# STATISTICAL APPROACH FOR PREDICTING REMAINING LIFE OF CROSSLINKED POLYETHYLENE INSULATED CABLES

A Thesis by

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I have examined the final copy of this Thesis for form and content and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science, with a major in Electrical Engineering.

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Dr. Ward Jewell, Committee Chair

We have read this thesis
And recommend its acceptance:

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Dr. Asrat Teshome, Committee Member

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Dr. Gamal Weheba, Committee Member

# DEDICATION

*To my parents and my family*

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# ABSTRACT

This study focuses on developing new remaining life model of the Cross linked polyethylene (XLPE) insulated medium voltage cables that are in use for hot and dry climate. Cross linked polyethylene insulating material degrades under the service condition acted upon by thermal and electrical stresses. Degradation of the materials is quantified by two main parameters Fourier Transform Infrared (FTIR) value and strength to withstand the electrical breakdown voltage. These parametric changes obtained by accelerated aging procedure developed with the help of Arrhenius Equation are tested for significance with that found in field aged cable with the help of statistical tools. Anderson-darling test for normality, Analysis of Variance (ANOVA), and one and two sample t- test were used to validate the lab aging procedure with field aging.

New aging model, based on two parameters, Fourier Transform Infra Red (FTIR) spectrum value and Electric Breakdown voltage (EBV), was developed to quantify the current equivalent age of the cable and hence remaining life of the cable. The model is validated for different field aged cables in this study.

# TABLE OF CONTENTS

## CHAPTERS

APPENDICES

# LIST OF TABLES

# LIST OF FIGURES

FIGURE PAGE

# LIST OF ABBREVIATIONS

| | |
|---|---|
| XLPE | Cross- Link Polyethylene |
| FTIR | Fourier Transformed Infrared Spectrum |
| PE | Polyethylene |
| HMWPE | High Molecular Weight Polyethylene |
| TRXLPE | Tree Retardant Cross Linked Polyethylene |
| HDPE | High Density Polyethylene |
| LDPE | Low Density Polyethylene |
| EPR | Ethylene-Propylene-Rubber |
| EVA | Ethylene Vinyl Acetate |
| PD | Partial Discharge |
| ACLT | Accelerated Cable Life Test |
| MCT | Mercury Cadmium Telluride |
| ANOVA | Analysis of Variance |
| DF | Degree of Freedom |
| SE | Standard Error |
| EBV | Electrical Breakdown Voltage |
| SSTO | Total Sum of Square |
| SSTR | Sum of Square due to Treatment |
| SSE | Sum of Square due to Error |
| MS | Mean Sum of Square |
| SD | Standard Deviation |

| | |
|---|---|
| OLS | Ordinary Least Square |
| SSR | Sum of Squared Residual |

## Chapter 1

# Introduction

### 1.1 Overview

Underground transmission and distribution has become a very popular method of transporting electric power, especially in large cities. This popularity can be attributed to the desire to preserve the landscape, and in some cases to ease the public's fear of harmful electric fields produced by overhead transmission lines. Although underground transmission and distribution is popular, there is a limit as to how much cable can actually be installed due to its high cost. Costs for underground transmission can range anywhere from 8 to 18 times that of overhead transmission costs [1].

Besides the cost, maintaining a stable underground transmission system can be very difficult compared to maintaining an overhead transmission system. The reason for this difficulty is the fact that many more parameters must be considered when analyzing and designing an underground system. A few of these parameters include the thermal aspects of underground cable, and the excess capacitance produced by a cable.

Thermally, underground cable is different from overhead transmission due to the fact that overhead transmission can dissipate heat into the atmosphere. Dissipation of heat in underground cable is more complex due to the fact that the thermal aspects of a cable depend on more parameters such as cable type, and soil type. The thermal aspects of a cable are necessary to consider because the current-carrying capacity of a cable depends on the thermal conditions of its environment. If the thermal conditions of a cable are not understood, faults are almost certain to occur.

Due to the extensive cost of underground transmission, it is important to attempt to prevent a fault or failure from occurring. Although preventing every fault on a system from taking place is impossible, several faults can be prevented simply by learning from past failures.

## 1.2 History of Power Cables

The use of power cable is assumed to be started back in 1880, with the start of incandescent lighting. The growth rate of urban electrification was too high to accommodate the number and size of the feeders required for distribution using overhead lines. The overhead line system was not only considered technically and aesthetically inadequate, but also it was assumed to pose safety hazards. For these reasons, underground electrification technology was introduced by the early 1890's [2]. Early overhead cables consisted of copper conductors insulated from the ground by porcelain and/or glass insulators. Natural rubber, gutta-percha, oil and wax, rosin and asphalt, jute, hemp, and cotton were the other solid and liquid materials used as the insulation in underground installations. Oil impregnated paper power insulation, of the three-conductor belted type, was used prior to World War I for voltages up to 25kV. The cables were highly susceptible to partial discharge due to the non-uniform stress distribution in the cable construction. This drawback was eliminated by introducing a low-viscosity oil-impregnated-paper insulating system. The formation of cavities (and hence the initiation of partial discharge) was avoided by maintaining the pressure on the insulating oil slightly above the atmospheric pressure.

The first oil filled pipe-type power cable was installed in North America during 1932 [3]. It proved to be so competitive economically that by about 1954 the total circuit mileage of installed pipe type power cable surpassed that of the self-contained oil-filled cable in the United States. Another advantage of using pipe-type power cable is that it eliminates problem due to metallic sheath voltage rise or sheath losses. The operating voltages of these pipe-type cables continuously increased over first few decades. In 1956 the first 230kV pipe-type cables were installed, and a 345kV cable was installed in 1964.

Forced cooling methods may be applied to remove heat generated in the cable and hence the load carrying capacity of these cables can be increased. However, it cannot cope with the increased dielectric losses in oil-impregnated paper. Hence composite paper-polypropylene-paper tapes were introduced, which have lower dielectric losses, in the 1980's. The dielectric loss and dielectric constant of this combination may be decreased by increasing in proportion the thickness of the polypropylene tape with respect to that of the two Kraft paper tapes [4].

Although hydrocarbon thermoplastic polyethylene (PE) had been invented in England in 1933, it took a substantial time to introduce it as an insulating material in power cables. The first solid polyethylene extruded power distribution cables were introduced in the 1950's. Initially plastic cables using low density high-molecular-weight polyethylene (HMWPE) were used for 35kV distribution voltage, and sometimes higher, until 1951 [5].

In 1952 a new type of plastic was produced with new properties and names such as cross linked polyethylene (XLPE). Commencing with 1964, a changeover began toward the deployment of XLPE, which provides an equivalent ampacity increase of 12% over an HMWPE insulated cable [6]. Initial research work on XLPE was carried out in Norway, Japan, Sweden and the United States and the cable was used primarily in short sections without joints. Tree retardant cross linked polyethylene (TRXLPE) was introduced to control water treeing in 1980.

## 1.3 Types of Insulating Materials

Thermoplastic (linear) polyethylene was the first material to be used for an extruded type of insulation, followed by high density polyethylene (HDPE), XLPE and finally Ethylene-propylene-rubber (EPR). XLPE and EPR have higher operating voltages compared to LDPE and HDPE cables. However EPR is not used for higher voltage cables, as it has higher voltage dielectric loss as compared to XLPE cables. Table 1.1 shows the dielectric constant, dissipation factor, thermal resistivity and operating temperature for different insulating materials.

| **Materials** | **Dielectric Constants** | **Dissipation Factor** | **Thermal Resistivity** | **Operating Temperature** |
|---|---|---|---|---|
| LDPE | 2.3 | 0.01 | 3.5 | 70 |
| HDPE | 2.3 | 0.01 | 3.5 | 80 |
| XLPE | 2.5 | 0.01 | 3.5 | 90 |
| EPR | 3.0 | 0.5 | 5.0 | 90 |
| Oil-paper | 3.5 | 0.3 | 5.0 | 85 |

**Table 1.1 Properties of insulating materials.**

XLPE, which is extruded within the temperature range of 116$^{o}$C to 132$^{o}$C is produced by compounding polyethylene with a radical at 240$^{o}$-260$^{o}$F. Vulcanized or cross linked materials are formed by the reaction of ethylene radicals in the polyethylene molecules with each other. The process causes polyethylene to change over from thermoplastic to thermosetting material, with a significant improvement in physical and electrical properties. A small amount of block carbon is added to increase the mechanical strength as well as to protect the XLPE against ultraviolet radiation during the process [7].

Dodecanol ($CH_{12}H_{25}OH$) is used in HMWPE as a tree inhibitor, the effectiveness of which was found to diminish with time. Ethylene vinyl acetate (EVA) was used as a tree retardant but has the same drawback under high voltage. In 1983, a tree-inhibiting compound commonly known to be polar was made available by Union Carbide as an additive in their XLPE compounds. The introduction of the polar tree-retardant additive into the XLPE compound augments the dielectric loss significantly.

The addition of a polar tree retardant to XLPE diminishes greatly the number and size of bow tie water trees when the current state of the art semi-conducting shields are employed; however the effect on vented-type water trees is essentially insignificant [8].

## 1.4 Problem Identification

This report concentrates on the condition assessment of the thousands of miles of cable installed in the dry regions of North America. Periodic cable maintenance and repairs are necessary in order to maintain the reliability of service.  Older cables may be prone to impurities and moisture if there were no controls/specifications on the cleanliness of the materials used for the insulation and semi-conducting shields. The condition of the older cables is unknown at this stage. With service life exceeding 20 years of an anticipated 30 years of useful life, it is reasonable to expect that the cables will exhibit deterioration in insulation properties. But is the deterioration significant? Should all of the older cables be replaced with new cables? Is there any evidence to suggest that 20 years is positively the useful life? This research project is undertaken to answer these very important questions.

Utilities allocate a certain amount for cable replacement on an annual basis. It makes sense to replace those cables that are near to the end of life immediately, and to defer replacement of other cables that are not in imminent danger of failing. Therefore, a scientifically sound method of prioritizing cable replacement is required. This project is undertaken with the aim of developing a methodology that helps maintenance personnel prioritize cable replacement. Aging of XLPE insulated distribution cable was developed in [9]. One parameter, electrical breakdown voltage, is more sensitive for age less than 10 years than that for the age greater than 10 years whereas, the FTIR value is more sensitive to for age more than 10 years. It was necessary to develop a model which deals with such situation and gives better idea about the remaining life of the cable and the maintenance personnel can prioritize the cable to be replaced.

## 1.5 Thesis Organization

The thesis is organized as follows. Chapter 2 presents the overview of the failure modes of XLPE cable with mechanisms of formation of different kinds of trees in the insulating materials. Chapter 3 describes the necessity of accelerated aging in the lab, the accelerated aging procedures, and observation of the changes in cable parameters in the lab. In chapter 4 data observed in the lab are subjected to statistical analyses, with the goal of correlating the parametric changes in lab aging results with those of field age samples. Chapter 5 describes a new multivariate aging model and its validation. Finally chapter 6 presents conclusions and recommendations for future work that can be carried out to further improve the aging model.

## Chapter 2

# Failure Modes of XLPE Insulated Cable

### 2.1 Introduction

Cables are subject to failure mainly due to factors like punctures due to rocks and bad splicing. Some failures are due to overheating as the result of overloading. Sometimes failures are caused by digging of the cable mistakenly. Large portion of insulation of cable failure are caused by mechanical or connector fault. Apart from these, the main cause of cable failure is the formation of a tree-like structure due to partial discharge within the material. Although around 90% of the failure are caused by mechanical or connector fault, treeing is also acknowledged as the major cause of potential failure.

### 2.2 Treeing Phenomena

Electrical treeing degradation has history as the development of paper/ oil insulation system. It has been observed in organic as well as polymeric materials and hence there must be some mechanism of development of the tree which is independent of the chemical nature of the material. Water tree was recognized during early 1970s, [10], and hence another cause of premature failure in polymeric insulating material was known.

A cable tree has been defined as 'latent damage in the insulation that consists of microscopic channels formed by partial breakdown of defective or overstressed region' and 'hollow tubes with non-conducting walls and containing the gaseous products of discharge' [11]. A tree is an electrical pre-breakdown phenomenon in the insulation of a cable. The term is used to describe the type of damage that progresses through a dielectric section under electrical stress, which resembles the form of a tree.

Trees are classified based on different criteria such as shape, location of origination, and other characteristics. Based on shape, trees can be classified as Broccoli, Strings, Delta, Bow tie, Plumes, Dendrites, Spikes and Fans. Trees can be classified as two major classes: electrical (dry) trees and water (wet) trees. This is a common classification of trees.

