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Artificial Accelerated Ageing Test of 22 kV XLPE Cable for Distribution System Applications in Thailand

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Abstract— This paper presents the experimental results on artificial ageing test of 22 kV XLPE cable for distribution system application in Thailand. XLPE insulating material of 22 kV cable was sliced to 60-70 μm in thick and was subjected to ac high voltage at 23°C, 60°C and 75°C. Testing voltage was constantly applied to the specimen until breakdown. Breakdown voltage and time to breakdown were used to evaluate life time of insulating material. Furthermore, the physical model by J. P. Crine for predicts life time of XLPE insulating material was adopted as life time model and was calculated in order to compare the experimental results. Acceptable life time results were obtained from Crine's model comparing with the experimental result. In addition, fourier transform infrared spectroscopy (FTIR) for chemical analysis and scanning electron microscope (SEM) for physical analysis were conducted on tested specimens.

Keywords— Artificial accelerated ageing test, XLPE cable, distribution system, insulating material, life time, life time model,

I. INTRODUCTION

Nowadays, underground high voltage (HV) cables are widely used for transmission and distribution networks. Cross-linked polyethylene (XLPE) is widely used for underground HV cables as an insulating material. XLPE has good electrical properties and can operation in high temperature. Although XLPE having good dielectric properties for high voltage applications, ageing of XLPE material can not avoidable after long time in service under various stress. XLPE insulated cable models for high voltage applications have been studied and investigated in order to evaluate a function of service stresses and ageing time. In order to improve dielectric performance of XLPE material, many researcher are studied improved XLPE properties [1] , such as increased thermal and mechanical properties [2], detected damage by water treeing in the cables [3], and studied multifactor aging proposed mathematical models based on experimental conditions of XLPE [4]. Several life models are purposed in order to evaluate a function of service stresses and aging time, such as the exponential model by Fallou [4], the inverse power law [4], the probabilistic model by Montanari [4],[5], and the physical model by Crine [4], [6].

In Thailand, voltage levels for distribution networks of Provincial Electricity Authority (PEA) of Thailand are 22 kV and 33 kV. Both overhead line and underground XLPE cables are usually used in PEA distribution networks. However, a function of service stresses and aging time of underground XLPE cable have been no studied. By this reason, accelerated ageing test have been conducted on 22 kV underground XLPE cable in order to elucidate a function of service stresses and aging time. In this paper, we were proposed the accelerated aging only electrical stress at room temperature. Furthermore, life time model purposed by Crine is adopted as the mathematical model to analyze the experimental results.

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II. INSULATION AGEING

Generally in services, an insulation system subjected to one or more stress that causes irreversible changes of insulating material properties with time, thus reducing progressively the attitude of insulation in enduring the stress itself. This process is called aging and ends when the insulation is no more able to withstand the applied stress. The relevant time is the time-to-failure or time-to-breakdown, alternatively called insulation life time [7]. Insulation life time modeling consists of looking for adequate relationships between insulation life time and the magnitude of the stress applied to it. In the case of electrical insulation, the stresses most commonly applied in service are electric field due to voltage and temperature due to loss, but also other stresses, such as mechanical stresses (bending, vibration) and environmental stresses (such as pollution, humidity) can be present.

III. AGEING MODELS

Although there are many models and theories proposed for aging of insulation but few are reliable, mainly because they are unable to describe all the interactions between the various parameters. The main goal of aging models is to establish a relationship for the aging process and the stresses causing it, and prove them. The models are done through an accelerated process. The most popular are experiments on insulation at voltages much higher than normal operating conditions of cables, at constant frequency. This paper adopted Crine's model for describe and prove the experimental results from accelerated aging test of XLPE insulating material.

