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Lifetime characteristics of Magnet wire MW 16-C under AC, DC voltages, and high temperatures

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LIFETIME CHARACTERISTICS OF MAGNET WIRE MW 16-C UNDER AC, DC VOLTAGES, AND HIGH TEMPERATURES

By

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LIFETIME CHARACTERISTICS OF MAGNET WIRE MW 16-C UNDER AC, DC

VOLTAGES, AND HIGH TEMPERATURES

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Polyimide is one of the most heat resistant polymers with high electric breakdown strength, good mechanical properties, and chemical resistance. Polyimide is used in severe environmental condition. Polyimide is commonly applied as electrical insulation in a fine gauge of inverter-fed motor windings and in high voltage coils of encapsulated fly-back transformers. The wire insulation may be exposed to multi-stresses like ac, dc high voltages, temperatures etc.

In this thesis, magnet wire insulation properties under multiple stresses are studied under ac, dc voltages and high temperatures. Accelerated degradation test is used to do study of Life -time characteristics of Magnetic wire MW 16-C, which has polyimide insulation. The results of accelerated aging test are evaluated with statistical tools Weibull and ALTA. The result shows that the time to failure can be represented by the inverse power law and the Arrhenius equation with respect to test voltage and temperature respectively.

DEDICATION

I would like to dedicate this research work to my beloved parents, Mr. Pramod Gadre and Mrs. Payal Gadre for their love, and support, and my advisor Dr. Stanislaw Grzybowski for his continuous support and encouragement.

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CHAPTER I

INTRODUCTION

1.1 Introduction

The investigation of failure mechanisms and forms of electrical insulation systems has an elementary role in electrical apparatus design and long-term performance, and on reliable and economical management of electrical assets. In fact, electrical insulation is the weakest point of an electrical apparatus, consequently design and time performance of electrical insulation must be well evaluated [1].Insulation offers electrical insulation, mechanical strength, heat dissipation and many other things. The insulating materials must be capable of meeting its operating conditions, including electrical, mechanical and thermal requirements, such as reliability and cost [2]. Dielectric breakdown strength of electrical insulation usually evaluates the quality of electrical insulation. Physical parameters like the voltage waveform, frequency, temperature, humidity, partial discharges, impurities, thickness of the insulation, number of the insulating layers, dielectric constant for ac voltages, and volume resistivity for dc voltages etc influence the breakdown voltage of insulating material [3].

There are three types of insulation: solid, liquid and gaseous, out of which solid insulation failure is permanent and in liquid and gaseous may not be permanent. As a result, the study of solid insulation plays a significant role in aging studies. Solid insulation is used in electrical devices like capacitors, transformers, cables, transmission lines, motors, and electronic devices like fly back transformers used in television, computer monitors, and ignition coils, solenoids, and sensors. The breakdown of electrical insulation of this equipment is due to the presence of degrading stresses, such as electrical, thermal, and frequency [4]. So under multi-stress conditions, it is very essential to analyze the life time of the insulation. Electrical insulation system design engineers choose the test method to be followed in studying the lifetime analysis of insulation and most of the time accelerated aging test is used for life-time analysis. Accelerated testing consists of a variety of test methods for shortening the life of products or hastening the degradation of their performance. The aim of such testing is to quickly obtain data which, properly modeled and analyzed, yield desired information on product life or performance under normal use. Such testing saves much time and money [5].Lifetime analysis of electrical insulation gives arithmetic information like failure time percentiles, probability of failures, and lifetime characteristics. An appropriate probability distribution is used to analyze results of accelerated aging test and to estimate the lifetime of the specified insulation at any desired stress mathematical models are used. In the previous years, multi-stress life models were developed at Mississippi State University High Voltage Laboratory. In this thesis, experiments were carried out on new insulating materials to verify the life models [2, 4].

1.2 Program of Study

Magnetic wire NEMA MW-16-C has polyimide insulation. It is one of the most heat resistive polymers with high electric breakdown strength, good mechanical properties and high radiation and chemical resistance. Therefore, use of polyimide insulated wires is becoming increasingly popular, particularly in severe environmental conditions [6].

This research's main objective is to verify empirical electrical-thermal model which was developed at the High Voltage Laboratory of Mississippi State University and to estimate the lifetime of NEMA 16-C (polyimide insulation) , when insulation is exposed to multi-stress service condition; including ac voltage, dc voltage and elevated temperatures. The parameters of the life model are estimated using Weibull ++, and ALTA (Accelerated Life Testing Analysis) Software. This software uses the maximum likelihood and the least squares technique to estimate the parameters for the given experimental failure data.

There is no any commercially documented standard for insulation testing of the electrical equipment but it is common practice to use twisted pairs of samples of magnetic wire stressed under different types of electric stress and subject to higher temperatures. Temperature classes of winding insulation are defined in recent NEMA MW 1000 standard. A dielectric test system (DTS-1500A), made by Directed Energy Inc. (DEI), was used in the experimental study. The samples were placed in an air-circulated oven and tested under ac and dc voltages and at room temperature, and high temperatures. A test system can supply voltage up to 12 kV ac and voltage of 10 kV dc, and temperatures as high as 260^{O}C. The present work verifies the generalized electrical-thermal life model, capable of estimating the life-time of magnet wire insulation over a wide range of ac and dc voltages, and temperatures. Also the time to failure is represented by inverse power law and the Arrhenius equation with respect to test voltages and temperature under ac supply.

1.3 Thesis Organization

The thesis is organized as follows. Chapter II discusses the different classes of magnet wire enamels and use of magnetic wire in today's market. Chapter III gives an idea about the Weibull distribution used for the statistical analysis of polyimide insulation and describes the effect of different parameters of Weibull on lifetime of insulation. Chapter IV describes breakdown of solid dielectrics. In chapter V the different life models used in the study such as, single and multi-stress models are explained in detail. Chapter VI focuses on the experimental setup required to carry out the research work, both with 60 Hz ac voltage and dc voltage at room and high temperatures. The experimental results are presented in chapter VII. Finally, chapter VII concludes the research work with possible future work to be performed in the High Voltage Laboratory.

CHAPTER II

MAGNET WIRE

2.1 Introduction

Magnet wire is an insulated copper or aluminum conductor, and these conductors come in round or rectangular and square shape. Magnet wire creates an electromagnetic field when wound into a coil and energized. The critical role is played by magnet wire in electricity as 90% of all electrical energy requires alteration. The application of magnet wire is in mainly three areas of energy conversion; that is, electrical to electrical, electrical to mechanical and mechanical to electrical. Electrical to electrical transformation involves transformers, which are used to transfer power. Electrical to mechanical transfer is necessary for motorized appliances, automobiles, industrial machinery, and residential and commercial HVAC systems. Mechanical to electrical transformation includes generators. It is also used in a broad range of communication applications, computers, telephones, cell phones, video games and televisions [7, 8, 9].

Magnet coils used to energize electrical and electronic equipment are covered with insulating material predominately wire enamels [10].Technology of magnetic wire enamel is continually moving forward in its skill. This technology has made the variety of enamels available for use in the production of magnet wire seemingly endless. However, the selection of one wire enamel over another in an application is based on a number of factors. The factors are based on the requirements of the end users and manufactures of magnet wire [11].

2.2 Application of Magnet Wire

Magnetic wire's demand is escalating day by day with growth of industry. In a wide range of areas different types of magnet wires are used.

2.2.1 Summarization of Magnet Wire Applications

Table 2.1 Application of Magnet wire [12]

Field	Applications		Required Properties
Electronics	FPC	Home appliances, cameras , electronic calculators, watches , audio devices, communication devices, computer devices like displays, printers	Soldering heat resistance, Dimensional stability ,Flexibility, Smaller moisture absorption ,Insulating properties
	Tape carrier ,Cover layer , Flat cable		
Information	Vertical magnetic recording film	Tapes, floppy disks	High smoothness, Heat proofness, High strength and elasticity ,High dimensional stability ,Isotropy
Electric insulating materials	Motor	Rolling stocks : Shinkansen, subways ,diesel locomotives ; Industrial use : construction equipments, aircrafts, submersible pumps	Mechanical strength and insulating properties at high temperatures
	Electric wire, cable, Layer insulation	Wirings in aircrafts, missiles and rockets, internal wiring of large size computers, wiring of electric heaters; Wiring of atomic power equipments; Fire preventing wiring, Transformer	Heat proofness ,Mechanical strength, Combustibility ,Radiation resistance

Table 2.1 (continued)

Others	Audio equipment	Acoustic diaphragms	
	New energy generator	Solar battery PCB	
	Atomic power equipments		
	Fire prevention equipments		
	Heat insulating materials	Extra-low/high temp storage tanks, space rockets	
	Heating devices	Surface heating elements	
	Adhesive tapes ,others	Condensers, bobbin sleeves for small size coils, tubes, seamless belts ,heat shrinkable tapes	

In this part of the chapter, different applications of magnet wires in major fields are discussed [11, 13, 14].

2.2.2 Motor

Motors are built according to its different applications with variety of sizes from fractional horsepower to multiple horsepower. A different build and size or gauge of magnet wire is used to build such variant sized motors. Inherently, motors provide many potential application difficulties for magnet wire. Motors may have a "hot spot" in service temperatures in surplus of 180^{O}C. The magnet wire may be stressed with mechanical stresses and abrasion. These stresses and abrasion arise from the winding process and/or from the final shaping of the wound magnet wire. Finally, when the magnet wire is in the motor, it may be subjected to chemical exposure. The chemicals may be element of its operating environment. Frequently, to improve the motor's resistance to its operating environment, it will be layered with an insulating varnish. The magnet wire's enamel coating must be well-matched with the motor's insulating varnish.

2.2.3 Transformers and Open coils

Even transformers and open coils are manufactured in different sizes and electrical requirements. Thus, the magnet wire will diverge in size. They too, cause area of concern for magnet wire application. An operating temperature of transformer varies from less than $105^{O}C$ to $220^{O}C$ and may be deep in a cooling oil or gas. Again, the magnet wire is subjected to winding stresses and abrasion. These stresses are less severe than that of the stresses in motor applications; though they are less, stresses still exist because the magnet wire coil often is shaped to conform to size requirements. Most of the time a transformer will be coated with an insulating resin to help in noise reduction and heat dissipation. In the coating process, the magnet wire will be submerged in an insulating resin, i.e., a chemical. Here too, chemical compatibility between a wire and an insulating resin is desired.

