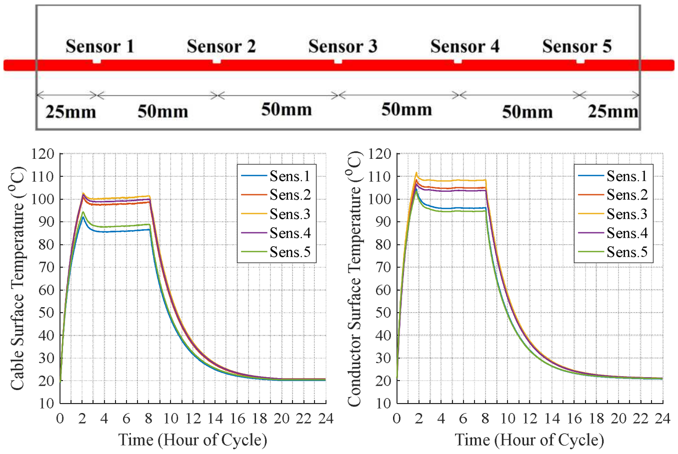

(a) (b)

Fig. 2. (a) 3.3 m XLPE insulated cable sample and (b) section view of the specially prepared cable terminal.


(a) (b)

Fig. 3. (a) Parallel placement of four cable samples within a chamber and (b) set-up of the accelerated thermal ageing experiment.

Fig. 4(a) shows the 24-hour temperature profiles monitored by type T thermocouples [19] at five positions along a particular cable sample surface, where lower temperatures were observed at the positions closer to the chamber's side walls due to greater convection heat losses. The conductor surface temperatures at the same positions of a dummy sample were also measured once by inserting thermocouples into the holes drilled on the dummy sample, as shown in Fig. 4(b). The difference in temperature between cable surface and conductor surface highlights a radial temperature gradient due to the Joule heat dissipation.



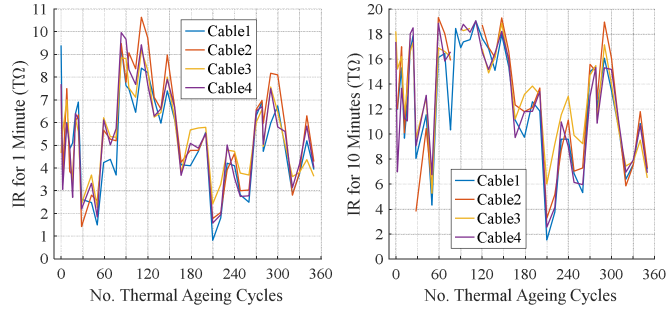
(a) (b)

Fig. 4. Temperature changes (ºC) in a 24-hour cycle measured at five positions along (a) cable surface and (b) conductor surface.

III. INSULATION PROPERTY MEASUREMENTS

A. *Insulation Resistance*

A Megger MIT1025 diagnostic IR tester [20] was used to measure IRs of cable samples after the application of 10 kV for 1 min and 10 mins, denoted by IR1 and IR10, respectively. The IR measurements after a particular thermal ageing cycle were performed at each cable for five times. Figs. 5(a) and 5(b) show the averages of IR1 and IR10 recorded over 350 cycles for the four XLPE cable samples respectively. The IR1 and IR10 both exhibit a U-shape variation in the first 90 cycles, followed by a relatively slow U-shape variation in the subsequent 210 cycles (i.e., from cycle 90 to cycle 300). This may be caused by the chemical components diffused from the semicon layers into the contacting insulation layers under the annealing effect [14]. Namely, the cumulation of chemical components at the initial heating stage promoted the hopping conduction in insulation, which reduced the total IRs. With the continuous application of thermal stress, the diffusion of chemical components from semicon layers was finished, and the chemical components cumulated in insulation began to be gradually exhausted, resulting in total IR growth [15]. Furthermore, the two consecutive U-shape changes show different variation rates, i.e., the former being relatively faster than the latter. This might be because the temperature gradient along the insulation radius (see Fig. 4) resulted in the diffusion and exhaustion of chemical components occurring at relatively higher rates in the innermost insulation layers which had higher temperatures. After cycle 300 at which the chemical components diffused into insulation layers may be almost fully exhausted, the IR degradation under the thermal ageing effect became dominant, as shown in Figs. 5(a) and 5(b). However, IR measurements after more thermal ageing cycles are required to validate the IR decline trend in the longer term. In addition, the cumulation and exhaustion of the chemical components within insulation as well as the diffusion depths during the accelerated thermal ageing experiment must be further examined to verify the explanation on the two consecutive U-shape IR variations.