A. Crine's Model

J. P. Crine et. al. have been purposed mathematical model to apply for predicts life time of XLPE insulating material [8]. Theoretical explanations are illustrated in [9]. This model proposed a simple physical model, is based on two parameters, the activation energy ΔG and activation volume ΔV (no adjustable constant), assumed electrical aging is a thermally activated process with an activation energy $\Delta G=\Delta H-T\Delta S$, where ΔH and ΔS are the activation enthalpy and entropy, respectively. It described the aging process of electrical insulation (XLPE) by reduces the height of the energy barrier controlling the process. When the time to go over barrier being the inverse of the rate. Time t will reach to aged state is given by

$$t = \left[\frac{h}{2fkT}\right] \cdot exp\left(\frac{\Delta G}{kT}\right) \cdot csch\left(\frac{1}{2} \cdot \frac{\varepsilon_0 \varepsilon' \Delta V F^2}{kT}\right) \quad (1)$$

This equation is well described aging results of XLPE by the linear relation at high fields. Considering predicts times at zero field in equation (1), t will be equal to infinity since *csch* (0) $=\infty$. Thus, there will be some sort of tail at low field, where t will slowly tend toward ∞. At high field, equation (1) can reduces to

$$t = \left[\frac{h}{2fkT}\right] \cdot exp\left[\frac{\Delta G - \frac{1}{2}\varepsilon_0 \varepsilon' \Delta V F^2}{kT}\right] \quad (2)$$

where

- $\varepsilon_0 =$ 8.85 × 10^{-12} F/m
- $\varepsilon' =$ relative permittivity of XLPE = 2.5
- h = Planck's constant = 6.626068 × 10^{-34} m^2.kg / s
- k = Boltzmann's constant = 1.3806503 × 10^{-23} m^2 kg s^{-2} K^{-1}
- F = Applied Voltage (kV)
- T = Temperature (K)
- f = Frequency (Hz)

As illustrated in equation (2), the activation energy, ΔG, and the activation volume, ΔV, are unknown variable. However, ΔG and ΔV can directly obtain from the experimental results in a linear relationship between F^2 and log t. In order to find such linear relationship, logarithm function is applied to the both side of equation (2), as illustrated in equation (3).

$$log(t) = log\left[\frac{h}{2fkT}\right] + log\left[exp\left(\frac{\Delta G - (1/2)\varepsilon_0 \varepsilon' \Delta V F^2}{kT}\right)\right] \quad (3)$$

By arrangement equation (3), equation (4) is obtained.

$$\begin{aligned} log(t) &= log\left[\frac{h}{2fkT}\right] + log\left[exp\left(\frac{\Delta G}{kT}\right)\right] \\ &+ log\left[exp\left(-\frac{\varepsilon_0 \varepsilon' \Delta V F^2}{2kT} \cdot F^2\right)\right] \end{aligned} \quad (4)$$

Finally, equation (5) is obtained.

$$log(t) = \left[log\left(\frac{h}{2fkT}\right) + \left(\frac{\Delta G}{kT}\right)\right] + \left(-\frac{\varepsilon_0 \varepsilon' \Delta V}{2kT} \cdot F^2\right) \quad (5)$$

Empirical form of equation (5) is $y = -ax+b$, where a is slope and b is intercept. Considering the experimental data, ΔG can obtain from slope at the high filed regime and ΔV can obtain from the intercept. Both parameters depend on size of the specimen.

IV. ACCELERATED AGEING

The accelerated aging is degrading stresses of insulation material, such as electrical stress, thermal stress, mechanical stress, and environmental stress. The accelerated aging process usually studies multi-stresses [4] (double or triple stresses). The multi-stresses widely used electrical - thermal stress and electrical – mechanical stress.

There are several methods to accelerate the aging process [4], [10-11]. But the most popular are experimental performed on insulation material at voltages and temperatures higher than normal operating conditions, there are two methods of apply voltage stress. The first method, the voltage is held constant until sample aged and breakdown. In the second method, the voltage stress is increased in steps until sample aged and breakdown. For both, when breakdown occurred are noted experimental data lifetimes for calculation life models. In our experimental, the first method (constant voltage stress) was conducted.

V. EXPERIMENTAL

The specimens for experimental made from unaged 22 kV XLPE distribution power cables having aluminum conductors 17 mm in diameter and XLPE insulation 3 mm thick, as shown in Fig. 1. This type of power cable is used in underground distribution system of Provincial Electricity Authority (PEA) of Thailand. A number XLPE of 1-cm wide ribbons at thickness 60-70µm were cut by a microtome from the insulation around a cables. All specimens were measured precisely before testing so the thickness effect is neglected. The accelerated aging test chamber consists of a pair of solid stainless cylinders, the lower grounded one is 30 mm in diameter and the upper-high voltage electrode is 10 mm in diameter, which was connected to a 50 Hz testing transformer.