2.2.4 Encapsulated Coil

Encapsulated coils receive the same stresses as transformers and open coils, and are also subjected to the additional stress of simultaneous heat and pressure. The wound magnet wire coil is placed in a mold and then a hot thermoplastic is introduced into the mold under pressure causing rapid material expansion and contraction, further stressing the wire's insulating coating.

2.3 Enamels of Magnet Wire

All of the magnet wires are either aluminum or copper wire conductors covered with some kind of enamels. Enameled wires are manufactured in both round and rectangular shapes. Rectangular wire is used in larger windings to make the most efficient use of available winding space. Magnet wires are classified by their diameter (AWG) or area (square millimeters), temperature class and insulation class. In this section properties of enamels are discussed depending on their Thermal Class.

The following table shows different kind of enamels and their thermal class:

Table 2.2 Enamels and their thermal class [2, 4, 16,17]

Thermal class	Type of Enamel	Thickness Gauge	Wire Type
105	Polyamide	MW 6	C
105	Polyvinyl acetal	MW 15	A,C
105	Polyvinyl acetal over coated with polyamide	MW 17	C
105 Solderable	Polyurethane	MW 2	C
105 Solderable	Polyurethane and self-bonding overcoat	MW 3	C
105 Solderable	Polyurethane overcoated with polyamide and self bonding overcoat	MW 29	C
105	Polyvinyl acetal and self-bonding overcaot	MW 19	C
130	Epoxy	MW 9	C
130 Solderable	Polyurethane overcoated with polyamide	MW 28	A,C
130 Solderable	Polyurethane	MW 75	C
155	Polyester	MW 5	C
155	Polyester (amide)(imide) overcoated with polyamide	MW 24	A,C

Table 2.2 (Continued)

155 Solderable	Polyester (imide)	MW 26	C
155 Solderable	Polyester (imide) overcoated with polyamide	MW 27	C
155 Solderable	Polyurethane	MW 79	C
155 Solderable	Polyurethane overcoated with polyamide	MW 80	A,C
180	Polyester (amide)(imide)	MW 30	C
180	Polyester (amide)(imide) overcoated with polyamide	MW 76	A
180	Polyester (amide)(imide) overcoated with polyamideimide and self-bonding overcoat	MW 102	A,C
180 Solderable	Polyester (imide)	MW 77	C
180 Solderable	Polyester (imide) overcoated with polyamide	MW 78	C
180 Hermetic	Polyester (amide)(imide)	MW 72	C
180 Solerable	Polyurethane	MW 82	C
180 Solderable	Polyurethane overcoated with polyamide	MW 83	C
200	Polyester (amide)(imide)	MW 74	C
200 Hermetic	Polyester (amide)(imide) overcoated with polyamideimide	MW 73	C
220	Polyester (amide)(imide) overcoated with polyamideimide	MW 35	A
220	Polyester (amide)(imide)	MW 74	A
220 Hermetic	Polyester (amide)(imide) overcoated with polyamideimide	MW 81	C
240 Hermetic	Polyimide	MW 16	C

CHAPTER III

STASTISTICAL ANALYSIS - WEIBULL DISTRIBUTION

3.1 Weibull Distribution

The reliability of the product adds to its quality and competitiveness. Engineers and designers take much effort to evaluate reliability, to review new designs and to modify design and manufacturing, to identify causes of failure, and compare designs, vendors, materials, manufacturing methods, and the like. The characteristic properties like breakdown voltage, tensile strength and melting temperature etc evaluate new material. This evaluation is done by comparison tests against an existing design with a proven service record. But now this kind of deterministic design approach has been gradually replaced by probabilistic procedures. There is a broad recognition that material properties are variable even for identical samples of the same material. In addition, the stresses to which the equipment will be exposed are not constant; they vary with certain probabilities of occurrence. Furthermore, safety factors used in a deterministic design are often difficult to justify and are often reduced to save money. Since a statistical design procedure takes all such factors into account, equipment with a projected life under specific operating conditions can be manufactured more economically [18]. Lifetime data analysis of a product plays the major role in the designing of a product.

The Weibull distribution is one of the most widely used lifetime distributions in reliability engineering. It is a flexible distribution and fits to a wide range of data based on the value of the shape parameter, β. The distribution can handle increasing, decreasing or constant failure-rates and can be created for data with and without non-failures. Time to failure need to be recorded to draw Weibull plots.

3.2 Weibull Probability Density function

It is well known that there is a wide spread in both the times to failure and the breakdown voltages of actually identical solid dielectric specimens. This scatter is intrinsic in the nature of long-term electrical degradation of insulation by electrical treeing. Although no rigorous experimental evidence has ever been presented, a simple Weibull probability distribution is commonly employed to represent the variability in both the failure times and voltages [15]. There are three forms of Weibull density function: Three Parameter Weibull Distribution, Two Parameter Distribution and One Parameter Distribution [19, 20]. In Weibull distribution, three parameters, scale parameter (α), shape parameter (β), and location parameter (γ) need to be chosen in order to adjust to distribution of the measured results. It is difficult to find a definite solution with this distribution since several parameter combinations can give the same configuration. Due to the same alignment, two-parameter Weibull distribution is commonly used which constitutes the scale parameter (α) and shape parameter (β) [16].In life data analysis, the two dimensional Weibull distribution is mostly used to describe the time-to-breakdown of solid dielectric insulation with voltage, as it is a convenient way for deriving the V-t characteristics or life models[26].At each stress level the times to breakdown is determined using the two-parameter Weibull distribution in the study [16].

3.2.1 The Three Parameter Weibull Distribution

Three parameter Weibull pdf is given by:

$$f(T) = \frac{\beta}{\alpha}\left(\frac{T-\gamma}{\alpha}\right)^{\beta-1} \exp - \left(\frac{T-\gamma}{\alpha}\right)^{\beta} \quad (3.1)$$

Where,

$$f(T) \geq 0, T \geq 0 \; or \; \gamma, \beta > 0, \alpha > 0, -\infty < \gamma < \infty,$$

And,

α = scale parameter

β = shape parameter

γ = location parameter

T = time to breakdown

f = probability of failure

3.2.2 The Two Parameter Weibull Distribution

Two parameter Weibull distributions is used mostly in lifetime data analysis as it is easy to portray time to breakdown of solid dielectric insulation with voltage

The two parameter Weibull pdf is obtained by putting γ= 0 i.e location parameter as zero and is given as,

$$f(T) = \frac{\beta}{\alpha}\left(\frac{T}{\alpha}\right)^{\beta-1} \exp - \left(\frac{T}{\alpha}\right)^{\beta} \quad (3.2)$$

3.2.3 The One Parameter Weibull Distribution

The one parameter pdf is obtained by setting γ= 0 and $\beta = C$= constant

$$f(T) = \frac{C}{\alpha}\left(\frac{T}{\alpha}\right)^{C-1} \exp - \left(\frac{T}{\alpha}\right)^{C} \tag{3.3}$$

Where, only one unknown parameter is scale parameter (α).The shape parameter (β) is known as a priori from past experience on identical or similar products.

3.3 Weibull Statistical Properties

3.3.1 Probability Density Function

If X is a continuous random variable, then the probability density function , pdf, of X is a function f(X) such that for two numbers, a and b with a ≤b

$$P(a \leq x \leq b) = \int_a^b f(x)dx \; and \; f(x) \geq 0 \; for \; all \; x' \tag{3.4}$$

This equation represents the probability that X takes a value in the interval [a, b] is the area under the density function from a to b as shown below.

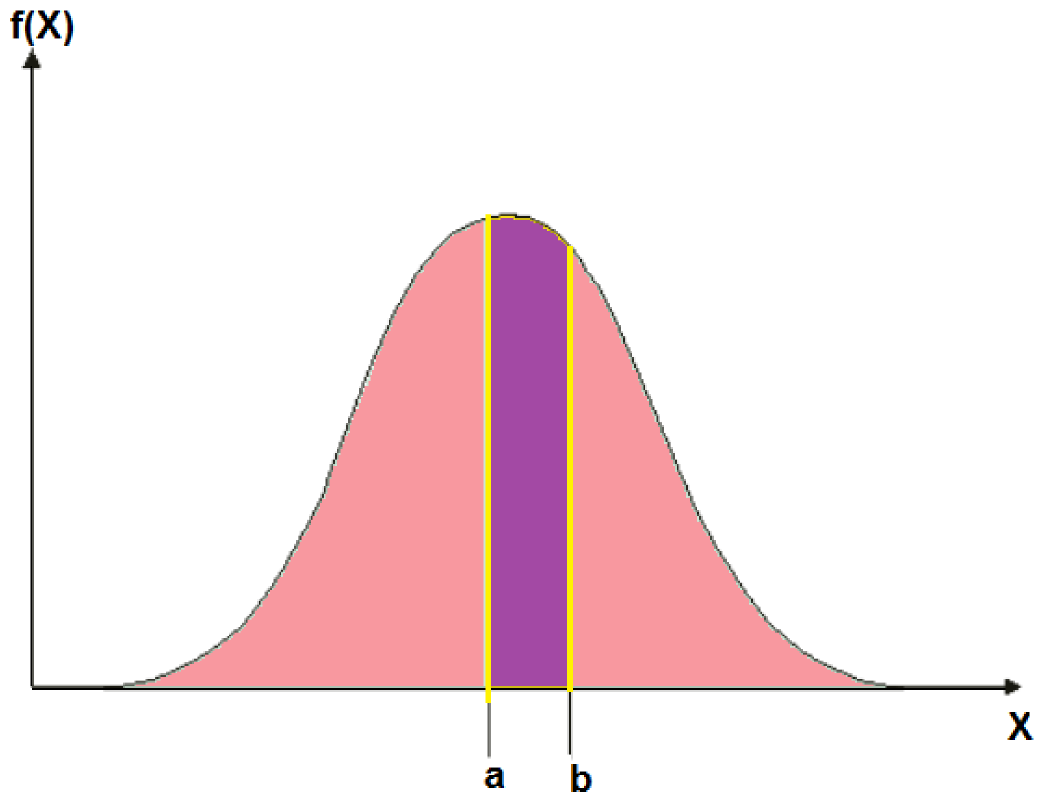

Figure 3.1 pdf characteristics [4,19,20]

3.3.2 Cumulative Distribution Function

The cumulative distribution function, cdf, is functions F(x) of a random variable, X, and is defined for a number x by,

$$F(x) = P(X \leq x) = \int_{0,-\infty}^{x} f(s)ds \quad (3.5)$$

That is, for a given value of x, F(x) is the probability that the observed values of X will be a most x.