Electrical trees can be characterized as consisting of a hollow channel resulting from the decomposition of material, clearly visible in translucent or transparent solid dielectrics when examined with an optical microscope and transmitted light. A water tree is characterized not by permanent hollow channels, but by very fine filamentary paths between small cavities through which moisture has penetrated under the action of a voltage gradient.

### 2.2.1 Water (Wet) Tree

Penetration of moisture is highly affected by the presence of electric field. Water trees initiate at a point of electric stress and grow parallel to the electric field lines. The growth of a water tree causes a reduction of the effective insulation thickness below the point that is required to withstand the electric stress, after which electrical tree causes the cable to fail.

It was observed that the growth rate of wet trees increases with the conductivity of water [12]. Thus the presence of conductive water and voltage stress are the fundamental requirements for the initiation and growth of water trees. However aging time, material nature, contaminants, operating temperature, and cable design are also factors affecting the initiation and growth of water trees.

### 2.2.2 Electrical (Dry) Tree

An electrical (dry) tree is also found to grow in a region of high electrical stress, such as metallic asperities, conducting contaminants, and structural irregularities. Partial discharge in voids can also generate degradation structures from the void surface. Those trees, which are initiated at electrode, are termed as vented trees. An electrical tree has three phases. First is the initiation phase, second is the growth or propagation phase, and third is the breakdown phase. No partial discharge occurs during the initial phase. During the propagation phase the tree propagates by continuous partial discharge activity, and cable insulation fails during breakdown phase.

#### *Initiation of Electrical Tree*

The electrical stress produced at a stress concentration site such as metallic asperities, conducting contaminations, and structural irregularities in the insulation become significantly large to initiate partial discharge in a very small cavity located near the tip. Breakdown of gas occurs within the cavity with the help of initiatory electrons [13]. These electrons are provided by natural radiation in the case of large sized cavities, whereas natural radiation along with the variation in the density and size distributions of the cavities will provide a large number of these electrons in small size cavities. The partial discharge will produce a rapid erosion of the insulation, producing discharge channels, which terminate at the needle tip and result in a visible electrical tree.

Laboratory tests with the needles in solids deny the requirement of the presence of an initial void to start a tree [14]. Electrical stress concentration, produced on rough or sharp edges of electrodes, and also on sharp edges of conducting contaminant particles, and high and divergent electric fields, is always necessary to initiate an electrical tree.

### *Growth of Electrical Tree*

The growth mechanism of electrical trees can be described as an array of fine erosion channels formed through a partial discharge (PD) activity within the evolving tree structure starting at the void or the tip of the needle [13]. Partial discharge causes the decomposition of insulation to gases. Various researches prove that the voltage stress at the tip of an electrical discharge depends on the characteristics of the gas formed, which depends on the material and local temperature produced by the discharge, rather than on the shape of the electrodes that originated it.

Chemically the growth of an electrical tree can be described as the transfer of energy between ions and surrounding walls when the gas formed in a cavity is ionized to form plasma. An electron avalanche is formed in some conditions, which enhances the effect further [15].

As the purpose of this study is to study the failure of XLPE cable across dry regions, water treeing is not the focus. This research work concentrates on modeling the aging procedure caused due to the growth of an electrical tree. Lab methods have been developed to age the cable in hot and dry conditions and to analyze the structural changes and changes in the electrical breakdown strength of the cable [25]. Data collected previously using these methods is used in this thesis to develop a multivariate analysis technique is developed in this thesis to predict the remaining life of a cable.

# Chapter 3

# Accelerated Aging

## 3.1 Introduction

As the cable insulation degrades with the age of the cable, it is necessary to know how long will it take for the insulation to age before failure occurs. It is important to know the length of life of the insulation under the stress and factors affecting it during operation of the cable. For testing, it is difficult to obtain cable samples from cables in the field. Thus aging methods have been developed to simulate the environment and stresses cables experience during operation, to produce samples of a certain equivalent age. In laboratory aging, the cable insulating materials are subjected to the electrical, mechanical, and thermal stresses that they encounter in service.

Aging the cables under normal operating conditions would take too long, hence accelerated aging methods are applied. Accelerated aging should be of as short duration as possible while inducing aging mechanisms identical to those the cables experience in field conditions. This requires the application of stresses that are higher than the normal values experienced by the cable during field operating conditions.

Several methods are in use to provide the elevated stress for accelerated aging of the cable. Most accelerated aging tests are performed by subjecting the test specimens to an elevated stresses for a fixed time period during which the insulating materials rapidly degrade to some level which can be compared to the properties of cable insulation attained over much longer periods in actual operating conditions. Initial aging tests were designed and performed with dry conditions, but water was recognized as the source of water trees in XLPE during 1970s [17]. Since then, accelerated aging has been developed to also form water trees in XLPE insulation.

## 3.2 Design of Accelerated Aging in Wet Condition:

One kind of wet aging test is the accelerated water treeing test in which the cables are aged in water filled pipes for 4, 6,and 12 months, then subjected to a step ac breakdown test. The alternate method is to age cables in water filled tanks either for a fixed time or to failure. This is called an accelerated cable life test (ACLT) [19].

Before ACLT aging begins, a partial discharge test is performed to ensure that the cable and terminals are discharge-free prior to aging. The test is carried out according to the AEIC CS-94 and AEIC CS6-96[20].

Aging is usually carried out in a rectangular shaped tank, but other shapes such as cylindrical are also used. Tanks used are large enough to accommodate at least 10 cable specimens, or a single cable equivalent to 10 specimens, plus control cables. The inner tank surface, the specimen mounts, and any other materials making contact with the tank are made of inert materials which will not corrode in the presence of water and will not form any electrolytic cell with any component in the cable samples.

### 3.2.1 Aging Test Parameters:

*Temperature*: Temperature plays a very significant role as an aging parameter for cables in tank–type testing. To produce the cable temperature required for accelerated aging, current is induced in the conductor through a current transformer. Heating may be cyclic or continuous. A current heating cycle of daily 8 h on, 16 h off, seven days a week is the most common practice. Maximum conductor temperatures of ambient to 90°C have been used in tests. Care should be taken not to overheat the sample. No portion of an active test sample conductor should exceed 100°C.

*Water*: Water is other primary test parameters in tank-type testing since moisture in the insulation causes the formation of water trees, which are the measure of cable aging. So it is important to maintain uniform water quality. It is preferred that the water in the tank be deionized with a resistivity not less than 1000 Ω.m. Since water quality can be affected by various factors during the experiments, water in the tank should be changed totally or partially when the resistivity is less than 250 Ω.m.

*Voltage*: Voltage stress is another critical parameter in the aging process and is important for water tree growth. Water tree initiation and growth is a function of localized electric stresses. Voltage level, stability, and quality are all important parameters that must be regulated and recorded. Voltage stress is supplied between the cable conductor and the metal shield or neutral wire of the system. The voltage level should be controlled within + 5 % and be free from substantial harmonics. The average voltage stress is usually between 2kV/mm and 8kV/mm. Frequency of the voltage is usually either 50 or 60 Hz. Voltage surges are produced in order to include the effect of lightning impulses and switching surges that occur during the service life of the cables.

*Test Matrix*: Two of the most significant parameters of the ACLT tests are the conductor temperature in the water and voltage stress. A standard matrix, described in [19] is commonly used which shows the test voltages and conductor temperatures. This allows a comparison between test results developed at two laboratories.

Failure: Failure is another critical parameter for the evaluation of aging. It is important to find the position, time under voltage, and number of current cycles at the time of failure.

Evaluation: The evaluation techniques that are commonly used in ACLT tests are time to failure and fixed time of aging, followed by dielectric strength and truncated population time to failure, with ac dielectric strength recorded on remaining samples.

### 3.3 Design of Accelerated Aging Test in Dry Condition:

This testing procedure is designed to evaluate the performance of the insulation of low and medium voltage XLPE cables being used in regions where water treeing is considered not to be the problem.

In the case of XLPE insulation, higher temperatures enhance not only the chemical reaction rate but also the degree of other thermally activated processes. At temperatures greater than $90^{o}$C, the crystalline regions melt and further oxidation occurs. It is well established that both the 60Hz and impulse breakdown strengths diminish with temperature. But this phenomenon is partly determined by hardness of the polymers, and is independent of the oxidation level. For XLPE at $90^{o}$C, the ac and impulse breakdown values are reduced by 6 and 19% respectively from those at room temperature, with further respective reductions of 18 and 48% at $115^{o}$C [21]. This illustrates that in the case of XLPE, the parameters which are independent of oxidation level maintain their functionality even at higher than melting ($90^{o}$C) temperatures.

### 3.3.1 Aging Test Parameters

The age of a cable can be estimated by using the well-known Arrhenius equation. This equation relates aging time and temperature with degradation of material. This model is preferred because it has been verified for many materials. It estimates the time to reach the end point of the material’s life by the equation

$$L = B \times e^{\frac{\phi}{kT}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.1$$

Where,

$L$ = Time to reach a specified endpoint or lifetime (h)

$B$ = Constant (usually determined experimentally for each material

$\phi$ = Activation energy (eV)

$k$ = Boltzman’s constant (0.8617 x $10^{-4}$ eV/K)

$T$ = Absolute temperature (K)

Let $t_a$ be the time that a material is heated with temperature $T_a$, and $t_s$ be the life of the material in service at temperature $T_s$ then,

$$t_a = B \times e^{\frac{\phi}{kT_a}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.2$$

and,

$$t_s = B \times e^{\frac{\phi}{kT_s}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.3$$

Dividing equation 3.3 by 3.2 we get

$$\frac{t_s}{t_a} = B \times e^{\frac{\phi}{kT_s} - \frac{\phi}{kT_a}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.4$$

Taking the natural log both sides results in

$$\ln\left(\frac{t_s}{t_a}\right)=\frac{\phi}{k}\times\left(\frac{1}{T_s}-\frac{1}{T_a}\right) \quad \text{……………………………………………3.5}$$

Since the temperature of the cables vary with the load, equivalent time spent ($t_0$) at various temperatures was calculated after selecting one reference temperature ($T_0$) using the equation

$$t_0=t_1\times e^{\left(\frac{1}{T_0}-\frac{1}{T_1}\right)\times\frac{\phi}{k}} \quad \text{……………………………………………3.6}$$

Once the total equivalent time ($t_0$) at an arbitrary reference temperature ($T_0$) is established, the aging time of the cable is set to one week for 5, 10 and 20 years equivalent, and two weeks for 20 years equivalent old. The temperature that is required to maintain for the cable for the duration $t_s$ can then be found by using the equation [24].

$$T_a=\left(\frac{1}{T_0}-\frac{k}{\phi}\times\ln\left(\frac{t_0}{t_s}\right)\right)^{-1} \quad \text{……………………………………………3.7}$$

$T_a$ calculated from equation 3.7 is the in Kelvin.

### 3.4 Lab Aging Procedures

To simulate field aged conditions, cables were obtained that had been removed from service in the field, as well as new cables from two different manufacturers. The outer jackets and armoring were removed and the cables were cut into samples of 30 cm length. A gravity convection oven was used for thermal aging of the new cables. Different temperature cycles were used to obtain effects as close as possible to field aging. It was assumed that the cables experience three different temperatures, 60°C, 80°C and 100$^{o}$C during operations in their life. It was assumed that for 50% of the life of field aged cables, they are operated at 80$^{o}$C, and 25% each at 60$^{o}$C and 100$^{o}$C [24].

Based on these assumptions, temperatures of the lab aging procedure were determined and duration of the aging time was calculated using the Arrhenius Equation. Table 3.1 shows the temperatures and durations used to age the cable for specific age [24].

| **S.N** | **Age in years** | **Temperature ($^{o}$C)** | **Time (hr)** |
|---|---|---|---|
| 1 | 5 | 155.25 | 168 ( 1 week) |
| 2 | 10 | 163.58 | 168 ( 1 week) |
| 3 | 15 | 168.97 | 168 ( 1 week) |
| 4 | 20 | 163.58 | 336 ( 2 weeks) |

**Table 3.1 Simulation of aging in lab**

### 3.4.1 Testing of the Aged Cables

To eliminate any block effect in the experiment, a randomized block design is adopted during the experiments. Two samples were used in each experiment based on the randomized block design to increase the confidence of the experiment.

#### *FTIR Spectrum Analysis*

Structural changes in the cable samples before and after aging were observed. The FTIR technique has proven to be useful for such studies. A Nicolet 205 FTIR spectrometer equipped with EZ-scope attachment (Spectra-Tech) was used with liquid nitrogen cooled Mercury Cadmium Telluride (MCT) as the detector. The depth of penetration depends on the type of crystal used, and ZnSe crystal is used for the experiments. Slices of cable 1 mm thick were prepared using a diamond saw for FTIR measurement. FTIR spectra were obtained for each subset of cable sample using five small samples taken from different places on the respective subset of cable samples. Average spectra for each subset of samples were found by averaging the five spectra for each case.