Furthermore, heater and temperature sensor are included for heat generation and temperature control. Afterwards placing the specimen between the electrodes, the electrodes were immersed in transformer oil in order to avoid surface flashover in air. Detail of the test chamber is illustrated in Fig. 2. The experimental diagram is shown in Fig. 3 and experimental layout is shown in Fig. 4

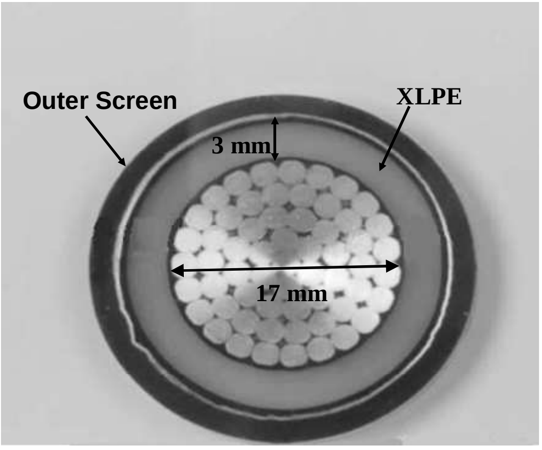

Fig. 1 22kV cables section schematic.

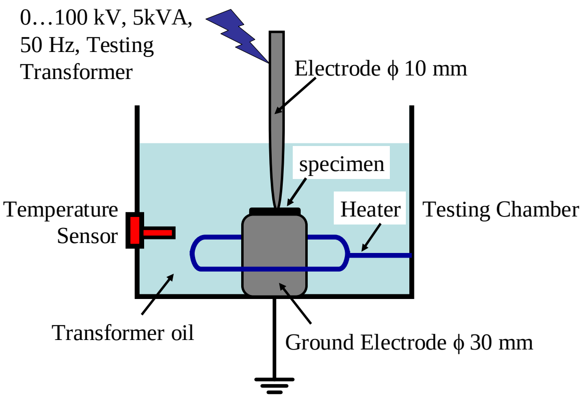

Fig. 2. Accelerated Ageing Test Chamber

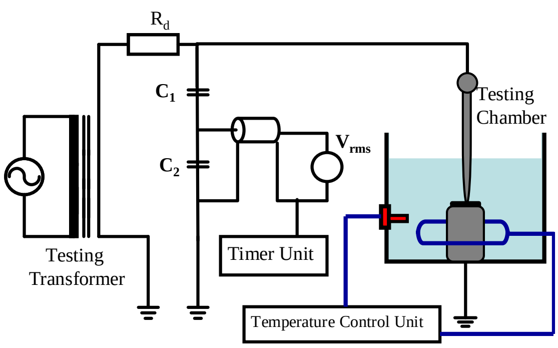

Fig. 3 Experimental Diagram

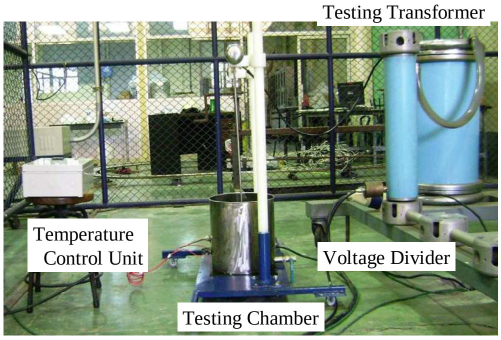

Fig. 4 Experimental Layout

As illustrated in Fig. 3, timer unit was used to measure time to breakdown of the specimen. At moment of the electrical and thermal stresses applying to the specimen, timer unit starts record the life time or breakdown time. Once the breakdown occurs, the relay trips automatically and the timer stops. Then, the breakdown time is recorded for analysis. For each breakdown voltage level, five specimens were tested. Once the tests were complete for a data set, the data points were averaged to obtain one data point.