3.3.3 The Reliability Function

The probability of a unit failing by time t is given as

$$f(t) = \int_{0,\gamma}^{\mathrm{t}} \mathrm{f(s)\ ds} \quad (3.6)$$

This is the unreliability function Q (t), probability of failure. The sum of reliability and unreliability probabilities is always unity.

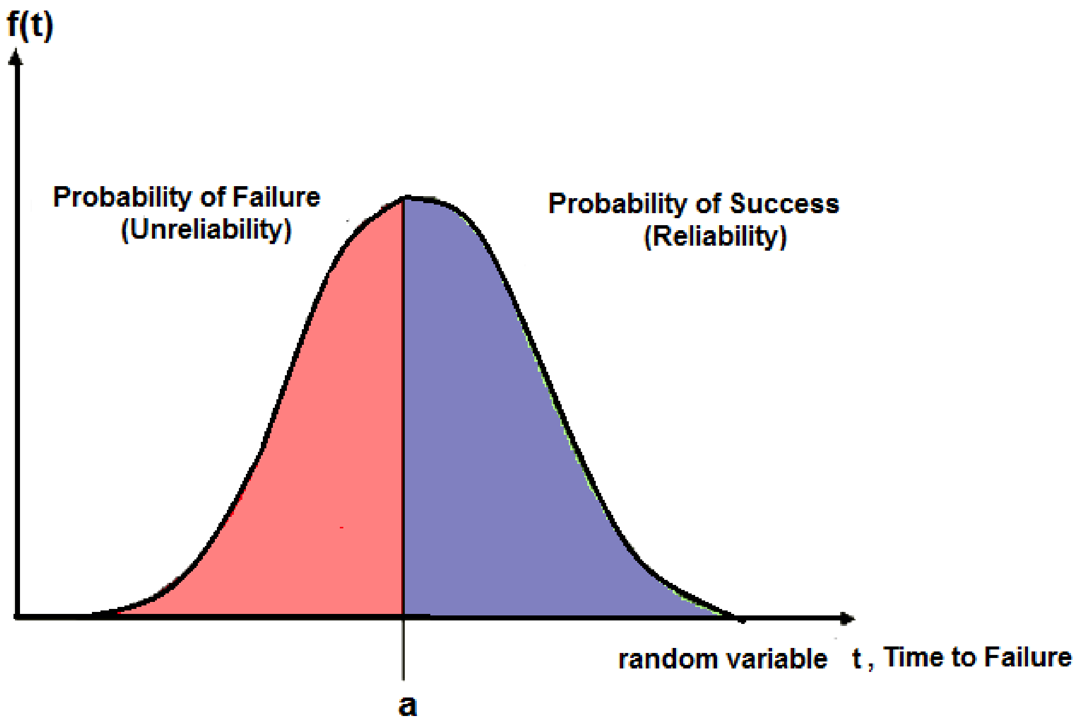

Figure 3.2 cdf characteristics and unreliability [4,19,20]

The reliability function of a three parameter Weibull distribution is given as,

$$R(T) = \exp - \left(\frac{T-\gamma}{\alpha}\right)^{\beta} \tag{3.7}$$

3.3.4 The Failure Rate Function

The number of failures occurring per unit time is a failure rate and mathematically it is shown as

$$\lambda(t) = \frac{f(t)}{1-\int_{0,\gamma}^{t} f(s)ds} = \frac{\mathrm{f(t)}}{\mathrm{R(t)}} \tag{3.8}$$

The Weibull failure rate function, λ (t), is

$$\lambda(t) = \frac{f(t)}{R(T)} = \frac{\beta}{\alpha}\left(\frac{T-\gamma}{\alpha}\right)^{\beta-1} \qquad (3.9)$$

3.4 Characteristics of Weibull distribution

Due to adaptability of the Weibull distribution, it is mostly used for life time data analysis. The three parameters, namely scale parameter (α), shape parameter (β) and location parameter (γ) are important to judge the model of life behaviors. The scale parameter α is usually a function of the applied voltage when the time is a random variable. The scale parameter α represents time required for 63.2 % of tested sample to fail. The shape parameter β or slope of the Weibull distribution is a measure of the time-to-breakdown. These parameters have influence on the Weibull distribution characteristics like pdf curve, reliability and failure rate. Following part of the chapter shows the influence of shape parameter β and scale parameter α on the Weibull distribution characteristics.

3.4.1 Shape Parameter (β)

The slope of regression line in probability plot is given by the shape parameter, β.

3.4.1.1 Effect of β on the pdf

From the figure 3.3 we can see that, for $0 \leq \beta \leq 1$, f (t) looks convex in shape and it decreases monotonically [$t \to 0$, $f(t) \to \infty$] [$t \to \infty$, $f(t) \to 0$] and for $\beta > 1$, f (t) increases as t tends to maximum value of pdf and it decreases subsequently.

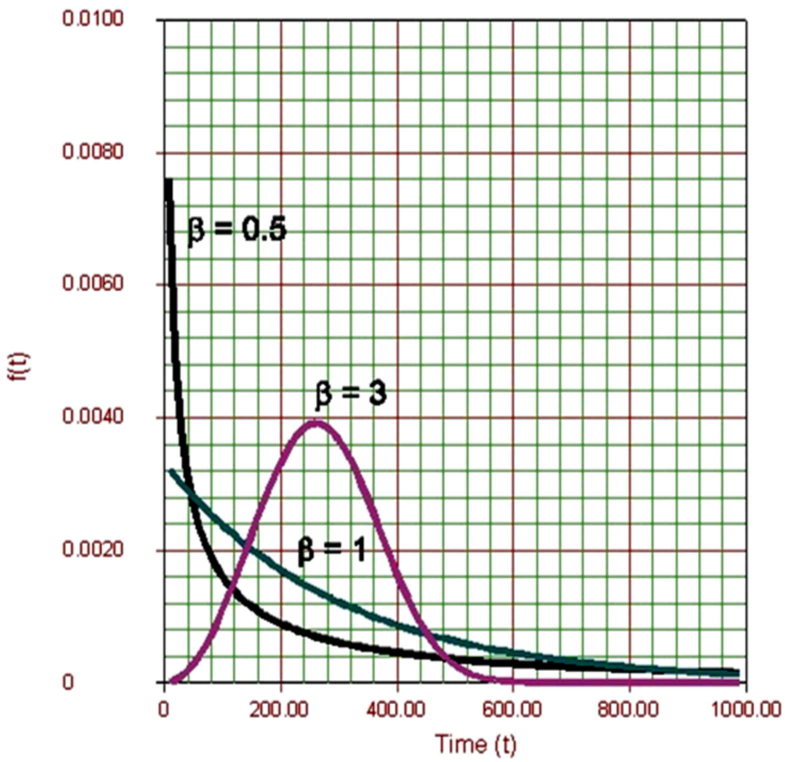

Figure 3.3 The effect of the Weibull shape parameter on the pdf [19,20]

3.4.1.2 Effect of β on the cdf and reliability function

Figure 3.4 shows effect of β on the cdf when scale parameter has fixed value,

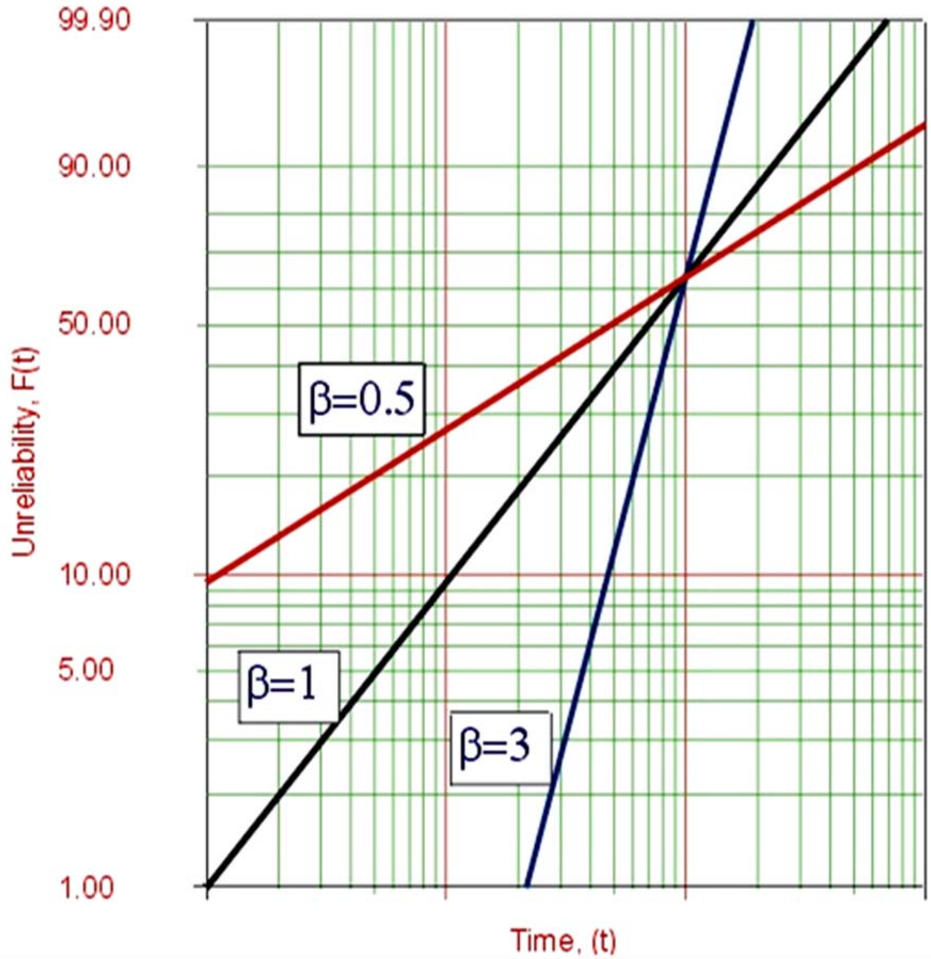

Figure 3.4 The effect β on the cdf [19,20]

Figure 3.5 shows the effect of different values of β on the reliability plot; from figure it's clear that reliability decreases sharply and has convex shape for values 0 <β <1 and even for β=1, but reliability decreases less sharply For β.>1 , reliability decreases as time increases. As wear out sets in, the curve goes through an inflection point and decreases sharply.