Each of the spectra obtained were compared for each subset and a noticeable change in trend in the region of wave no 2750-3000 cm$^{-1}$ was observed. The quantitative concentration of the compound was found by evaluating the area under the curve within the region of 2750-3000 cm$^{-1}$ [23]. Table 3.2 Shows the numerical values obtained from the FTIR spectrum analysis for this region. This region is the focus of the remainder of this thesis.

| **Run**<br>**Subset** | **1** | **2** | **3** | **4** | **5** | **Average** |
|---|---|---|---|---|---|---|
| New | 17812.7 | 18279.3 | 16493.5 | 16746.8 | 17191.7 | 17304.8 |
| 5 Years | 17271.7 | 17108.9 | 17387.3 | 17807.5 | 18181.6 | 17551.4 |
| 10 Years | 17865.3 | 17107.8 | 17323.3 | 17607.2 | 17740.7 | 17528.86 |
| 15 Years | 19221.2 | 18551.2 | 19054.1 | 18489.5 | 18795.8 | 18822.36 |
| 20 Years | 19614.8 | 18410.9 | 18727.9 | 18709.6 | 20156.5 | 19123.94 |

**Table 3.2 FTIR values for lab aged cable**

### *Electrical Breakdown Voltage test*

Since electrical trees are initiated at, and grow from sites of stress concentration rather than in uniform fields, it is important that the selected experimental procedure provide constant and reproducible conditions of electrical stressing. Among the different experimental procedures, the needle test is selected, based on ASTM D 3756-97 [20]. The needle test provides comparative data, but not the degree of correlation with actual performance in service, which is the main focus of this work. The test procedure involves the placement of a needle of carefully controlled and identical geometry into a compression-molded block of polymer as shown in Figure 3.1 and 3.2. The test geometry consists of two parts, the holding compartment and the needle driver. The holding compartment is a Plexiglas cubicle designed to support samples with diameters up to 4.5 cm (~1.75 in). The needle driver is a ¼-28 machined screw designed to impel a drill blank (needle) inside the samples. To measure the depth of penetration of the needle inside the samples, a dial caliper is used, as shown in Figure3.1 and 3.2. The depth of penetration is calculated by subtracting the initial and final position readings from the dial caliper.

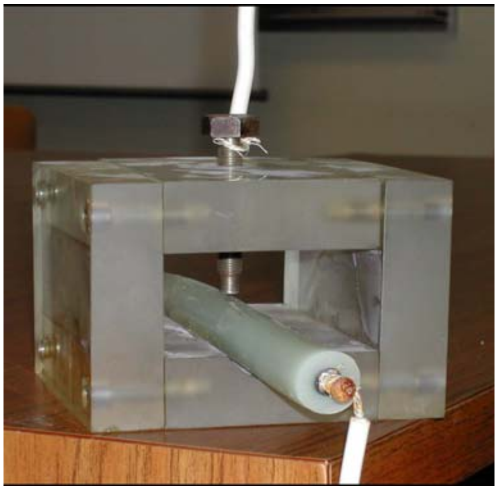

**Fig3.1. Electrical Breakdown Voltge test Set up [25]**

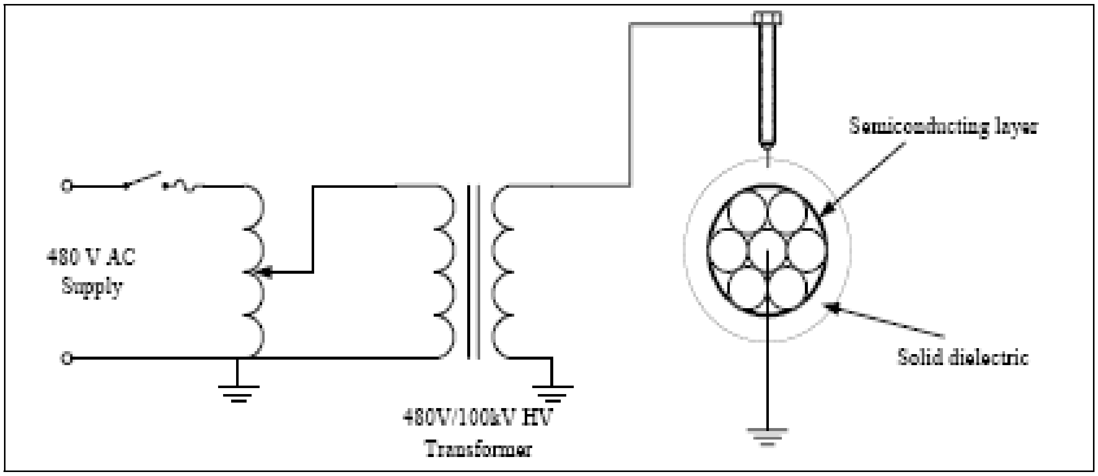

**Fig3.2: Electrical circuit diagram for breakdown voltage test [25]**

The outer jacket and armoring were removed from the samples, which were then cut into 30 cm pieces for this purpose. The depth of needle was varied and voltage time product was recorded for new, field aged, and lab aged cables.

Mean Electrical breakdown strength was obtained for lab aged samples, which is tabulated in Table 3.3 (table 6.5 of [23])

| Equivalent lab age | 0 | 5 | 10 | 15 | 20 |
|---|---|---|---|---|---|
| Electrical Breakdown Strength (kV) | 13.6 | 11.8 | 9.6 | 8.9 | 8.6 |

**Table 3.3: Electrical breakdown strength voltage for lab aged cable**

# Chapter 4

# Statistical Analysis

## 4.1 Introduction

Statistical methods were used to analyze the data obtained. The Anderson-darling test was used to test whether the data obtained from tests are distributed normally or not. *P-value*s obtained from the analysis are the measures of whether the data is distributed normally.

### 4.1.1 Analysis of Variance (ANOVA) Test

Analysis of variance (ANOVA) was used as the measure of the total variability of the data. The total sum of the squares can be expressed as [22]

$$SSTO = SSTR + SSE$$

Where, $SSTR$ is the sum of squares due to treatments, and $SSE$ is the sum of the squares due to error.

A formal test of the hypothesis of no differences in treatment means ($H_0 : \mu_1 = \mu_2 = ..... = \mu_n$ and $H_1 : \mu_i \neq \mu_j$ for at least one pair (*i*,*j*)) can be performed using F-Statistics [22]. If the null hypothesis of no difference in treatment means is true, $F^*$ is distributed as F with *a-1* and *N-n* degrees of freedom and $F^*$ is

$$F^* = \frac{MSTR}{MSE}$$

Where,

$$MSTR = \frac{SSTR}{n-1} \qquad \text{with } n\text{-}1 \text{ degree of freedom}$$

and $MSE = \frac{SSE}{N-n}$ with *N-n* degree of freedom

Here N is the total number of reading and n is the umber of readings on a single factor (subset)..

The above equation is used to test the null hypothesis that there is no significant difference between the treatment means. The null ($H_0$) hypothesis can be rejected if

$$F_0 > F_{\alpha,n-1,N-n}$$

Where, $\alpha$ is the level of significance.

During ANOVA the sample and error are assumed to be distributed normally, which can be tested using Anderson-darling test, described above.

### 4.1.2 Test of Hypothesis:

A statistical hypothesis is a statement about the parameters which reflects some conjecture of the model. Since the distribution being tested was from a very small population, the t-test was used to test the hypothesis. The problem can be stated as

$$H_0 : \overline{x}_1 = \overline{x}_2$$

vs.

$H_1 : \overline{x}_1 \neq \overline{x}_2$, where $\overline{x}_1$ and $\overline{x}_2$ are the means of different populations. The alternate hypothesis, $H_1 : \overline{x}_1 \neq \overline{x}_2$, specifies the two-sided alternate hypothesis.

Once the null and alternate hypotheses are set up, the two-sample t-test can be used to test the hypothesis. The test statistic for comparing two population means, $\overline{x}_1$ and $\overline{x}_2$ in a completely randomized design is stated as,

$$t_0 = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{\sigma_1}{n_1} + \frac{\sigma_2}{n_2}}}$$

Where, $\sigma_1$ and $\sigma_2$ are the variances of the populations 1 and 2 respectively.

To determine whether to reject *Ho*: $\bar{x}_1 = \bar{x}_2$ is compared to the t-distribution with $n_1 + n_2 - 2$ degree of freedom. If $|t_0| \geq t_{\alpha,df}$, the hypothesis *Ho* can be rejected; that is, the two population means are different. *P-value*s obtained from the test give the probability of the null hypothesis $H_0$ being true. The population samples should be distributed normally to use t- test. The Anderson-darling test was used to determine whether the distributions are normal or not.

## 4.2 Statistical Analysis of FTIR Values:

Each of subset of data was tested for normality using the Anderson-darling test for normality. Statistical software, Minitab$^{TM}$, was used for this purpose. The Anderson-darling test is used to test the normality of the sampled distribution by testing the null hypothesis that the sampled distribution was normally distributed versus the alternate hypothesis that the sample was not distributed normally. A rule of thumb is that the *p-value* obtained by Anderson-darling test should be less that 0.05 for acceptance of the null hypothesis. The results of the Anderson-darling tests along with *p-value*s are shown in table 4.1. The results confirm that the sampled distributions were distributed normally.

| **Variable** | **Mean** | **Standard Deviation** | ***p-value*** |
|---|---|---|---|
| New | 17305 | 739.8 | 0.742 |
| 5 year | 17551 | 473.0 | 0.519 |
| 10 year | 17529 | 309.7 | 0.705 |
| 15year | 18796 | 323.7 | 0.298 |
| 20 year | 19124 | 732.1 | 0.265 |

**Table 4.1 Normality test of FTIR values**

After the data were tested for normality, Analysis of Variance (ANOVA) was done to find how significantly subsets are different from each other. ANOVA was again performed using Minitab$^{TM}$ software. A 95% confidence level was used. The result of the ANOVA is in Table 4.2

| **Source** | **DF** | **SS** | **MS** | ***F**** | ***P-value*** |
|---|---|---|---|---|---|
| Factor | 4 | 13922994 | 3480748 | 11.80 | 0.000 |
| Error | 20 | 5899922 | 294996 | | |
| Total | 24 | 19822916 | | | |

**Table 4.2: One way ANOVA for FTIR values**

From these results it can be noted that F-ratio, the ratio of subset mean square and error mean square, was computed to be 11.80. The value of F-ratio from an F-ratio table for 95% confidence level, 4 factor degree of freedom and 20 error degree of freedom is 2.87. As the $F_{0.05,4,20}$ computed, 11.80, is greater than that from table, 2.87, it can be concluded that the subset means are different, indicating the FTIR values are significantly different with respect to different years of aging in the laboratory.

Then a one-sample t-test was used to test the hypothesis that each aged subset had a different value of FTIR from that of the new sample. T-test results were used to compare two subset means in a completely randomized design. For the confidence level of 95%, we can say that the sample means are significantly different if $t_0 > \pm t_{0.025,\ 8}$. Results of the t-test are shown in Table 4.3.

| **Variable** | **DF** | **SE Mean** | $t_0$ | ***p-value*** |
|---|---|---|---|---|
| 5 years | 4 | 195.4 | 1.26 | 0.276 |
| 10 years | 4 | 138.5 | 1.62 | 0.181 |
| 15 years | 4 | 144.7 | 10.30 | 0.001 |
| 20 years | 4 | 327.4 | 5.56 | 0.005 |

**Table 4.3 Results of one sample t-test for FTIR values**

The data show that the $t_0$ values obtained for the subset means of 5 and 10 years are less than, and those for 15 and 20 years samples are greater than, the $t_0$ value of 2.3, which is obtained from the t-table for a 95% confidence level and 4 degrees of freedom. Thus we can conclude that the accelerated lab aging experiments produce significant results for simulated age more than 10 years.