The Experimental were conducted at temperatures 23˚C, 60 ˚C and 75 ˚C. In addition, the specimens were tested under different electrical stress levels varying from 75kV/mm to 130kV/mm, as shown in Table I.

TABLE I ELECTRICAL STRESS LEVELS FOR THE EXPERIMENTAL

E (kV/mm)	Experimental Results (sec) 23 ˚C	60 ˚C	75 ˚C
75	X	X	O
90	O	O	O
100	O	O	O
110	O	O	X
120	O	O	X
130	O	X	X

O : Tested level X : Un - tested level

VI. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental were carefully conducted in order to obtain the precisely results. Experimental results, time to failure or time to breakdown of the specimen, are illustrated in Table II.

TABLE II TIME TO FAUILURE OF XLPE INSULATING MATERIAL

E (kV/mm)	Experimental Results (sec) 23 ˚C	60 ˚C	75 ˚C
75	-	-	1373.5
90	25,200	5973.7	400.8
100	3,120	778.2	12
110	476	81.8	-
120	61.5	6.9	-
130	8	-	-

For ΔV and ΔG calculation, the results at temperatures 23 ˚C, 60˚C and 75˚C form accelerated aging test in Table II are plotted in semi-logarithm graph. Then a linear relationship between F^2 and log *t* is obtained by using linear fitting technique, as shown in Fig. 5, Fig. 6 and Fig. 7, respectively.

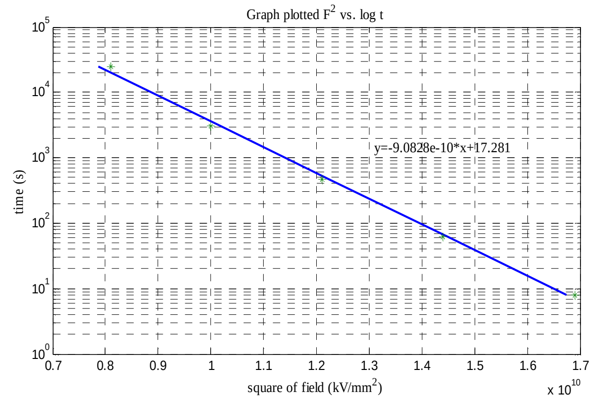

Fig. 5 A Linear Relationship Between F^2 and log *t* at 23˚C

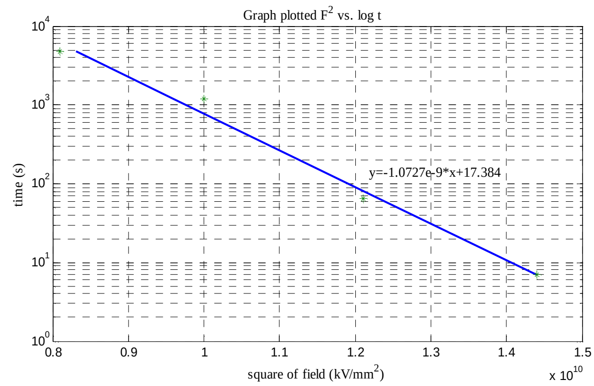

Fig. 6 A Linear Relationship Between F^2 and log *t* at 60˚C

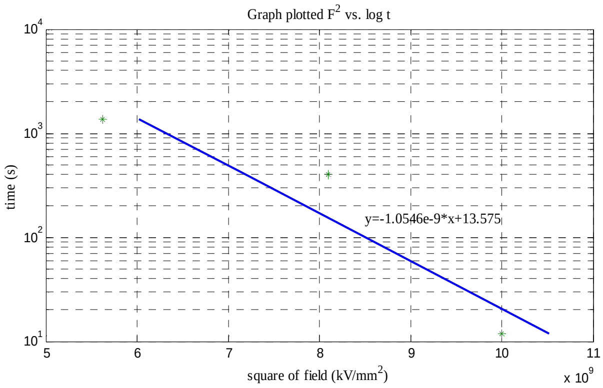

Fig. 7 A Linear Relationship Between F^2 and log *t* at 75˚C

From a straight line of relationship between F^2 and log *t*, ΔV and ΔG are determined according to equation (5) and are illustrated in Table III.