(a) (b)

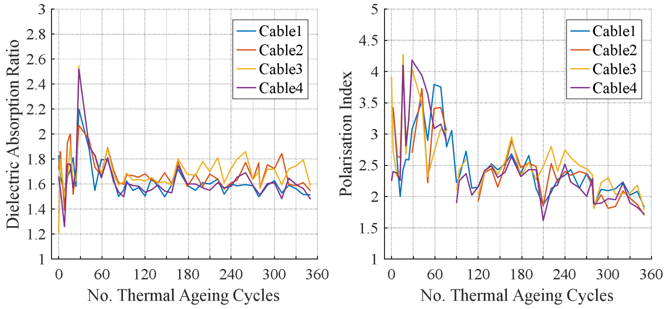
Fig. 5. The averages of (a) IR1 (TΩ) and (b) IR10 (TΩ) measured for the four cable samples during 350 thermal ageing cycles.

B. *Dielectric Absorption Rate and Polarisation Index*

In addition to IR values, the dielectric absorption ratio (DAR) and polarisation index (PI) were simultaneously measured by the Megger diagnostic IR tester. DAR and PI are traditionally defined by the ratio of IR1 to the 30-sec IR and the ratio of IR10 to IR1 [21], respectively, which indicate the slopes of an IR characteristic curve against the time of voltage application [8]. Insulation conditions can be assessed by the values of DAR and PI, as listed in Table II, for example, which must be considered tentative and relative subject to experience with time-IR methods over a period of time [21]. Fig. 6 shows the averages of DAR and PI measured on the four cable samples during the 350 cycles. The DAR and PI both exhibit great fluctuations over the first 90 cycles, which corresponds to the first U-shape IR variations. This might imply that the chemical components diffused from semicon into insulation has led to unstable DAR and PI. However, in the subsequent 210 cycles (from cycle 90 to cycle 300) which witnessed the second U-shape IR variations, even though there exist some relatively large fluctuations in PI, the DAR and PI are shown to be on average relatively stable. This highlights the need of checking the cumulation and exhaustion of chemical components within insulation to determine whether the second U-shape IR changes were caused by the relatively slower diffusion and exhaustion of chemical components at the outermost insulation layers.

TABLE II. INSULATION CONDITION INDICATED BY DAR AND PI [21]

Insulation Condition	DAR Value	PI Value
Dangerous	–	< 1
Questionable	1 – 1.25	1 – 2
Good	1.4 – 1.6	2 – 4
Excellent	> 1.6	> 4



(a) (b)

Fig. 6. The averages of (a) DAR and (b) PI recorded for the four cable samples during 350 thermal ageing cycles.

IV. CONCLUSIONS AND FUTURE WORK

Cross-linked polyethylene (XLPE) insulation of heavily loaded medium-voltage power cables can be subjected to thermal stress which changes the insulation properties such as insulation resistance (IR). To provide insights into XLPE IR variations of extruded power cables under thermal stresses, this paper has described an accelerated thermal ageing experiment performed on four XLPE insulated cable samples and presented yearlong IR measurements using the application of 10 kV for 1 min and 10 mins respectively. The corresponding DAR and PI were also measured.

The IRs of the cable samples have been observed to exhibit two consecutive U-shape variations, followed by a rough decay. The first U-shape IR variations over the first 90 24-hour ageing cycles may imply the cumulation and subsequent exhaustion of chemical components which were diffused from semicon into insulation and promoted hopping conduction in insulation. The variations of chemical components may have also affected the DAR and PI values which showed large fluctuations over the first 90 cycles. The second U-shape IR variations which had relatively slower rates of change were suspected to be caused by the different diffusion/exhaustion rates of chemical components at inner and outer insulation layers given the radial temperature gradient along the insulation radius. Further experimental work is required to measure the variations and diffusion depths of the chemical components in insulation over the annealing process and verify the explanation of the two consecutive U-shape IR variations. Furthermore, IR measurements after more thermal ageing cycles will be performed to validate a longer-term IR reduction under the thermal ageing effect after the two U-shape variations. Based on the specific IR variation pattern observed, the IR degradation model proposed in previous work [22] which estimates IR for the thermal ageing effect only will be extended to additionally consider the promotion of hopping conduction by chemical component diffusion under the annealing effect.

ACKNOWLEDGMENT

Part of this research was developed under the UK Engineering and Physical Sciences Research Council (EPSRC) grant EP-T001445-1.

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