### 4.2.1 Correlating Lab Aged Cable with Field Aged Cable:

Lab aged cable was compared with field aged cables to determine the significance of the accelerated aging procedure. Cable samples of 13, 20, 26, and 40 years of field age were obtained from a utility. From another utility, cables of age 2 years and 5 years were received. These had been removed from service as a consequence of high degradation due to overloading and poor workmanship. The FTIR spectrum was observed on each of those samples. FTIR values obtained for those cables are shown in table 4.4

| | **1** | **2** | **3** | **4** | **5** | **Avg** |
|---|---|---|---|---|---|---|
| 13 years | 19851.0 | 19747.5 | 19585.9 | 19430.5 | 19511.0 | 19625.18 |
| 20 years | 18623 | 18585 | 18523 | 18783 | 18618 | 18626.4 |
| 26 years | 20368 | 22324 | 19931 | 20071 | 18636 | 20266 |
| 40 years | 21203 | 20771 | 20712 | 20556 | 20904 | 20829.2 |

**Table 4.4 FTIR data for field-aged cables**

Each of the above subsets of data was subjected to the statistical analysis. First of all, each was tested for normality with the Anderson-Darling test for normality with the help of Mintab$^{TM}$ software. The results of the Anderson-Darling test are as shown in Figure in Appendix (A), and the results are summarized in table 4.5.

From Table 4.5, since the *p-values* of each subset of the data are greater than 0.05, it can be concluded that that each subset is distributed normally.

| | **Mean** | **Standard Deviation** | ***p-value*** |
|---|---|---|---|
| 13 years | 18626 | 96.19 | .244 |
| 20 years | 19625 | 172.1 | .742 |
| 26 years | 20266 | 1328 | .343 |
| 40 years | 20829 | 243.5 | .648 |

**Table 4.5 Normality on FTIR test data for field-aged samples**

Once those subsets of data were proved to be distributed normally, Analysis of Variance (ANOVA) was performed to see the how significantly the subsets differed from each other. The results of the test are tabulated in Table 4.6.

| **Source** | **DF** | **SS** | **MS** | **F** | **P** |
|---|---|---|---|---|---|
| Factor | 8 | 62354806 | 7794351 | 21.03 | 0.000 |
| Error | 36 | 13345371 | 370705 | | |
| Total | 44 | 75700177 | | | |

**Table 4.6: One way ANOVA test for lab aged and field aged cables**

The F-Value obtained from the ANOVA is 21.03 for the factor degree of freedom 8 and error degree of freedom 36. From the Table of *F-values*, for the 95% level of confidence with 8 and 36 degrees of freedom the *F-value* is 2.25. This value is less than that calculated, thus the null hypothesis that the sample means are same can be rejected.

After testing for normality and performing ANOVA, each subset of the field aged cable was tested for the significance. The two sample t-test was used to test the significance. Each subset of field aged cable was tested for significance with all the subsets of lab aged cable's FTIR data. The results are in Table 4.7-4.10.

| **Variable** | **T** | ***p-value*** |
|---|---|---|
| New | 3.96 | 0.017 |
| 5 years | 5.37 | 0.006 |
| 10 years | 7.57 | 0.002 |
| 15 years | -1.12 | 0.325 |
| 20 years | -1.51 | 0.206 |

**Table 4.7: Two sample t-test results for FTIR values of 13 year field aged cable.**

| **Variable** | **T** | ***p-value*** |
|---|---|---|
| New | 6.83 | 0.002 |
| 5 years | 9.87 | 0.000 |
| 10 years | 13.23 | 0.000 |
| 15 years | 5.06 | 0.002 |
| 20 years | 1.49 | 0.210 |

**Table 4.8: Two sample t-test results for FTIR value of 20 year field aged cable**

| Variable | T | *p-value* |
|---|---|---|
| New | 4.36 | 0.005 |
| 5 years | 4.34 | 0.012 |
| 10 years | 4.49 | 0.011 |
| 15 years | 2.41 | 0.074 |
| 20 years | 1.68 | 0.143 |

**Table 4.9: Two sample t-test results for FTIR value for 26 year field aged cable**

| Variable | T | *p-value* |
|---|---|---|
| New | 10.12 | 0.001 |
| 5 years | 14.64 | 0.000 |
| 10 years | 18.73 | 0.000 |
| 15 years | 11.23 | 0.000 |
| 20 years | 4.94 | 0.008 |

**Table 4.10: Two sample t-test results for FTIR value for 40 year field aged cable**

From the table it can be seen that the calculated *p-value* for the 13 year old cable is highest for the lab aged sample of 15 years, ie, the 13 year field aged cable has the highest probability of its mean being equal to 15 year lab aged samples. A similar conclusion can be drawn for the field aged cable of 20 years, since that has the highest *p-value* for the 20 year lab aged population. The population of 26 year field-aged cable has the highest *p-value* for the 20 year lab aged cable population. The 40 year field aged cable has a *p-value* that is much lower than that for any subset of lab aged sample data. From this two-sample t-test analysis, it can be concluded that the FTIR value of lab aged cable has close correlation with that of field aged cable.

### 4.2.2 Analysis of FTIR Values on Field Aged Cable

Cable samples obtained for testing were removed from service for replacement. The replacement was done because of the observed high rate of degradation in the insulation material. Later it was discovered that the cable installation was not done properly. Two samples of this cable, aged 2 years and 5 years in the field, were tested for FTIR values. The observed FTIR values from those tests are tabulated below.

| | **FTIR Values** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2 years | 20520 | 19719 | 19026 | 20110 | 20401 | 22729 | 21712 | 19531 |
| 5 years | 18550.5 | 22302.1 | 21090.4 | 19108.4 | 20445.1 | 18335.4 | 20620 | 19947.3 |

**Table 4.11: FTIR Values of field aged cable**

These FTIR values were tested for normality using Anderson-darling test for normality. Results of Anderson-darling test are shown in table 4.12.

From the table it can be seen that *p-value*s for each subset of the samples were found to be greater than 0.05, which means that the data are distributed normally.

| | **Mean** | **Standard Deviation** | ***p-value*** |
|---|---|---|---|
| 2 years | 20050 | 1348 | 0.855 |
| 5 years | 20469 | 1214 | 0.406 |

**Table 4.12 Normality test for field age cable**

Analysis of variance (ANOVA) test was performed to test how significantly the subsets differ from each other. The results are obtained are shown in Table 4.13.

| **Source** | **DF** | **SS** | **MS** | **F** | **P** |
|---|---|---|---|---|---|
| Factor | 6 | 61769261 | 10294877 | 12.01 | 0.000 |
| Error | 34 | 28934170 | 851005 | | |
| Total | 40 | 90703431 | | | |

**Table 4.13 One-way ANOVA test for lab aged and 2, 5 years field aged cable samples**

The results show that the between-subset mean square (10294877) is much higher than the error mean square (851005), indicating the means of the subsets are different. F-values obtained from the analysis are higher than $F_{0.05,\,6,\,34}$ 3.4 which confirms the subsets are significantly different.

Two-sample t-tests were performed to find the probability of each subset of the samples obtained from field to be equal to the subsets obtained from lab aged cables. Results obtained from the tests are summarized in table 4.15 and 4.16

| | **t** | ***p-value*** |
|---|---|---|
| New | 4.37 | 0.001 |
| 5 years old | 4.85 | 0.001 |
| 10 years old | 5.08 | 0.001 |
| 15 years old | 2.52 | 0.032 |
| 20 years old | 1.60 | 0.140 |

**Table 4.14 Two sample t-test for 2 year field aged cable**

| | **t** | ***p-value*** |
|---|---|---|
| New | 5.84 | 0.000 |
| 5 years old | 6.19 | 0.000 |
| 10 years old | 6.52 | 0.000 |
| 15 years old | 3.69 | 0.006 |
| 20 years old | 2.49 | 0.032 |

**Table 4.15 Two sample t-test for 5 year field aged cable**

The *p-value*s on the table give the probabilities of the subsets of data being equal. Because *p-value*s for each case are greater than those for 20 year lab aged cables, the samples have the highest probability of being equal to 20 years lab aged cable. This indicates the cables were almost at the end of their expected life.

## 4.3 Statistical Analysis of Electrical Breakdown Voltage Strength

Lab aged cable was again compared with field aged cables, using the Electrical Breakdown Voltage (EBV) test, to determine the significance of the accelerated aging procedure. Cable samples of 13, 20, 26, and 40 years of field age were tested. EBV results recorded for those cables are as shown in table 4.17.

| | **1** | **2** | **3** | **4** | **5** | **Avg** |
|---|---|---|---|---|---|---|
| New | 14.1 | 13.3 | 13.7 | 12.9 | 14.5 | 13.7 |
| 13 years | 9.8 | 9.1 | 9.55 | 9.4 | 8.9 | 9.35 |
| 20 years | 8.7 | 9.0 | 8.9 | 9.3 | 9.2 | 9.02 |
| 26 years | 9.1 | 8.5 | 8.65 | 9.2 | 8.9 | 8.87 |
| 40 years | 8.45 | 8.25 | 8.8 | 8.7 | 8.1 | 8.46 |

**Table 4.16 Electrical Breakdown Voltage test results for field-aged cables**

The Anderson-darling test was used to test the normality of the subsets with the null hypothesis that each sample distribution was distributed normally. $H_0$ is rejected if the *p-value* is less than 0.05, and the distribution is assumed to be distributed normally if the *p-value* obtained is greater than 0.05. The results of the tests show that each subset of data is distributed normally.

ANOVA is used to find how significantly the subsets differ from each other. The F-value is computed to be 153.72, which is greater than $F_{.05,4,20}$ from the F-ratio table 2.87. It can be concluded that the subset means are different from each other. The output of AVOVA is in Table 4.18.

| **Source** | **DF** | **SS** | **MS** | **F-value** | ***p-value*** |
|---|---|---|---|---|---|
| Factor | 4 | 93.247 | 23.312 | 153.72 | 0.000 |
| Error | 20 | 3.033 | 0.152 | | |
| Total | 24 | 96.28 | | | |

**Table 4.17 ANOVA test results for field-aged cables**

## Chapter 5

# Aging Model

### 5.1 Introduction

The parametric changes in the XLPE cable such as changes in FTIR value and electrical breakdown voltage were modeled using a linear regression model. In Chapter 4 it was established that the area under the FTIR curve in the region 2750-3000 cm$^{-1}$ increase, and the capacity to withstand the electrical breakdown voltage decreases, with age.

A model was developed from these data to estimate the age of XLPE cable from the results of FTIR analysis and electrical breakdown voltage tests. A multivariable regression method is used in this model.

### 5.1.1 Multivariable Linear Regression Model:

If y is the dependent variable, and is modeled as a linear function of one independent variable, the model can be stated as follows [26],

$$y = a + bx \qquad \text{………………………………………..………5.1}$$

Where *a* and *b* are constants and x is the independent variable.

The general form of the model as a linear function of n independent variables is given by

$$y = a_0 + a_1x_1 + a_2x_2 + .........+ a_n \qquad \text{…………………………….………………...5.2}$$

The technique used to determine the coefficients $a_0, a_1, ...., a_n$ is the Ordinary Least Square (OLS) method. The values of the coefficients are chosen to minimize the sum of the squared residuals (SSR). SSR is given by,

$$SSR = \sum (y - \hat{y})^2 = \sum (y - a_0 - a_1 x_1 - ............ - a_n x_n)^2$$ ………………..…5.3

To minimize the SSR, we need to find partial derivatives of the SSR with respect to $a_0, a_1, ....a_n$ respectively. This generates n equations as

$$\frac{\partial SSR}{\partial a_0} = -2\sum (y - a_0 - a_1 x_1) = 0$$ ……………………………………………...5.4

$$\sum y = na_0 + a_1 \sum x_1$$ ……………………………….………..…5.5

Similarly,

$$\frac{\partial SSR}{\partial a_1} = -2\sum x_1 (y - a_0 - a_1 x_1) = 0$$ ………………………….……..…………5.6

Or,

$$\sum x_1 y = a_0 \sum x_n + a_1 \sum x_1{}^2$$ ………………………………….5.7

.

.

.

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.

$$\sum x_n y = a_0 \sum x_n + a_1 \sum x_n^2 \qquad \text{..................................5.8}$$

There will be $n+1$ equations, which can be solved to find $n+1$ constants.

### 5.1.2 Goodness of Fit

The Ordinary Least Square (OLS) technique is used to find the values of the constants which best fit by minimizing the sum of squared residuals. There is no guarantee that the 'best fitting' function fits the data well. So it is necessary to assess the adequacy of the fitted equation.

The goodness of fit can be estimated by a standard statistic called $R^2$ [22], given by,

$$R^2 = 1 - \frac{SSR}{\sum (y - \bar{y})^2} \equiv 1 - \frac{SSR}{SST} \qquad \text{.......................................5.9}$$

$R^2$ shows the proportion of the variation in $y$ that is accounted for by the estimated equation. $R^2$ is bounded between 0 and 1.