TABLE III PARAMETERS OF CRINE'S MODEL

Parameters	Experimental Results (sec)		
	23 ˚C	60 ˚C	75 ˚C
Δ V[m^3]	3.26×10^{-25}	$4.4560e^{-25}$	$4.5782e^{-25}$
Δ G [J]	2.09×10^{-19}	$2.3692e^{-19}$	$2.2952e^{-19}$

Finally, Crine's models from the experimental results are obtained according to equation (2). By the obtaining Crine's model, life time of XLPE insulating material can be calculated. The calculation results are shown in Table IV. Acceptable results are obtained.

TABLE IV LIFE TIME RESULTS FROM CRINE'S MODEL

E kV/mm	Crine's Model Results		
	23 ˚C	60 ˚C	75 ˚C
75	-	-	2085.7
90	18,944	4780	153.4
100	3,533	1200	20.7
110	552	65.5	-
120	72	7	-
130	8	-	-

In order to confirm the precisely of Crine's model, life times from the experimental and from Crine's model are plotted together in semi-logarithm graph, as shown in Fig. 8, Fig. 9 and Fig. 10, respectively.

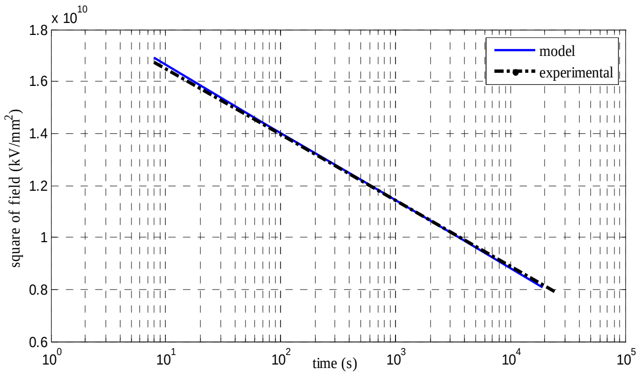

Fig. 8 Comparison Life Time from Experimental and Crine's Model at 23˚C

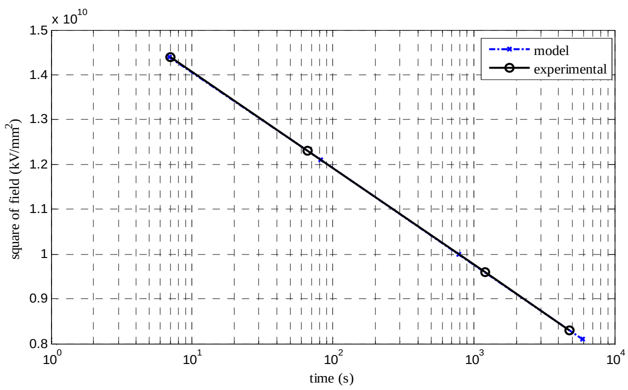

Fig. 9 Comparison Life Time from Experimental and Crine's Model at 60˚C

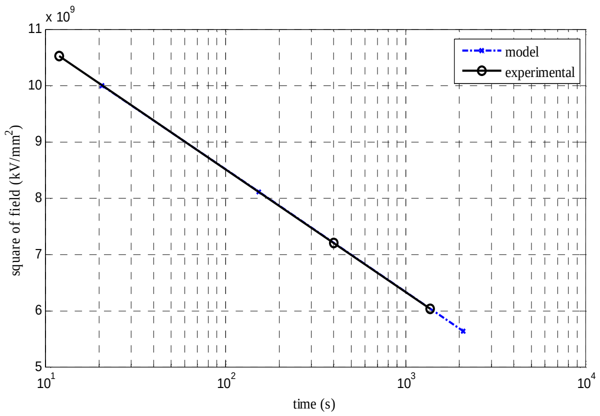

Fig. 10 Comparison Life Time from Experimental and Crine's Model at 75°C

In order to observe physical damage, tested specimen surface observation by using the scanning electron microscope, SEM, was performed. Example of SEM observation results are shown in Fig. 11 and Fig. 12. Carbon from carbonization was observed at the damaged point.