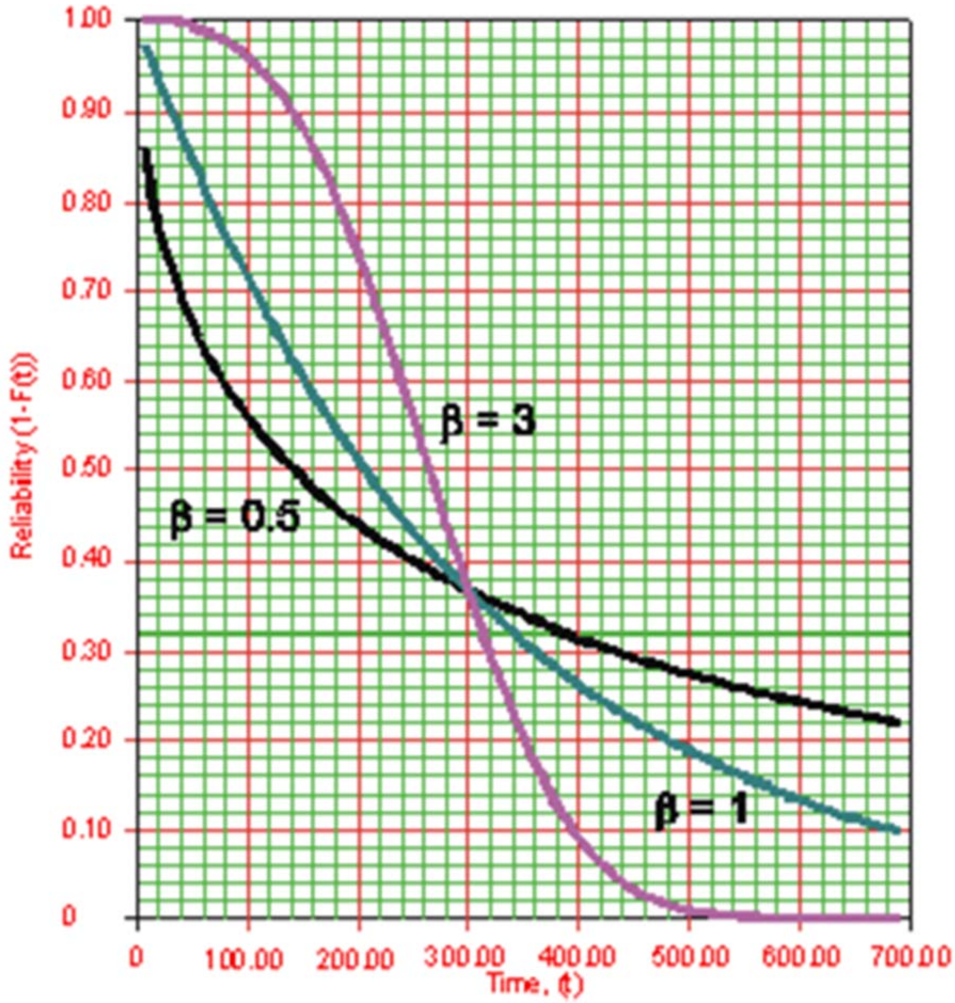

Figure 3.5 The effect β on the reliability [19, 20]

3.4.1.3 Effect of β on the failure rate

The value of β has a marked effect on the failure rate of the Weibull distribution. Figure 3.6 showed that with $\beta < 1$ exhibit a failure rate that decreases with time, $\beta = 1$ have a constant failure rate and $\beta > 1$ have a failure rate that increases with time.

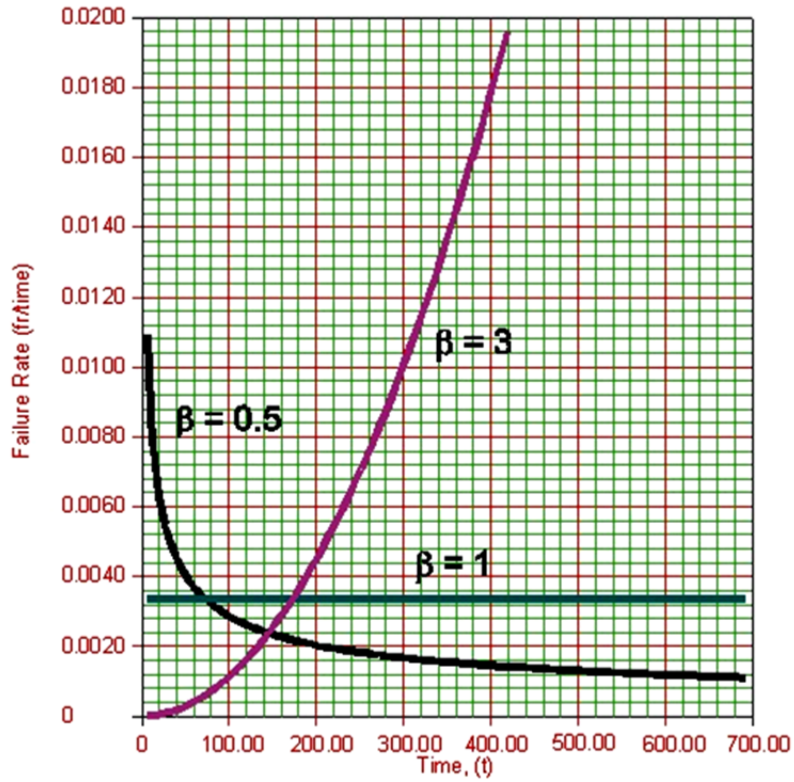

Figure 3.6 The effect β on the failure rate [19,20]

The value of shape parameter describes the failure methodology. If shape parameter $\beta < 1$, then failure is due to reasons like Burn-in testing and/or environmental stress screening are not well implemented, troubles in the production line, inadequate quality control, packaging and transit problems. If shape parameter $\beta > 1$, then failure is due to wear -out type failure means natural aging.

3.4.2 Scale Parameter (α)

Effect of change in scale parameter on distribution is like change of the abscissa If α is increased then the distribution gets stretched out to the right and its height decrease If α is decreased then the distribution gets pushed towards the right and its height increases.

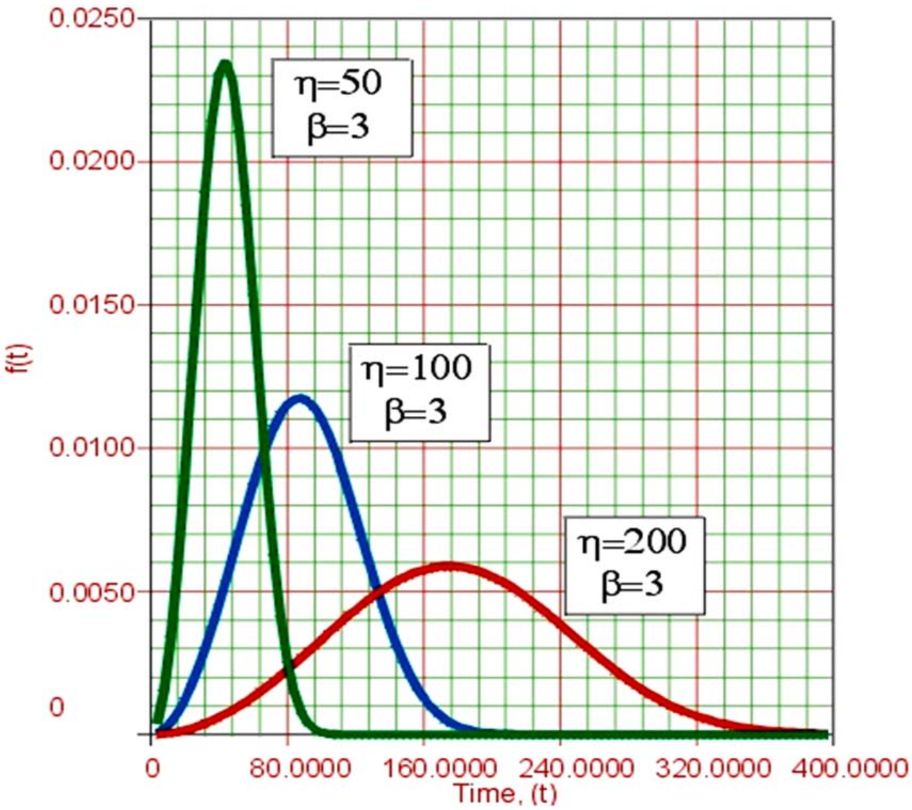

Figure 3.7 The effect α on the pdf [19,20]

In both the cases shape and location remains the same.

CHAPTER IV

BREAKDOWN IN SOLID DIELECTRICS

4.1 Introduction

Solid insulation plays a significant role in designing of the high voltage equipment. Solid insulation provides the insulation between live parts, and it helps as a mechanical support to the system. A good quality dielectric should have low dielectric loss, high mechanical strength, should be free from gaseous inclusion, and moisture, and be resistant to thermal and chemical deterioration. Solid dielectrics have higher breakdown strength internally compared to liquids and gases.