## 5.2 Aging Model of XLPE Insulated Cable

Chapter 4 shows that FTIR value and electrical breakdown voltage change significantly with cable age. It was established that the area under the FTIR curve in the region 2750-3000 cm$^{-1}$ increases and the electrical breakdown voltage decreases with age. Table 5.1 gives the variation of mean FTIR value and mean electrical breakdown voltage with time.

| Time | 0 | 5 | 10 | 15 | 20 |
|---|---|---|---|---|---|
| FTIR Value | 17304.7 | 17551.4 | 17528.9 | 18795.8 | 19123.9 |
| EBV | 13.8 | 11.8 | 9.6 | 8.9 | 8.6 |

**Table 5.1 Variation of FTIR Values and EBV with time.**

The actual data plots of the FTIR value and electrical breakdown voltage are shown in figures 5.1 and 5.2 respectively.

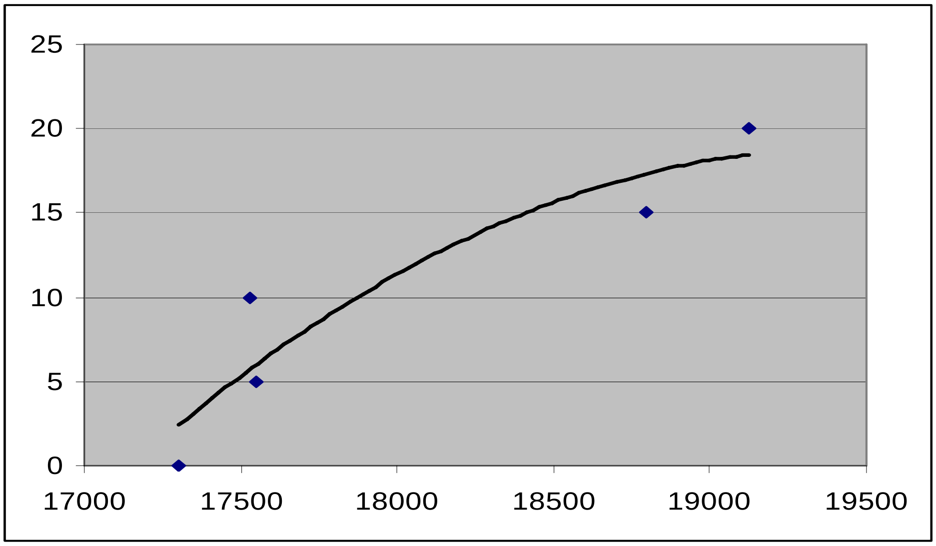

**Fig 5.1: FTIR value vs time**

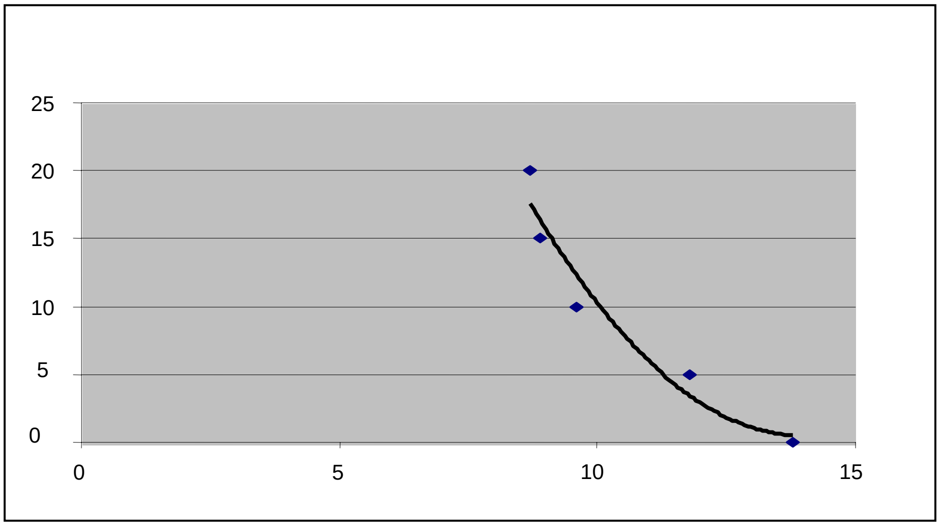

**Fig 5.2: Electrical breakdown voltage vs time.**

The age of the cable will be modeled as a linear regression of two independent variables, FTIR values and electrical breakdown voltages. The model is given by

$$L(F,E)=a_0+a_1F+a_2E \qquad \text{……………………………………………5.10}$$

Where,

$L$ = Age of the cable in years

$F$ = FTIR value

$E$= Electrical Breakdown Voltage in kV.

$a_0$, $a1$,$a2$ are constants or the rate of change of respective parameters, determined using OLS.

SPSS$^{TM}$ software was used to calculate the coefficients and R$^2$ values to evaluate the goodness of fit. The coefficients were found to be,

$$a_0 = -46.47$$
$$a_1 = 4.35 \times 10^{-3}$$
$$a_2 = -2.095$$

Age of the XLPE insulated cable received from field can be modeled as,

$$L = -46.47 + 4.35 \times 10^{-3} \times F - 2.095 \times E \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.11$$

***Goodness of Fit***

The $R^2$ value obtained was 0.982. This implies that, out of the total variations in dependent variable *L*, 98.2% of the variations have been explained by the independent variables F and E. This $R^2$ value equal to 0.982 indicates a good fit of the data by the model.

### 5.3 Estimating Remaining Life of Cables

From previous chapters it is established that the FTIR value and Electrical breakdown voltage withstand capacity is valid statistical parameters to estimate the age of an XLPE cable. These parameters change with cable age. It is necessary to know these values at failure to be able estimate the age of a cable.

### 5.3.1 FTIR Values

FTIR analysis was performed on field aged samples of cable that had failed while in service. The quantitative concentration of a compound can be determined from the area under the FTIR curve in the characteristic regions of the IR spectrum. $CH_3$ asymmetric stretching vibration occurs at 2975-2950 $cm^{-1}$, while asymmetric $CH_2$ absorption occurs at about 2930 $cm^{-1}$. The symmetric $CH_3$ vibration occurs at 2885-2865 $cm^{-1}$ while symmetric $CH_2$ absorption occurs at about 2870-2840 $cm^{-1}$. In general, the area under the curve for wave number 2750-3000 $cm^{-1}$ is representative of –CH, $-CH_2$ and $–CH_3$ carbon/hydrogen stretching vibrations. Table 5.2 shows the worst five values (out of ten readings obtained for each) for the area under the wave number 2750-3000 $cm^{-1}$ FTIR spectra for failed cables from the field [23].

### 5.3.2 Electrical Breakdown Voltage

Electrical breakdown voltage tests were performed on the same failed samples. The worst 5 values are also tabulated in table 5.2. The average of these values is assumed to the minimum breakdown strength required for the cable to operate without failure [23].

| No | FTIR Value | EBV |
|---|---|---|
| 1 | 19851.0 | 8.11 |
| 2 | 19747.5 | 8.51 |
| 3 | 19585.9 | 9.32 |
| 4 | 19430.5 | 8.90 |
| 5 | 19511.0 | 8.51 |
| Avg | 19625.18 | 8.67 |

**Table 5.2: FTIR and EBV data for failed cables.**

From the above table the end value for FTIR values was found to be 19625.18 and that for electrical breakdown voltage to be 8.67kV.

Using the previously developed aging model, total expected life for XLPE cable can be calculated as

$$L_{end} = a_0 + a_1 19625.18 + a_2 8.67$$

which gives the value of expected life to be 20.925 years. This means the total expected life of the cable is nearly equal to 21 years. From this expected length of life, the expected life of each tested sample cable was computed by subtracting the calculated estimate of cable age from the expected length of the life. These values, along with their respective FTIR values and electrical breakdown voltages, are tabulated in Table 5.3

| **Remaining Life** | 20.925 | 15.925 | 10.925 | 5.925 | 0.925 |
|---|---|---|---|---|---|
| **FTIR Value** | 17304.7 | 17551.4 | 17528.9 | 18795.8 | 19123.9 |
| **EBV** | 13.8 | 11.8 | 9.6 | 8.9 | 8.6 |

**Table 5.3 Variation of FTIR values and EBV with remaining life.**

The actual data plots of the FTIR values and electrical breakdown voltages versus remaining life of the cable are shown in figures 5.3 and 5.4.

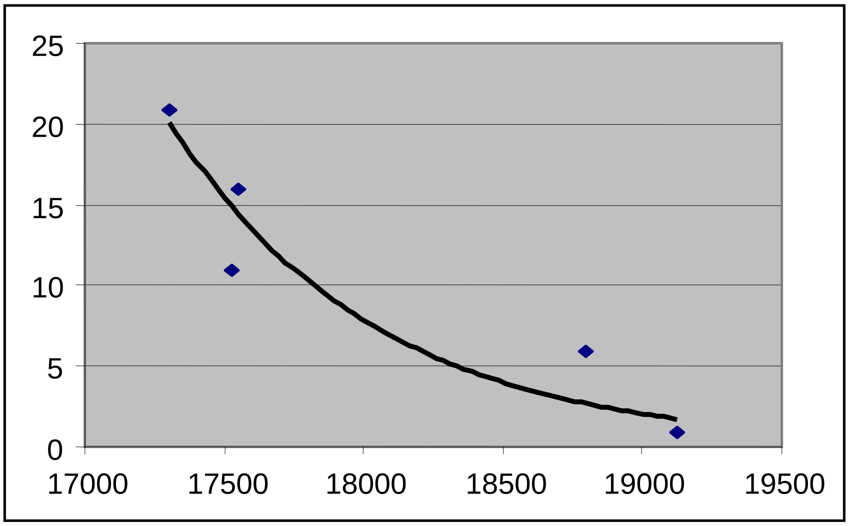

**Fig 5.3. FTIR value VS remaining life**

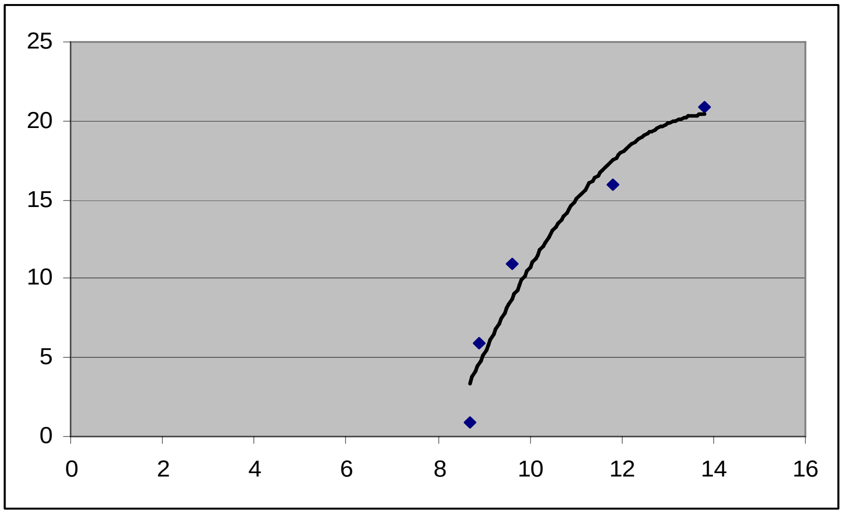

**Fig 5.4 Electrical breakdown voltage vs remaining life.**

From the graph it can be seen that the remaining life of the cable decreases with increasing FTIR value, and decreases with the increasing electrical breakdown voltage of the cable. The remaining life of the cable can be considered as the multivariable linear regression model of the two independent variables, FTIR value and electrical breakdown voltage, given by

$$L_{remaining} = a_3 + a_4F + a_5B \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.12$$

Where,

$L$ = Remaining life of the cable in years

$F$ = FTIR value

$B$= Electrical Breakdown Voltage in kV.

$a_3$, $a_4$ and $a_5$ are constants or the rate of change of respective parameters calculated by ordinary least square (OLS) method.

SPSS™ software was used again to find the coefficients and R$^2$ values to evaluate the goodness of fit. The coefficients were found to be,

$a_0 = 67.189$
$a_1 = -4.35$
$a_2 = 2.095$

Remaining life of the XLPE insulated cable received from field can be modeled as,

$$L_{remaining} = 67.19 - 4.35 \times 10^{-3} \times F + 2.095 \times E \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.11$$

***Goodness of Fit***

The R$^2$ value obtained was 0.982. This implies that, out of the total variations in the dependent variable L, 98.2% of the variations have been explained by the independent variables F and B. An R$^2$ value of 0.982 indicates a good fit of the data in the model.