Chemical analysis was performed by the Fourier transform infrared spectroscopy (FTIR) for un-aged and aged specimens. Furthermore, SEM observation results agree with chemical analysis results. For XLPE insulating material, C=C peaks at 1610 cm^{-1} appeared for aged specimen [12]. As illustrated in Fig. 13 for unaged specimen and Fig. 14 for aged specimen at 23°C, C=C peaks at 1610 cm^{-1} is only observed on FTIR result of aged specimen comparing with unaged specimen. Appearing of C=C peaks at 1610 cm^{-1} confirmed carbonization process due to ageing process.

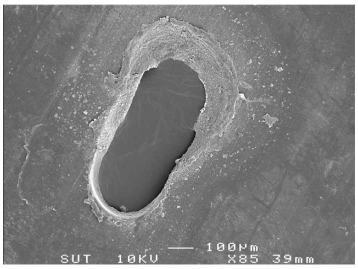

Fig. 11. Surface Damaged due to Electric stress 140kV/mm (1 s) at 23°C

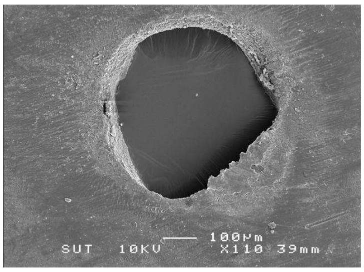

Fig. 12. Surface Damaged due to Electric stress 140kV/mm (30hours) at 23°C

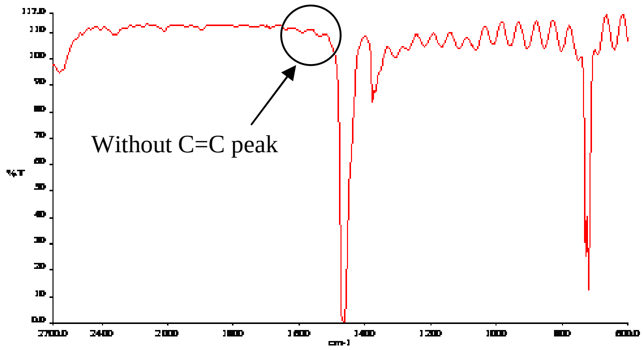

Fig. 13 Chemical Analysis by FTIR for Unaged Specimen

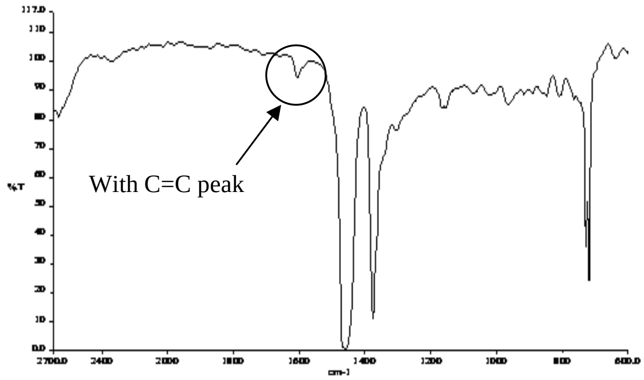

Fig. 14 Chemical Analysis by FTIR for Aged Specimen

After well conducting the experimental and carefully analysis the experimental results, very acceptable results in life time from Crine's model were obtained when comparing with the experimental data. However, accuracy of the experimental results depends on the precisely thickness of specimen, voltage stress stabilization and accuracy of temperature control unit.

VII. CONCLUSION

Accelerated aging test of XLPE insulating material from 22kV high voltage cable was conducted. Three temperature levels, 23°C, 60°C and 75°C, and electrical stress between 75 - 140 kV/mm are testing conditions. Electrical stress and time to breakdown were used to evaluate life time of insulating material. Crine's model parameters, ΔV and ΔG values, were obtained from a linear relationship between F^2 and log t. Life time can be reasonable well predicted by Crine's model for given electrical stress and temperature. Acceptable lift time results can be obtained when using Crine's model for calculation. Furthermore, lift time result from Crine's model agree with the experimental data. Physical observation by using SEM and chemical analysis by using FTIR supported the experimental results, as well.

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