The breakdown of solid dielectrics depends upon the magnitude of voltage as well as the time for which voltage is applied. The strength of the solid dielectrics depend upon many factors like ambient temperature, humidity, duration of test, impurities or structural defects, type of voltage applied means ac , dc or impulse , pressure etc. The breakdown of solid dielectrics depends upon magnitude of voltage applied as well as time for which voltage is applied. Figure 4.1 shows the mechanism of failure. The various mechanism of breakdown of solids is divided according to time scale and they are as following [21].

- Intrinsic Breakdown
- Electromechanical Breakdown
- Thermal Breakdown
- Electrochemical Breakdown

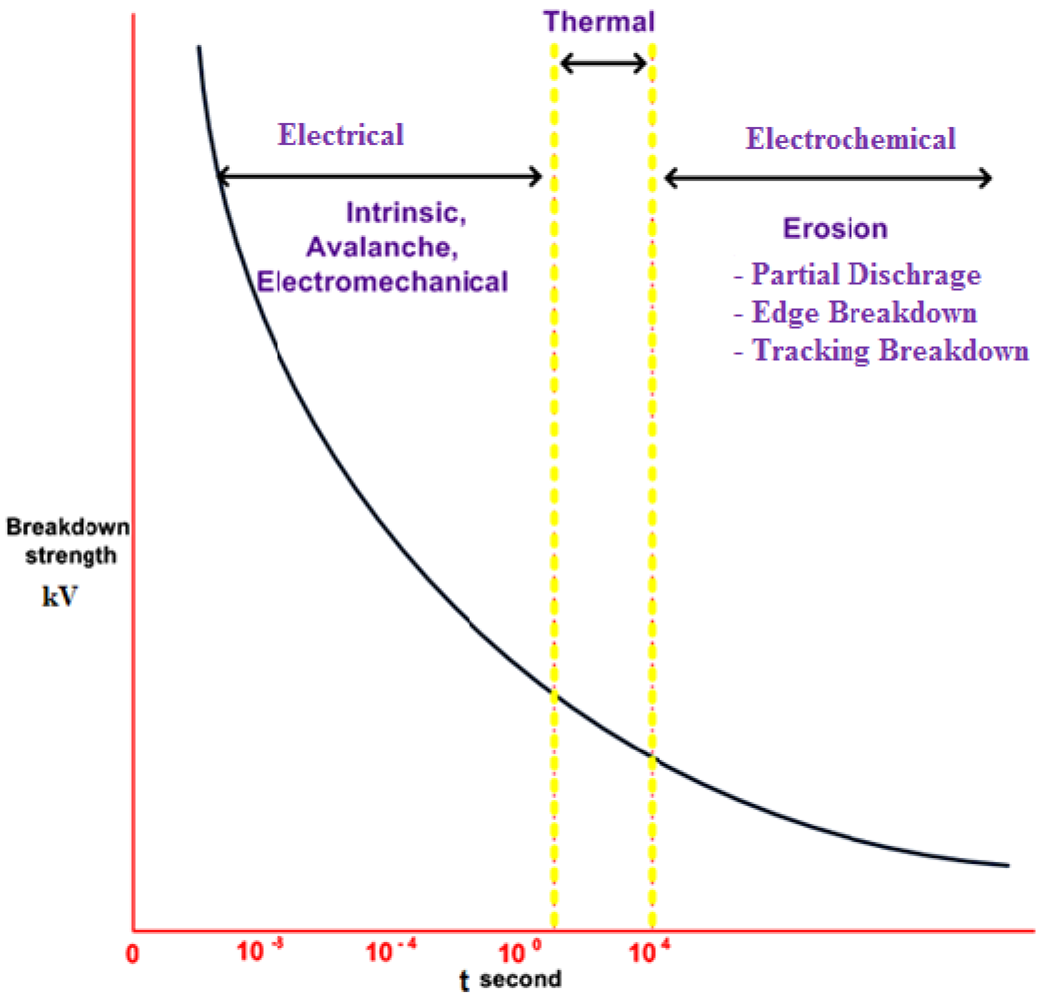

Figure 4.1 Mechanism of failure and variation of breakdown strength verses time of stressing [21]

4.2 Intrinsic Breakdown

The mechanism that leads to a sudden loss of insulating capabilities even after a short period of stressing, without appreciable preheating and without partial discharges, is called intrinsic breakdown [22]. When voltages are applied only for short durations of the order of 10^8 s the dielectric strength of a solid dielectric increases very rapidly to an upper limit called the intrinsic electric strength. The intrinsic strength mainly depends on structural design of material and temperature [23].

Intrinsic breakdown depends upon the presence of free electrons which are capable of migration through the lattice of the dielectric. Usually, a small number of conduction electrons are present in solid dielectrics, along with some structural imperfections and small amounts of impurities. The impurity atoms, or molecules or both act as traps for the conduction electrons up to certain ranges of electric fields and temperatures. When these ranges are exceeded, additional electrons in addition to trapped electrons are released, and these electrons participate in the conduction process. Based on this principle, two types of intrinsic breakdown mechanisms have been proposed [23].

4.2.1 Electronic Breakdown

Intrinsic breakdown occurs in time of the order of 10^{-8} s and therefore is assumed to be electronic in nature. The initial density of conduction (free) electrons is also assumed to be large, and electron-electron collisions occur. When an electric field is applied, electrons gain energy from the electric field and cross the forbidden energy gap from the valence band to the conduction band. When this process is repeated, more and more electrons become available in the conduction band, eventually leading to breakdown [23].

Figure 4.2 Schematic energy level diagram for an amorphous dielectric [21]

4.2.2 Avalanche or Streamer Breakdown

This is similar to breakdown in gases due to cumulative ionization. Conduction electrons gain sufficient energy above a certain critical electric field and cause liberation of electrons from the lattice atoms by collision. Under uniform field conditions, if the electrodes are embedded in the specimen, breakdown will occur when an electron avalanche bridges the electrode gap.

An electron within the dielectric, starting from the cathode will drift towards the anode and during this motion gains energy from the field and loses it during collisions. When the energy gained by an electron exceeds the lattice ionization potential, an additional electron will be liberated due to collision of the first electron. This process repeats itself resulting in the formation of an electron avalanche. Breakdown will occur, when the avalanche exceeds a certain critical size [23].

In practice, breakdown does not occur by the formation of a single avalanche itself, but occurs as a result of many avalanches formed within the dielectric and extending step by step through the entire thickness of the material [23].

4.3 Electromechanical Breakdown

In a dielectric material charges of opposite nature are induced on the two opposite surfaces when it is subjected to an electric field. Because of opposite charges force of attraction is developed and material is subjected to electrostatic compressive forces. Material breakdowns when these electrostatic compressive forces exceed the mechanical compressive strength. If the thickness of the specimen is d_0 and is compressed to thickness d under an applied voltage V, then the electrically developed compressive stress is in equilibrium if

$$\varepsilon_0 \varepsilon_r = \frac{V^2}{2d^2} = Y \ln\left[\frac{d_0}{d}\right] \quad (4.1)$$

Where,

- ε_0 is permittivity of free space
- ε_r is permittivity of the material
- Y is the Young's modulus

$$V^2 = d^2 \left[\frac{2\,\mathrm{Y}}{\varepsilon_0 \varepsilon_r}\right] \ln\left[\frac{\mathrm{d}_0}{\mathrm{d}}\right] \quad (4.2)$$

Usually, mechanical instability occurs when $\frac{d}{d_0} = 0.6$
Substituting this Eq.4.2, the highest apparent electric stress before breakdown,

$$E_{max} = \frac{V}{\mathrm{d}_0} = 0.6 \left[\frac{Y}{\varepsilon_0 \varepsilon_r}\right]^{\frac{1}{2}} \quad (4.3)$$

The above equation is only approximate as Y depends on the mechanical stress. Also when the material is subjected to high stresses the theory of elasticity does not hold good and plastic deformation has to be considered [21, 23, 24].

4.4 Thermal Breakdown

Most dielectrics show increasing electrical conductivity and decreasing thermal conductivity as the temperature increases. For this reason, breakdown at high temperatures tends to thermal in nature [40].

When an electric field is applied to a dielectric, conduction current however small it may be, flows through the material. The conduction current and dielectric losses due to polarization heats up the specimen and the temperature rise. The heat generated is transferred to the surrounding medium by conduction through the solid dielectric and by radiation from its outer surfaces. The heat generated is equal to the heat used to raise the temperature of the dielectric, plus the heat radiated then equilibrium is reached.

The heat generated under dc stress E is given as

$$W_{dc} = E^2 \sigma \quad \frac{W}{Cm^3} \tag{4.4}$$

Where,

- σ is the dc conductivity of the specimen

Under ac fields, the heat generated

$$W_{ac} = \frac{E^2 f \, \varepsilon_r \tan\delta}{1.8 * 10^{12}} \, \frac{\mathrm{W}}{\mathrm{Cm}^3} \tag{4.5}$$

Where,

- f= frequency in Hz,
- δ = loss angle of the dielectric material,

The heat dissipated (W_r) is given by

$$W_r = C_V \frac{dT}{dt} + div\,(K\ grad\ T) \tag{4.6}$$

Where,

- C_V= specific heat of the specimen,
- T = temperature of the specımen,

- K = thermal conductivity of the specimen,
- t = time over which the heat is dissipated.

Equilibrium is reached when the heat generated $W_{dc\ or}\ W_{ac}$ becomes equal to the heat dissipated (W_r). In actual practice there is always some heat that is radiated out. If $W_{dc\ or}\ W_{ac}$ is greater than W_r then system undergo breakdown.