### 5.4 Validation of the model:

To validate the remaining life model, calculations were done for the remaining life of the different field-aged samples tested. The FTIR value and EBV were measured for those samples and the remaining life of the cable was calculated with the model. Table 5.5 shows the results of the calculations.

| **Age (years)** | **FTIR Value (*F*)** | **EBV Value (kV) (*E*)** | **Remaining life (years) $L_{remaining}$** |
|---|---|---|---|
| 13 | 18624 | 9.2 | 5.4 |
| 5 | 19070 | 8.9 | 2.9 |
| 7 | 17450 | 11.8 | 16 |

**Table 5.5: Calculation of remaining life of cables**

The 5 year field aged cable was a failed cable. According to the engineers for utility, the premature failure of the cable was due to the poor workmanship at one of the joints. The model predicts this expected early failure with a low remaining life estimate. For the 13 and 7 years field aged cables, the remaining life calculations are consistent with calculated and commonly expected cable life values.

## Chapter 6

# Discussion, Conclusion and Futerworks

### 6.1 Discussion

The properties of insulating materials degrade with time in service due to the various stresses to which they are subjected. An accelerated aging procedure was developed [23] to obtain information about this degradation for cable in hot, dry climates. The procedure was designed to optimize cost of the procedure, quickness and accuracy. The accelerated procedure was validated.

The area under the FTIR spectrum in the region 2700-3000 $cm^{-1}$, and the ability to withstand the electrical breakdown voltage using needle plane geometry, were verified as parameters quantifying cable degradation. Statistical analyses on the values obtained for field-aged samples were correlated with those obtained for lab-aged samples. The analysis can estimate how close a cable removed from the field is to failure.

The estimated remaining life of a cable was modeled as dependent on two independent variables, FTIR values and Electrical Breakdown Voltage. The calculated remaining life of 13 and 7 year field-aged cables are as expected for cables under normal operating conditions. The estimated remaining life for a 5 year field-aged cable that failed in service is very low, which corresponds to a rate of degradation of the cable that is very high, and an expected early failure.

## 6.2 Conclusion

The Arrhenius equation was used to model aging for medium voltage cross linked polyethylene cables. Two parameters, FTIR value and Electrical breakdown voltage, were used as the measure of degradation of the XLPE material. Statistical methods were used to validate these parameters.

Degradation patterns of the parameters were studied. It was concluded that the rate of change of FTIR values increases, while the rate of change of Electrical breakdown voltage decreases, with the age of the cable. Thus FTIR values change more rapidly for older cables, while Electrical breakdown strength changes faster for new cables.

A new multivariable linear regression aging model for XLPE cable was developed using these two parameters. This model estimates the age and remaining expected life of a cable in service. The model was verified through testing and analysis of samples of field-aged cables of known age.

## 6.3 Future Works

The results apply only to cable in a dry and hot environment. Wet trees and the effects of moisture are not considered. Other parameters dealing with such types of degradation are needed to design a more generalized aging model valid in all climates.