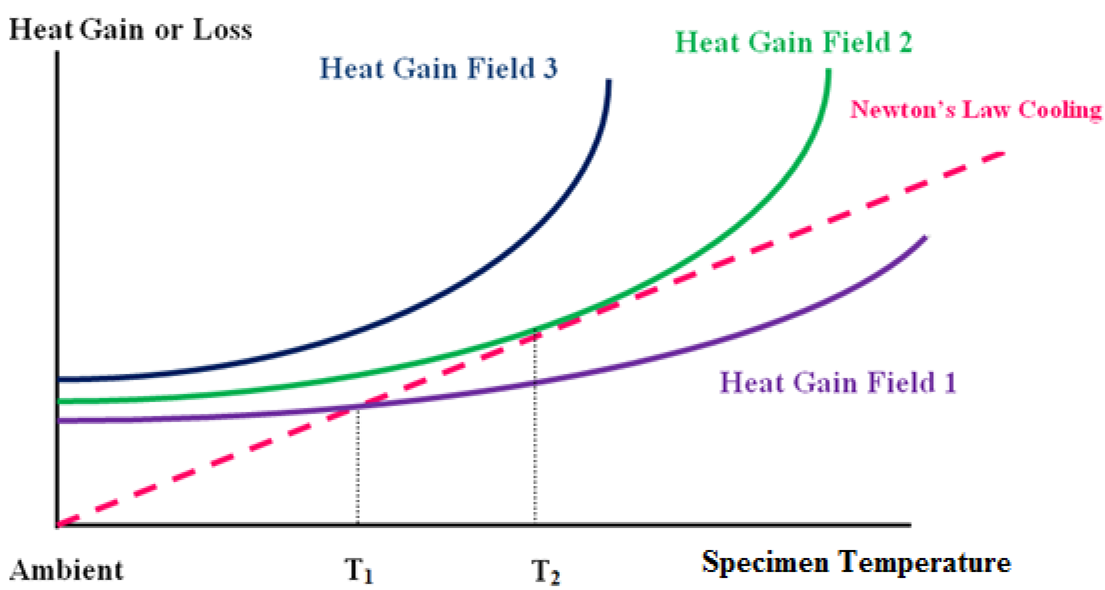

Figure 4.3 Thermal stability or instability under different applied fields [21]

Above Figure 4.3 shows the thermal instability condition. As temperature of system increase, even conductivity increase. When rate of heating exceeds rate of cooling, specimen undergo breakdown. From Figure we can see that field 1 is in equilibrium at temperature T_1, field $_2$ is in state of unstable equilibrium at T_2 and field 3 does not reach the state of equilibrium at all [21, 23].

4.5 Erosion Breakdown

Solid dielectrics have voids within the material or boundaries between electrode and solid dielectric .These voids are filled with the medium of lower breakdown strength, lower permittivity and higher filed intensity than solid dielectric. These filled mediums are gas or liquid dielectrics. Therefore, under normal working stress of the insulation system the voltage across the cavity may exceed the breakdown value and may initiate breakdown in void.

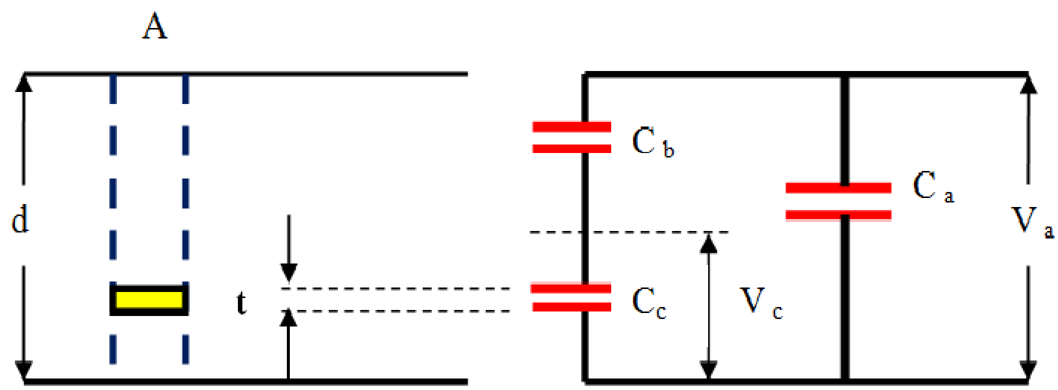

Figure 4.4 Electrical discharge in cavity and its equivalent circuit [21]

In above Figure 4.3, d is the thickness of dielectric, t is thickness of cavity .The analogue circuit is also shown, in this C_C is capacitance of cavity, C_b is capacitance of dielectric . C_C and C_b are in series and C_a is the capacitance of the rest of dielectric. Assume that the cavity is filled with gas and field strength across cavity (C_c) is

$$E_{c=\varepsilon_r} E_a \quad (4.7)$$

Where, ε_r is relative permittivity of the dielectric.

Let E_{cb} is cavity breakdown stress of gas filled cavity, then capacitance of cavity and capacitance of dielectric is given as

$$C_b = \frac{\varepsilon_0\, \varepsilon_r\, A}{d-t} \quad (4.8)$$

$$C_c = \frac{\varepsilon_0\ A}{t} \quad (4.9)$$

The voltage across cavity is

$$V_c = \frac{C_b}{C_b + C_c} V_a = \frac{V_a}{1+\frac{1}{\varepsilon_r}\left(\frac{d}{t}-1\right)} \quad (4.10)$$

Thus, the voltage across the dielectric which will initiate discharge in the cavity is

$$V_{ai} = E_{cb}\, t \left\{1 + \frac{1}{\varepsilon_r}\left(\frac{d}{t} - 1\right)\right\} \tag{4.11}$$

A void in the material is mostly almost spherical in practice so the internal field strength of the spherical cavity is given by

$$E_c = \frac{3\varepsilon_r E}{\varepsilon_{rc} + 2\varepsilon_r} = \frac{3E}{2} \tag{4.12}$$

For $\varepsilon_r \gg \varepsilon_{rc}$, and E is average stress in dielectric. Cavity may breakdown when V_c cavity voltage reaches breakdown value V^+ of the gap t under an applied voltage V_a.

The sequence of breakdowns under sinusoidal alternative voltage is shown in Figure 4.5. The red curve shows the voltage that would appear across the cavity if it did not break. As V_c reaches value V^+, discharge takes place, the voltage V_c collapses and the gap quenches. The voltage across the cavity then starts growing again until it reaches V^+, when new discharge occurs. Therefore, several discharges may take place during the positive cycle of the applied voltage. Also, during negative cycle of applied voltage, several discharges take place when cavity voltage V_c reaches V^-.

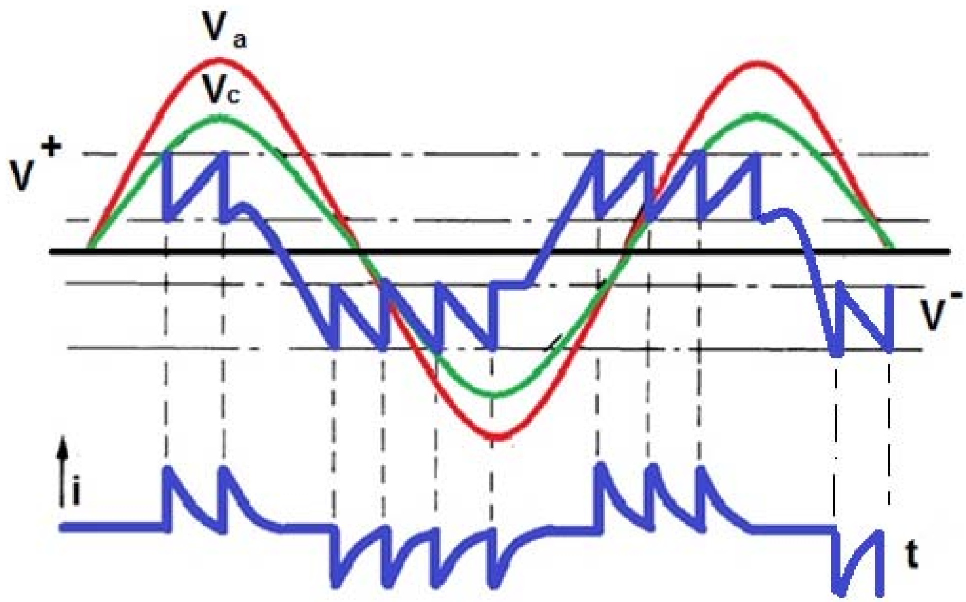

Figure 4.5 Sequence of cavity breakdown under alternating voltages [21]

Surface of the insulation provides instantaneous anode and cathode when gas in the cavity breakdowns. Few of electrons imposed on anode are so active to break chemical bonds of the insulation surface. Insulation gets damaged when cathode bombardments by positive ions causes increase of surface temperature and generate local thermal instability. In addition channels and pits are formed and they elongate through insulation by edge mechanism. Erosion takes place in the beginning over a large area when discharges occur on the insulation surface. Surfaces became rough because of erosion and slowly break through the insulation and at some point will give rise to channel propagation and tree like growth through the insulation [21,23,24].

Previous studies show that the failure mechanism of tested samples of magnet wire under ac voltage show multi failure mode of operation, namely partial discharge and aging caused by electrical stresses. On the other hand, aging at dc voltage shows that the failure of the tested samples is attributed basically to thermal and electrochemical breakdown. In this study of Magnet wire MW 16-C the partial discharge / erosion breakdown is main cause of failure of wire along with electrical stresses for ac voltages and under dc voltage breakdown occurred because of thermal instability. So, this chapter describes impact of these physical quantities on breakdown of magnet wire.

CHAPTER V

LITERATURE REVIEW

5.1 Introduction

Insulation of system is of a prime importance in designing of electrical equipment. For reliable design of electrical equipment, continuous efforts have been made to study ageing mechanism of electrical insulation system and to formulate mathematical model to describe the ageing process under the dominating factor of influence [25].

The two well know approaches for studying the electrical breakdown of polyimide insulating material are phenomenological studies and statistical analysis of failures of electrical insulation due to presence of degrading stresses, such as electrical, thermal and other environmental factors. The complete understanding of breakdown mechanism is required in phenomenological studies. Physical and/or chemical tests are performed on the insulating material in phenomenological studies and then mathematical model functional with life time is developed. In approach of statistical analysis, alike specimens of solid insulation are subjected to life tests to measure time to breakdown of samples. Weibull probability distribution is used to model the data of life tests [26].

To set up a correlation between aging process and the stresses causing it, to propose models, and to validate them is the main objective of aging studies. An accelerated aging process is the key for all this and the results of accelerated aging studies are applied to normal operating conditions. Due to time limitation, realistic long-term tests at working stresses are not achievable. For example, underground transmission cables are designed for forty years of service. Hence, it's very helpful for designer engineers to envisage end of life with certain degree of accuracy in small time duration by accelerating the aging process. This is the reason that the accelerated aging tests are generally accepted methods for estimating the service-life and other characteristics of solid electrical insulation [28].