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# APPENDICES

# APPENDIX A

## Minitab™ software output for Anderson-darling test

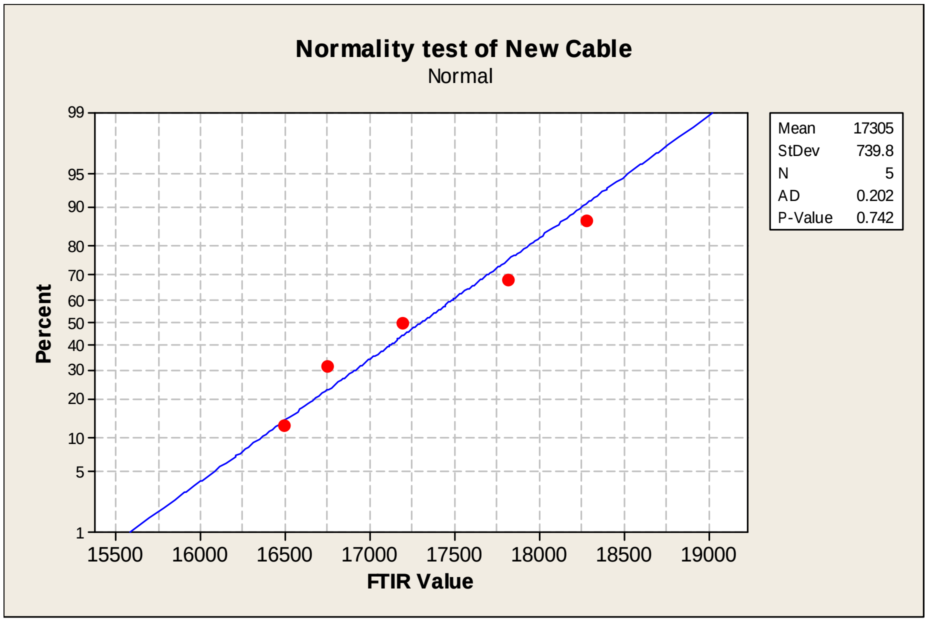

**Fig A.1. Anderson-darling test for Normality for FTIR value of new cable**

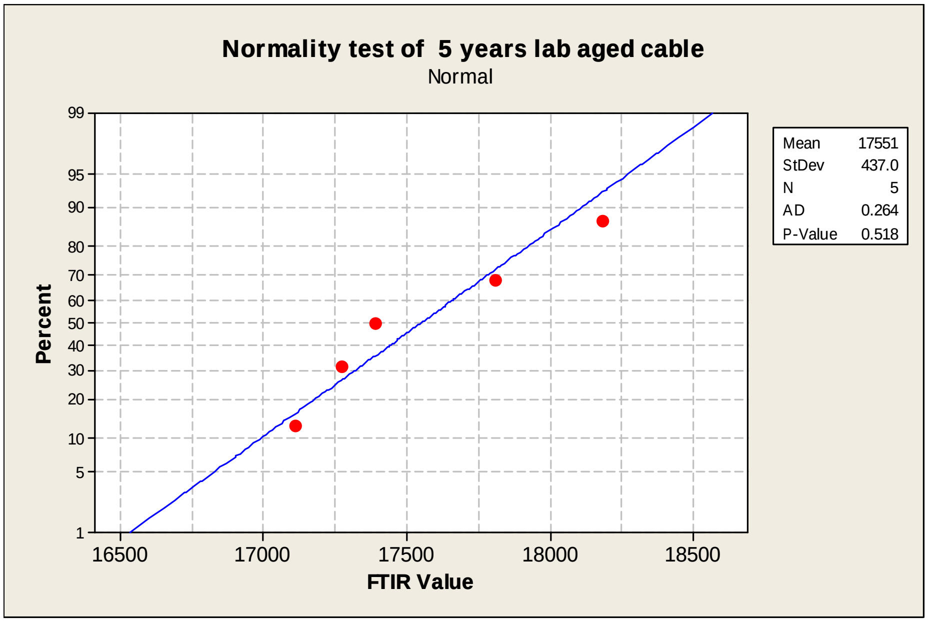

**Fig A.2 Anderson-darling test for Normality for FTIR value of 5 years lab aged cable**

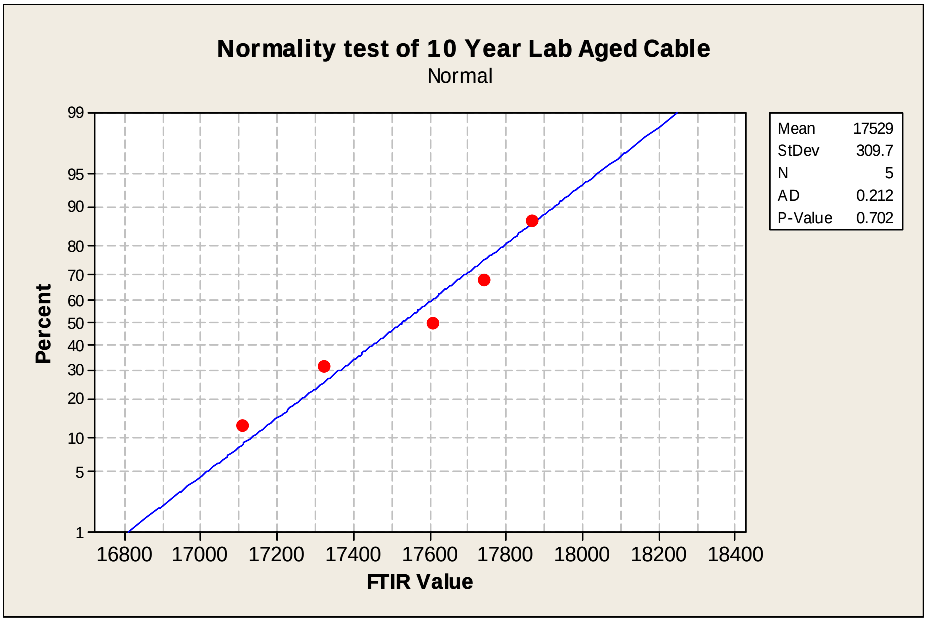

**Fig A.3 Anderson-darling test for Normality for FTIR value of 10 years lab aged cable**

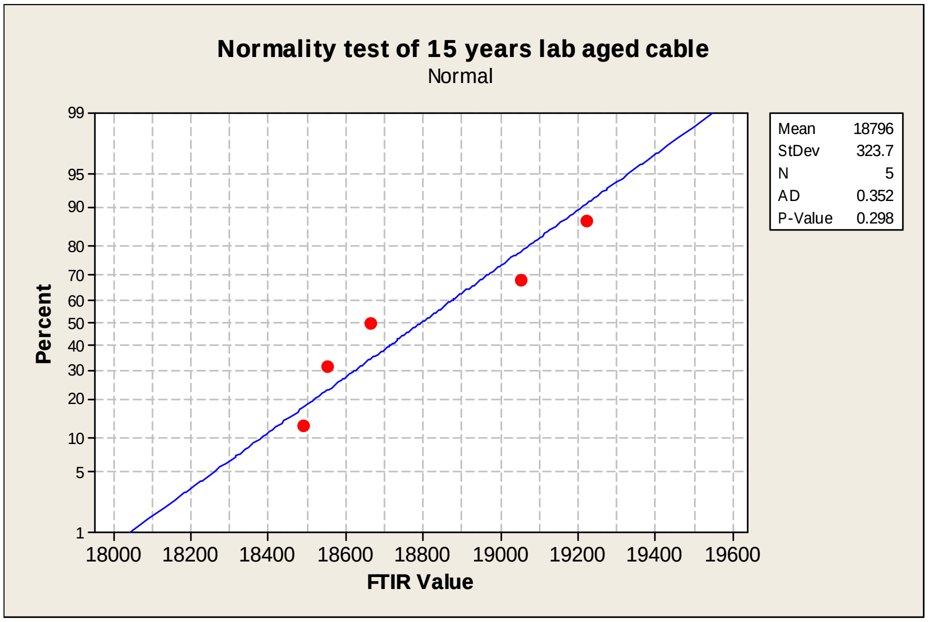

**Fig A.4 Anderson-darling test for Normality for FTIR value of 15 years lab aged cable**

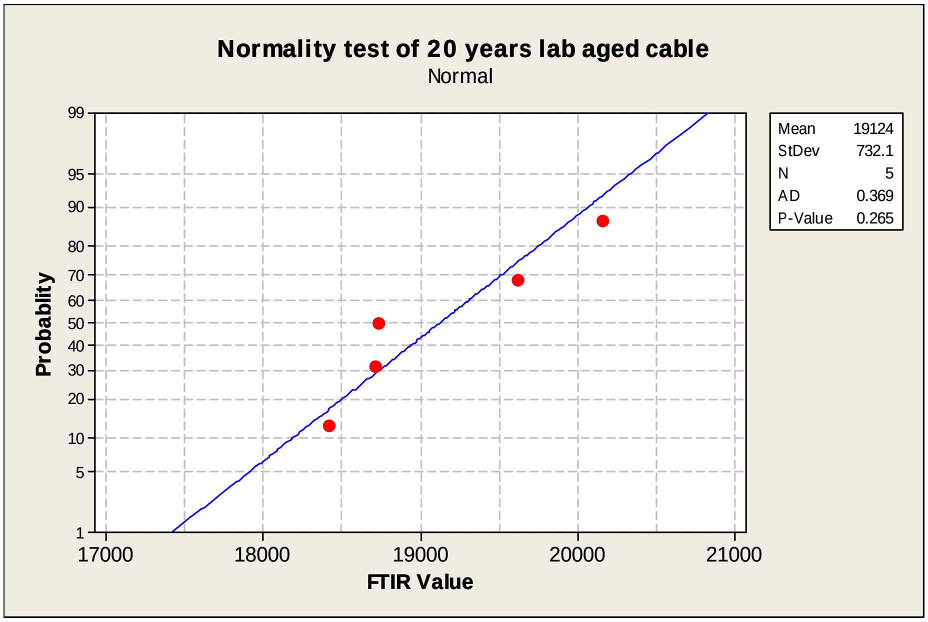

**Fig A.5 Anderson-darling test for Normality for FTIR value of 20 years lab aged cable**

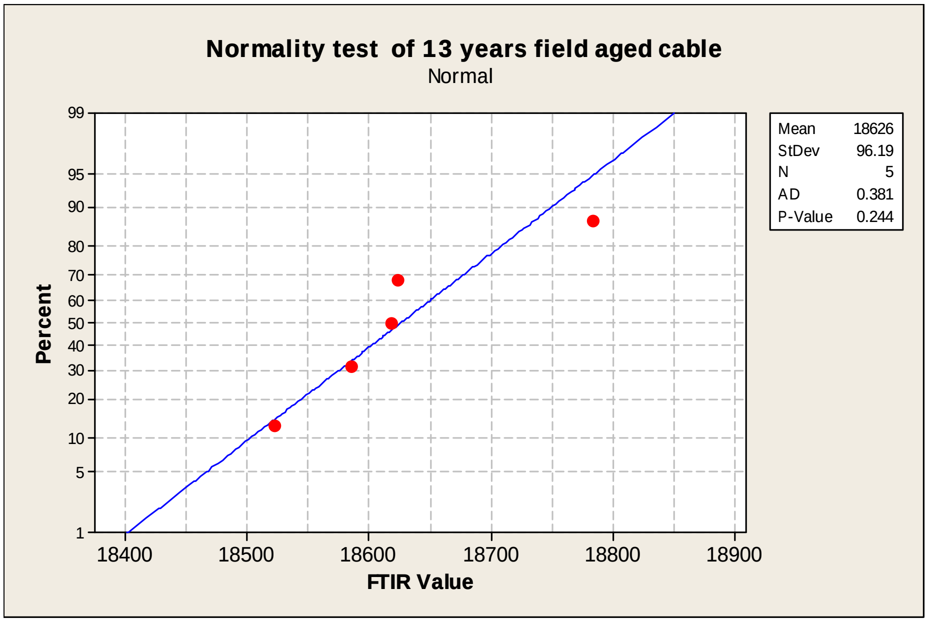

**Fig A.6 Anderson-darling test for Normality for FTIR value of 13 years field aged cable**

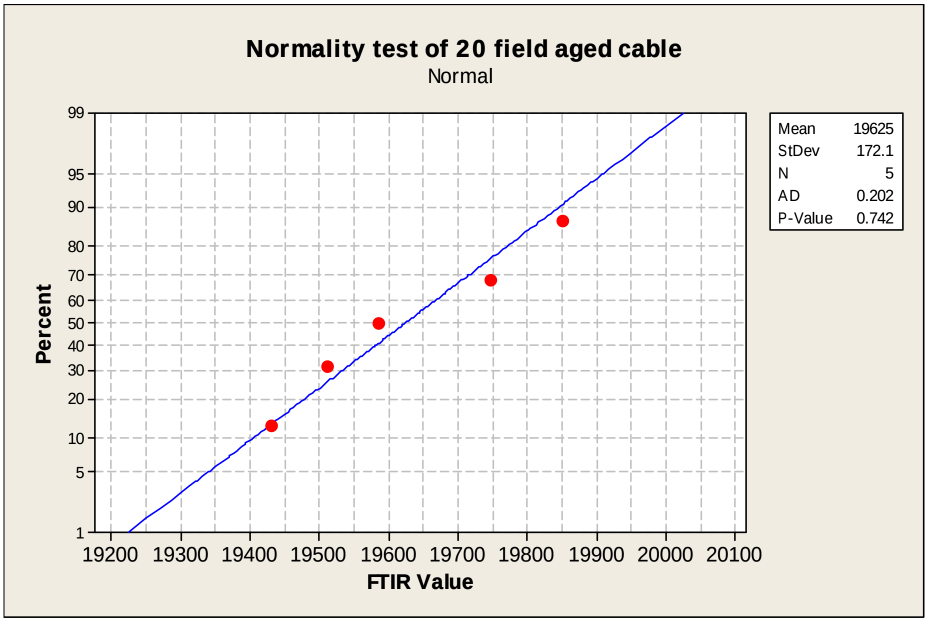

**Fig A.7 Anderson-darling test for Normality for FTIR value of 20 years field aged cable**

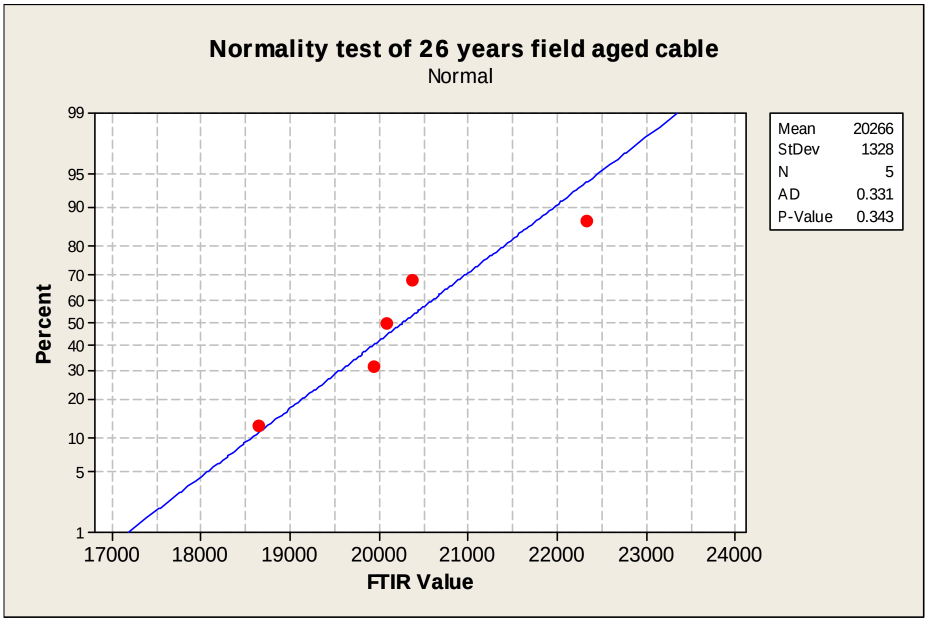

**Fig A.8 Anderson-darling test for Normality for FTIR value of 26 years field aged cable**

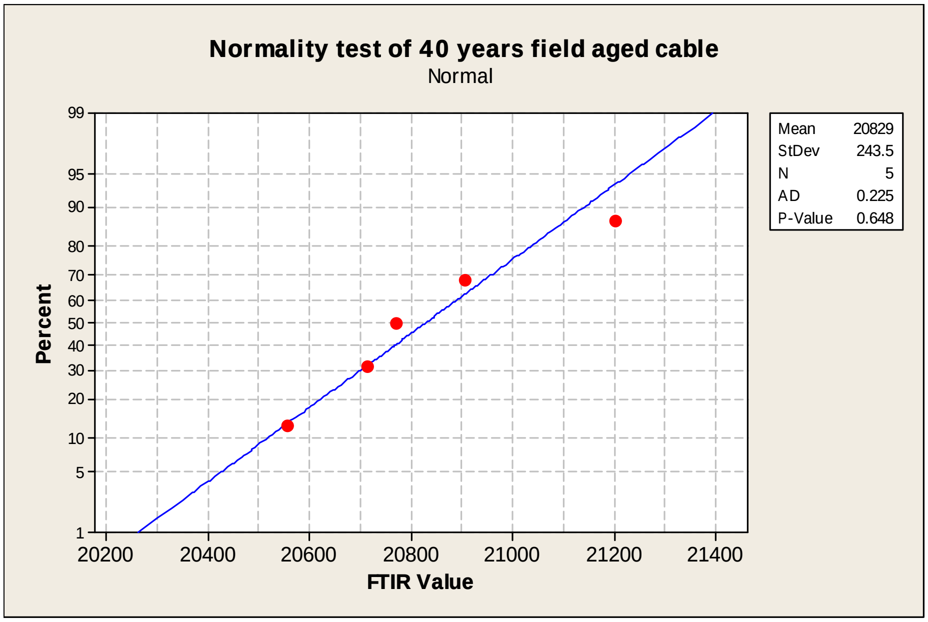

Fig A.9 Anderson-darling test for Normality for FTIR value of 40 years field aged cable

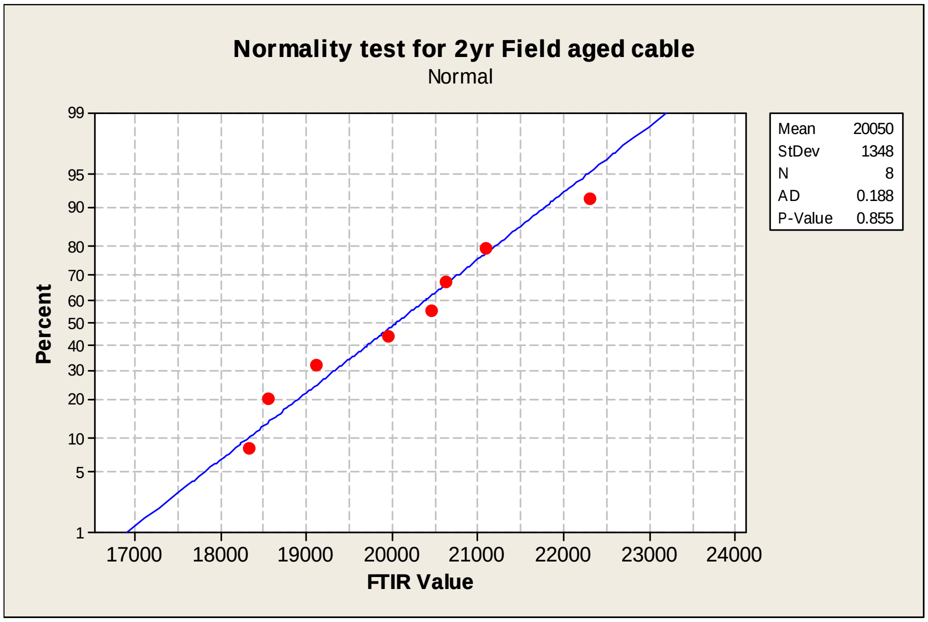

Fig A.10 Anderson-darling test for Normality for FTIR value of 2 years lab aged cable

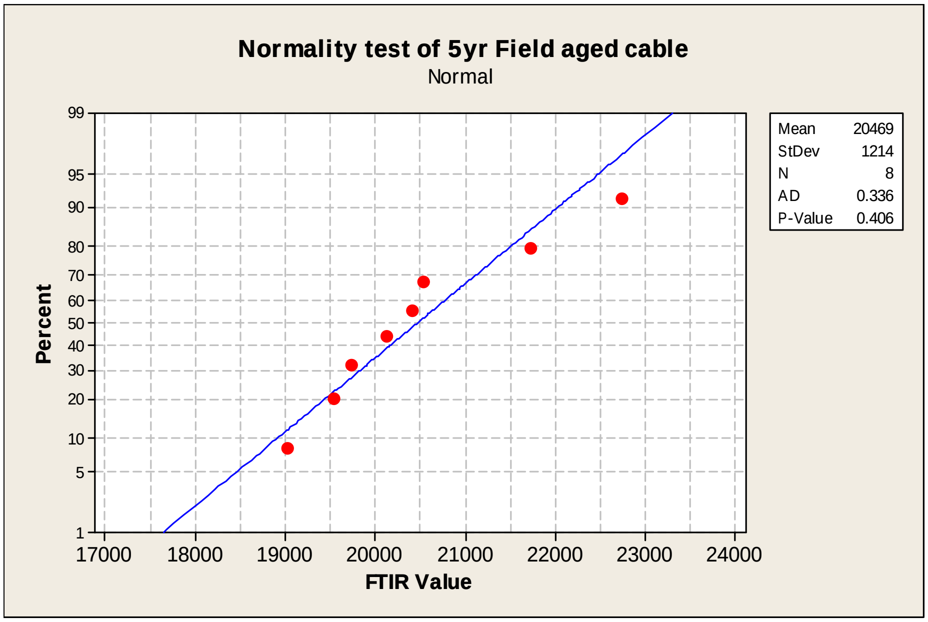

Fig A.11 Anderson-darling test for Normality for FTIR value of 5 years lab aged cable