Accelerated aging test is performed mainly with one or a few dominant stress parameters, while the others are kept near operating stress. Single stress and multi-stress life models are mainly used to estimate the lifetime model of the insulation.

5.2 Single Stress Life Models

Voltage and Temperature are two important factors used for the accelerated aging test. There are two single life stress models namely life models for electrical stress and life models for thermal stress. Life models for electrical stress include the inverse power law model and exponential law model and that for thermal stress is the Arrhenius model [27].

5.2.1 Life Models for Electrical Stresses

The electrical aging models describe aging in any insulation system that experiences an electrical field. Electrical stress is the major factor that causes degradation of electrical insulation of the system. Two major models relating the test stress with the time to failure are universally accepted: the inverse power model and the exponential model. These models are empirical models as they neither take into account the exact type of ageing process, e.g., whether partial discharges are present or not nor they consider the system structure, like the particular electrode configuration. Though, the models have demonstrated to fit reasonably well with experimental data [27,29,30].

5.2.1.1 Inverse Power Law

In the aging studies under electrical stresses the inverse power law is the most frequently used model and is given as,

$$L(V) = k\,V^{-n}$$
$$\log L = \log k - n \log V \qquad (5.1)$$

Where, L is the time -to-breakdown and is usually a Weibull scale parameter α at 63.2 % probability, or any other percentile, V is applied voltage, and k,n are constants to be determined for the specific tested material . By plotting the graphs with the time to breakdown for corresponding voltage stress in logarithm plot, a straight line is obtained, which determines the constant parameters. The inverse law is valid if plot fits straight line [27,29,30].

5.2.1.2 Exponential Law

The other than Inverse power law the best know model of lifetime calculation is Exponential law and is given as,

$$L(V) = c \exp(-k\,V)$$
$$\log L = \log c - k\,V \qquad (5.2)$$

Where, L is time to failure, V is applied voltage, and c and k are constants to be found from experimental data. Again, the validity of exponential model is checked by plotting the data points on semi-log paper and plot should be straight line to be valid [27,29,30].

5.2.2 Life Model for Thermal Stresses

One of the major factors that decide the rating of electrical insulation is its thermal capability. The thermal capability of insulating material is found out by thermal aging test. Thermal aging, i.e. aging due to elevated temperature, is associated with thermally activated rate processes. The backbone of the thermal aging studies is Arrhenius relation. Dependency of chemical reaction rate on the temperature is shown by this Arrhenius equation.

$$L(T) = A \exp\left(\frac{B}{T}\right) \tag{5.3}$$

Where, L is time-to-breakdown, T is absolute temperature, A and B are constants determined by the activation energy of the reaction. Similar to the voltage aging models, when log life is plotted against reciprocal of absolute temperature (l/T), a straight line results [27,29,30].

5.3 Multi stress Life Models

Multi stress models are of special significance in recent growth in the aging studies on electrical insulation. In multi stress life tests, system is subjected to more than one stress at a time. When an insulating system is subjected to more than one aging factor interactions may come into play. There are two main types of interaction direct interaction and indirect interaction. In direct interaction factors act simultaneously and indirect interaction essentially remains the same whether the aging factors are applied sequentially or simultaneously. An example of direct interaction is oxidation - both oxygen and elevated temperature is needed at the same time to give synergy effect. Indirect interaction may be the result of mechanical and electrical stress. Micro voids created by the mechanical stress may give rise to partial discharge activity. Interaction causes the ageing process to proceed at a faster rate compared to the sum of the corresponding single stress rates. In which way principal ageing models for combined thermal-electrical stress take synergy effects into account [30]. Multi stress models relate the connections of electrical and thermal stresses by using multiplicative law. The life under combined stresses is linked to product of life under single stress in multiplicative law. The formula derived from the multiplication of the inverse power law model and Arrhenius relationship and is given as,

$$L(V,T) = k\,V^{-n}\,exp\left(\frac{B}{T}\right) \tag{5.4}$$

Above equation (5.4) is the basis for Simoni'd and Ramu's electrical-thermal life models. The other model that expresses relation between electrical exponential model and Arrhenius relationship is given as,

$$L(V,T) = Cexp\left(\,AV + \frac{B}{T}\right) \tag{5.5}$$

Equation 5.5 is the origin of the Falo's model. Montanari et.al presents one more model based on the inverse power law. A concise outline of all electrical- thermal life models of Simoni, Ramu, Fallou, and probabilities model of Montanari are discussed in this chapter along with electrical-thermal-frequency life models.

5.3.1 Simoni's Model

The Simoni's model shows that the insulation life-time at a specific voltage and temperature, in relative terms with respect to a reference life-time determined at room temperature and an electrical stress and is given by [25].

$$L(V,T) = \ t_0\left[\frac{V}{V_0}\right]^{-\mathrm{n}} \exp\left(-\mathrm{B}\Delta\left(\frac{1}{\mathrm{T}}\right)\right) \tag{5.6}$$

Where, t_0 is the time-to-breakdown at room temperature, V=V_0 $\Delta\left(\frac{1}{T}\right) = \frac{1}{T} - \frac{1}{T}$,

and B and n are constants to be determined experimentally [33].

5.3.2 Ramu's Model

The Ramu's model is obtained from a multiplication of classical single stress laws, and is given by [26],

$$L(V,T) = K(T)\,[V]^{-n(T)} \exp\left(-B\Delta\left(\frac{1}{T}\right)\right) \quad (5.7)$$

Where, K (T) = exp (K_1-$K_2\Delta\left(\frac{1}{T}\right)$), n (T) = exp (n_1-$n_2\Delta\left(\frac{1}{T}\right)$), K_1, K_2, n_1, and n_2 are constants. $\Delta\left(\frac{1}{T}\right)$ is the same as that defined for the Simoni's model [34].

5.3.3 Fallou's Model

Fallou projected a semi-empirical life model which is stood on the exponential model for electrical aging,

$$L(V,T) = C\exp(AV + \left(\frac{B}{T}\right)) \quad (5.8)$$

Where, C, A, and B are electrical stress constants and must be determined experimentally from time-to-breakdown curves at constant temperatures [37].

5.3.4 Montanari's Probabilistic Model

The relation between the failure probability p to the insulation life L_p is given by the probabilistic life model of combined electrical and thermal stresses of Montanari et al. It is based on substituting the scale parameter in the Weibull distribution with the life using inverse power law. For a given time-to-breakdown probability p, the probabilistic model is given as,

$$L_p(V,T) = L_s(\frac{V}{V_s})^{n}\,[-\ln(1-p)]^{\left(\frac{1}{\beta(T)}\right)} \quad (5.9)$$

Where, L_p is a lifetime at probability p, L_s is a time-to-breakdown at reference voltage V_s, and β is the shape parameter [26, 35].

5.3.5 Electrical-Thermal Model

At Mississippi State University High Voltage Laboratory, electrical-thermal model is developed when insulation of magnetic wire is stressed with voltage and temperature performing accelerated aging test. The Electrical-Thermal model is given as,

$$L(V,T) = C\exp\left(\frac{A}{V} + \frac{B}{T}\right) \quad (5.10)$$

Where, L is the life-time at 63.2% probability of breakdown, V is the applied voltage, T is the temperature, and C, A, and B are constants to be determined by analyzing the combined voltage-temperature life data.

Natural logarithm plot is used to liberalize the equation 5.10. The life-time versus the stress, either voltage V or temperature T, and keeping the other one constant is plotted to find a set of linear curves. The slope of the linearized Arrhenius equation when the voltage is constant is given by B and the slope of the exponential electrical function model when the temperature is constant is A [2,26].

Assume life-time is a random variable then the model shown by equation (5.10) can be transformed into a probabilistic model by setting the scale parameter α of the Weibull distribution equals to L (V,T). The time-to-breakdown of the electrical insulation under combined electrical and thermal stresses is statistically distributed according to a Weibull distribution, then the Weibull pdf can be written as,

$$L(V,T) = K\exp\frac{B}{V}\,T^{-n} \quad (5.11)$$

Where, L is the life-time at 63.2% probability of breakdown, V is applied the voltage, T is the temperature and K, B and n are constants to be determined by analyzing the combined voltage- temperature life data [2, 26].

5.3.6 Electrical-Thermal-Frequency Model

The life time model due to thermal and electrical stresses at ac voltage and dc voltage for industry frequency is discussed till now. The insulation material like insulation in the inverter-fed motors, no longer experiences a traditional sine wave voltage that is a steady state condition, but instead experiences a pulse-wave with significant harmonics and transients. The work was done at Mississippi State University using high frequency square pulse voltage as an electrical stress to obtain the lifetime model of magnet wire insulation. S. Grzybowski et al. deduced the frequency-electrical-thermal life model based on the application of high frequency pulse voltage. The electrical-thermal- frequency life-time model is a general multi stress model, which includes the effect of voltage magnitude, temperature and frequency. It is a probabilistic life-time model and is given by

$$L(V,T,F) = K\, f^{\,(m_1+\frac{m_2}{V})} \exp\left(\frac{A}{V}+\frac{B}{T}\right) \tag{5.12}$$

Where t time-to-breakdown at 63.2% probability of failure, for specific voltage and temperature V is the test voltage at the specific temperature, T, T is the test temperature in Kelvin, f is the frequency in Hz, K, A, m_1, and m_2 are constants must be determined experimentally [2, 16,26].

CHAPTER VI

EXPERIMENTAL SETUP

6.1 Introduction

Magnet wires are used in machine windings and magnetic wire's insulation is stressed by the voltage and temperature. These stresses do degradation of the insulation. The ability to predict accurately the long-term voltage endurance performance of wire is essential both to the wire manufacturer and to the motor manufacturer [32].Therefore it is very important to study the degradation of the insulation stressed by voltage and temperature. To study the accelerated degradation of machine insulation, a popular practice used is to study the twisted pair samples under different aging conditions. The twisted pair samples are prepared according to NEMA standard. This standard specifies the number of twists and the tension to be applied for making the twisted pair depending on the size of the wire. In this experiment the magnet wire tested was NEMA MW 16-C, wire size was 14 AWG, diameter of 0.0641 inches nominal.