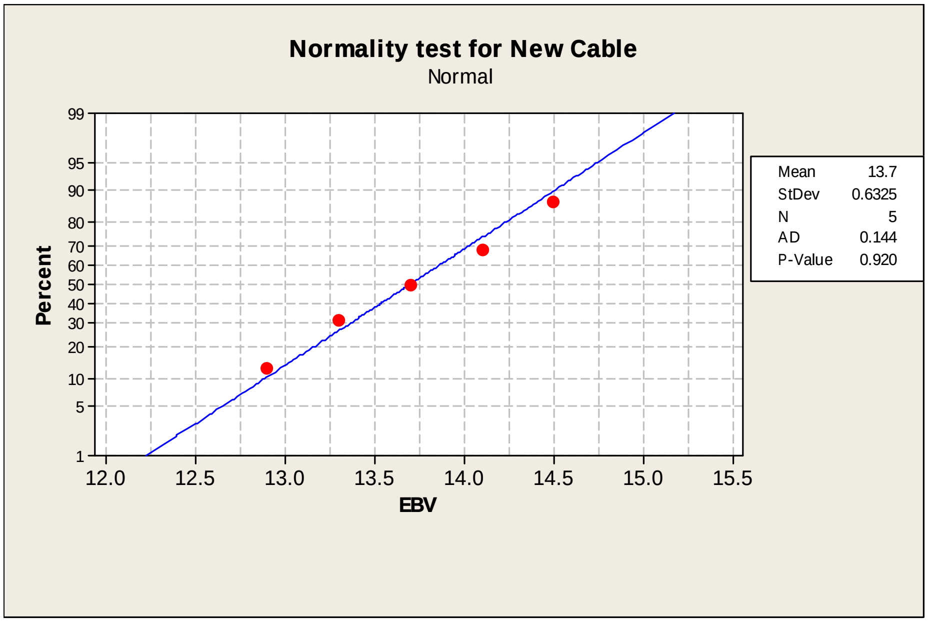

Fig A.12 Anderson-darling test for Normality for EBV of new cable

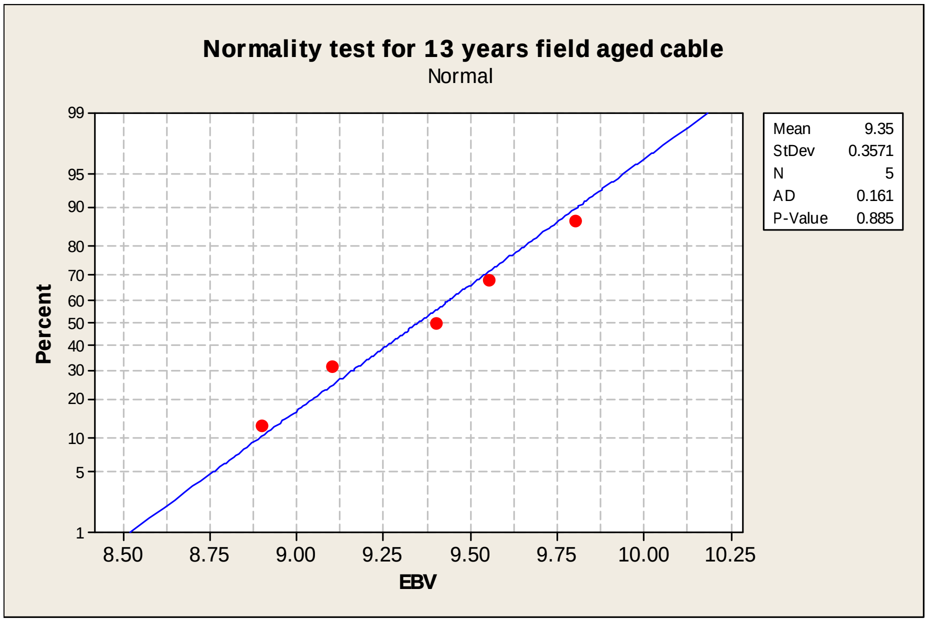

**Fig A.13 Anderson-darling test for Normality for EBV of 13 years old field aged cable**

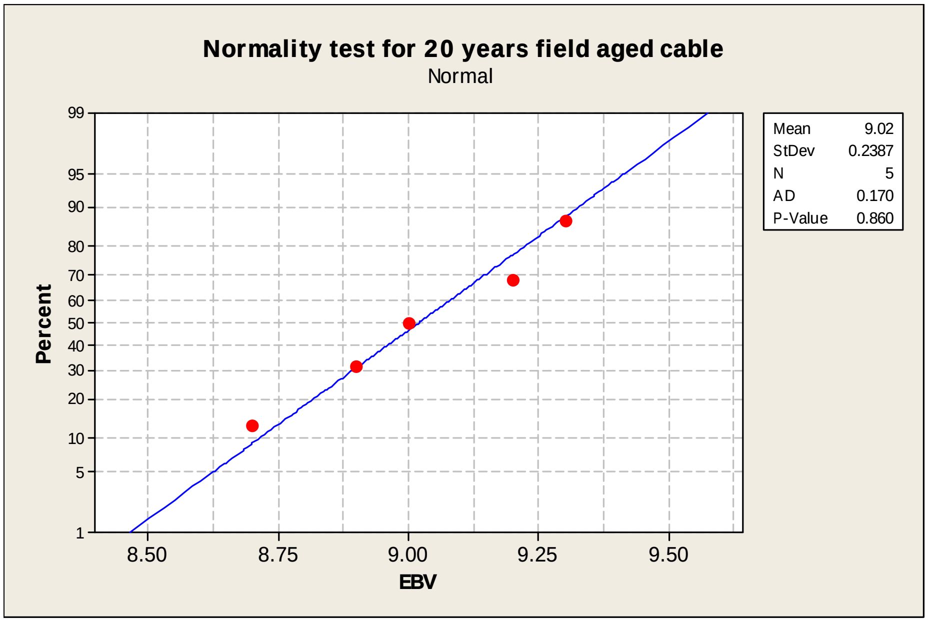

**Fig A.14 Anderson-darling test for Normality for EBV of 20 years old field aged cable**

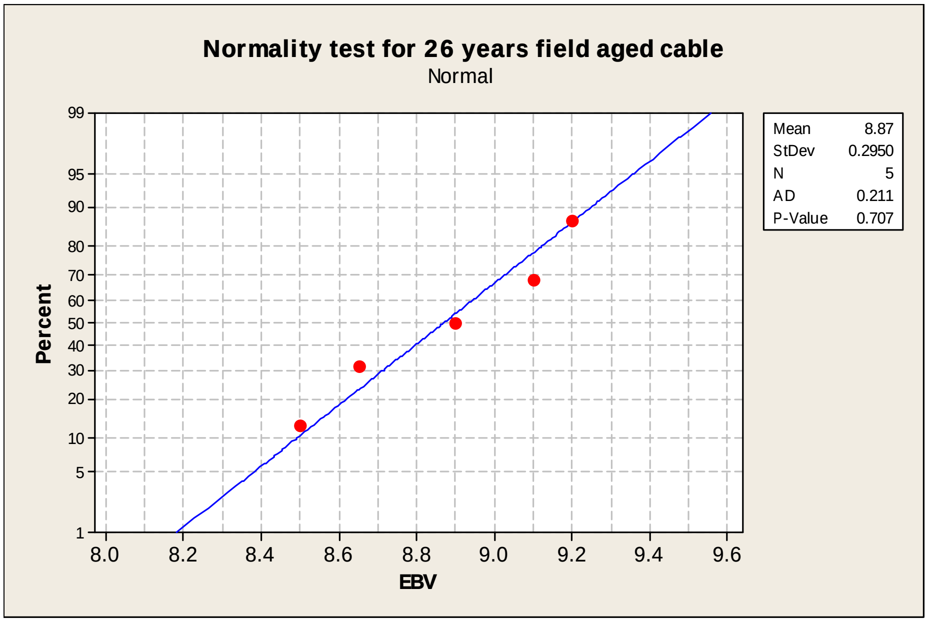

Fig A.15 Anderson-darling test for Normality for EBV of 26 years old field aged cable

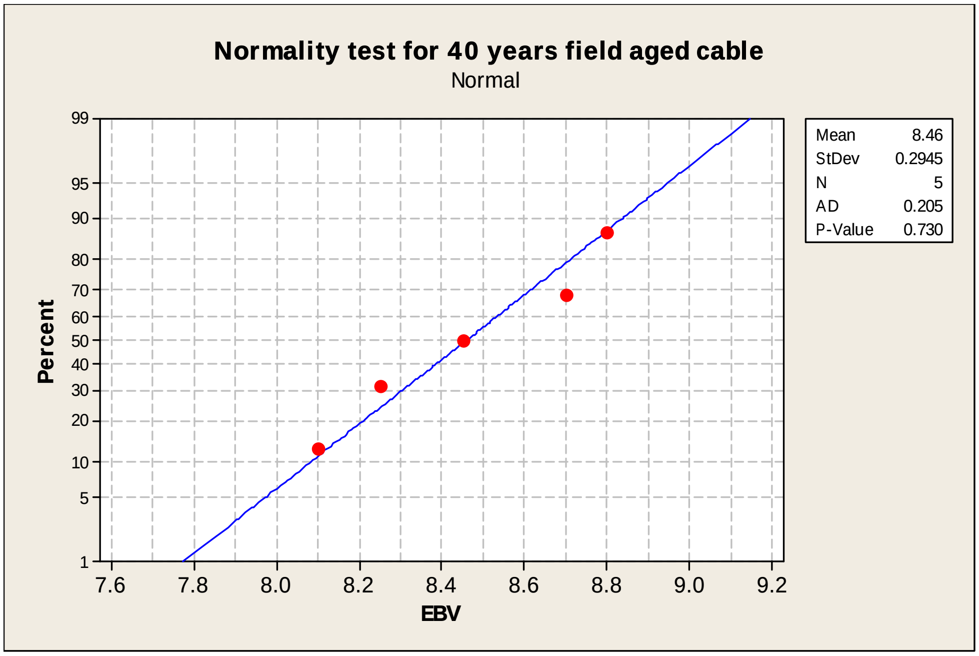

Fig A.16 Anderson-darling test for Normality for EBV of 40 years old field aged cable

# APPENDIX B

## Output of SPSS$^{TM}$ software for linear regression model.

## B.1 Regression Analysis of Age of XLPE Insulated Cable

**Variables Entered/Removed[b]**

| Model | Variables Entered | Variables Removed | Method |
|---|---|---|---|
| 1 | EBV, FTIR[a] | . | Enter |

a. All requested variables entered.

b. Dependent Variable: TIME

**Model Summary**

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate |
|---|---|---|---|---|
| 1 | .991[a] | .982 | .964 | 1.5066 |

a. Predictors: (Constant), EBV, FTIR

**ANOVA[b]**

| Model | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| 1 | Regression | 245.460 | 2 | 122.730 | 54.069 | .018[a] |
| | Residual | 4.540 | 2 | 2.270 | | |
| | Total | 250.000 | 4 | | | |

a. Predictors: (Constant), EBV, FTIR

b. Dependent Variable: TIME

**Coefficients[a]**

| Model | | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. |
|---|---|---|---|---|---|---|
| | | B | Std. Error | Beta | | |
| 1 | (Constant) | -46.471 | 31.886 | | -1.457 | .282 |
| | FTIR | 4.349E-03 | .001 | .459 | 2.915 | .100 |
| | EBV | -2.094 | .563 | -.586 | -3.719 | .065 |

a. Dependent Variable: TIME

## B.2 Regression Analysis of Remaining Life of XLPE Insulated Cable

**Variables Entered/Removed**[b]

| Model | Variables Entered | Variables Removed | Method |
|---|---|---|---|
| 1 | EBV, FTIRVA[a] | . | Enter |

a. All requested variables entered.

b. Dependent Variable: REM.LIFE

**Model Summary**

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate |
|---|---|---|---|---|
| 1 | .991[a] | .982 | .964 | 1.50661 |

a. Predictors: (Constant), EBV, FTIRVA

**ANOVA**[b]

| Model | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| 1 | Regression | 245.460 | 2 | 122.730 | 54.069 | .018[a] |
| | Residual | 4.540 | 2 | 2.270 | | |
| | Total | 250.000 | 4 | | | |

a. Predictors: (Constant), EBV, FTIRVA

b. Dependent Variable: REM.LIFE

**Coefficients**[a]

| Model | | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. |
|---|---|---|---|---|---|---|
| | | B | Std. Error | Beta | | |
| 1 | (Constant) | 67.396 | 31.886 | | 2.114 | .169 |
| | FTIRVA | -4.35E-03 | .001 | -.459 | -2.915 | .100 |
| | EBV | 2.094 | .563 | .586 | 3.719 | .065 |

a. Dependent Variable: REM.LIFE