6.2 Dielectric Test System

The accelerated degradation of the insulation of magnetic wire was performed using the Dielectric test system (DTS) as shown in Figure 6.1 .The DTS-1500 is an integrated test system used to study the failure mechanism of the machine winding insulation by simulating the electrical and thermal stresses under controlled and accelerated conditions. The DTS-1500 test system is designed to vary and monitor electrical and thermal test parameters for up to five samples simultaneously.

The Dielectric test system was set up with

- An ac source test system for accelerated degradation testing of twisted pair samples that can be varied from 0 to 12 kV
- A 10 kV dc source test system for accelerated degradation testing of twisted pair samples
- A convection air-circulating oven whose temperature can go up to 260^{O}C starting from room temperature to aid testing at a controlled and elevated temperature of twisted pair magnetic wire samples. Five samples can be aged simultaneously in the oven.
- For an ac system, an oscilloscope which was calibrated with 1:1000 ratio using a voltage divider.
- A timer that counts the time to breakdown for the samples.

Figure 6.1 The Dielectric Test System

6.3 Sample Preparation

According to NEMA standard to study of the electrical insulation system for a machine winding a twisted pair method is used. The twisted wire sample is as shown in Figure 6.2.

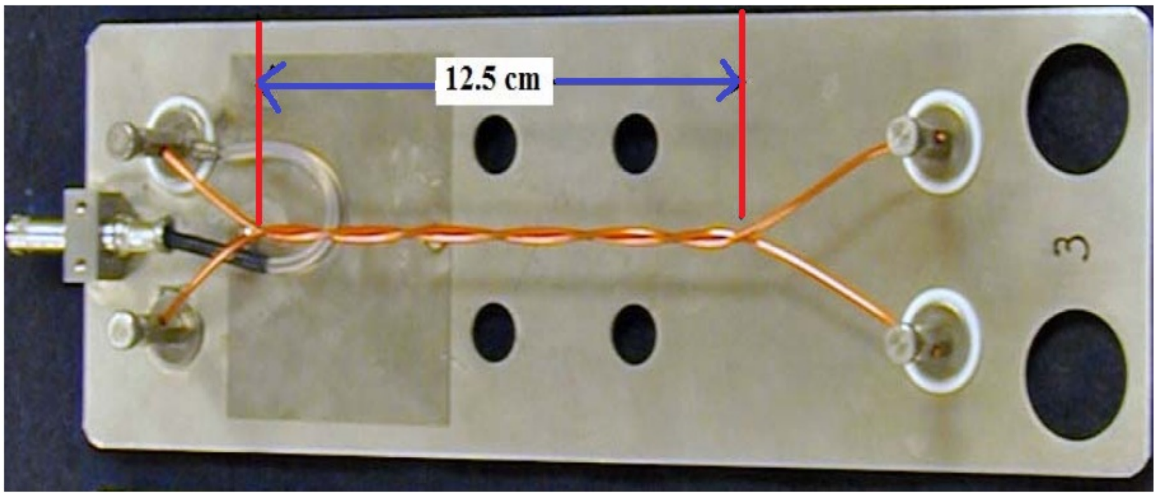

Figure 6.2 Twisted Pair sample on DTS tray [16]

NEMA standard specifies the number of twists required for the twisted wire samples. A specimen of wire is formed into a "U" shape, and the two legs are twisted together the number of 360^{o} rotations specified in Table 6.1 to form an effective length of 4.75±0.25 inches (121 mm±6 mm). The total tension on the two legs and the total number of rotations is shown in Table 6.1 [16, 38].

In the DTS largest wire diameter can be used is a 14 AWG size round conductor. More than 4 full twists are not allowed with a tension force of 12 pounds to magnetic wire according to NEMA standard. A device that counts the number of twists and puts consistent tension on the wire during the twisting process, called twist fabricator, is used to prepare samples.

Table 6.1 Tension and rotation of Twisted samples [16, 38]

AWG Size	Total Tension on Specimen (± 2 %)	Total Number of Rotations
8-9 *	24 lb (107 N)	3
10-11	24 lb (107 N)	3
12-14	12 lb(53 N)	4
15-17	6 lb (27 N)	6
18-20	3 lb (13 N)	8
21-23	1.5 lb (7 N)	12
24-26	340 gm (3.3 N)	16
27-29	170 gm (1.7 N)	20
30-32	85 gm (0.8 N)	25
33-35	40 gm (0.4 N)	31
36-37	20 gm (0.2 N)	36

.

Figure 6.3 shows the dielectric twist fabricator used to prepare the samples according to the NEMA standard for a 14 AWG size round conductor. After preparation of the sample, insulation is removed from both ends of the wire for a solid electrical connection to the high voltage and ground terminal in the DTS.

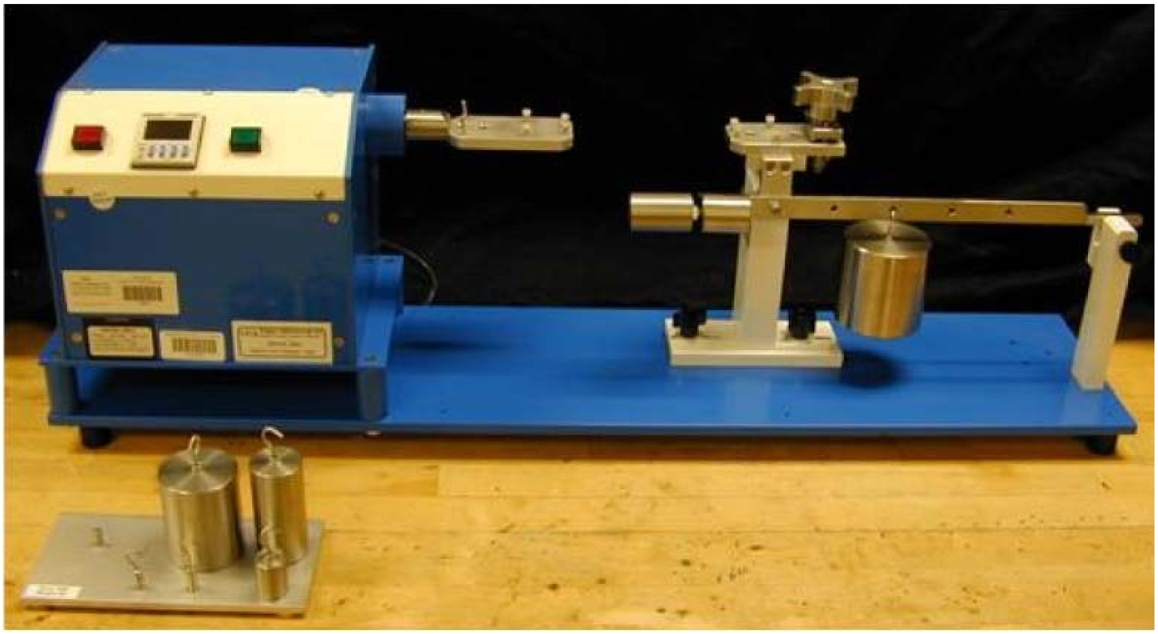

Figure 6.3 Dielectric Twist Fabricator [16]

The two different kinds of samples are made to take measurements. The twisted pair sample on one side energized with high voltage on one leg and other leg is grounded but, in one sample two legs on other side is left open floating as shown in Figure 6.4.And in second kind of sample, the two legs which are of other side of sample are turn round as shown in Figure 6.5.

Figure 6.4 First Kind of Sample

Figure 6.5 Second Kind of Sample

6.4 Accelerating Aging with 60 Hz ac voltage

For accelerated aging of insulation of magnetic wire constant stress test procedure is used. In constant stress test the applied voltage is held constant and time-to-breakdown is noted. The NEMA MW-16 C wire is used for the experiment which has temperature rating of 240^{O}C. Figure 6.6 shows the experimental set up to obtain time-to-breakdown of NEMA MW 16-C insulation at various 60 Hz ac stress level.

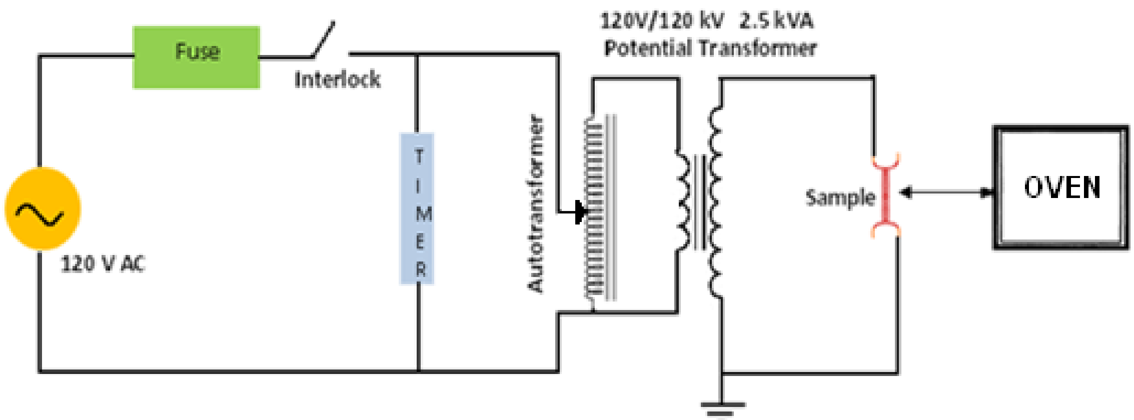

Figure 6.6 Setup Circuit for accelerated aging at 60 Hz ac voltage [16]

The main breaker connected to the ac source trips the interlock when a sample is broken by sensing high current flow through the short circuited magnet wire which stops the timer. After breakdown the entire system was shut down in order to determine which sample was broken. All samples were removed from the oven and were tested using insulation tester to find the broken sample. The insulation tester used is shown in Figure 6.7. It is basically a mega ohm-meter which applies high dc voltage across the twisted pair samples and measures the insulation resistance. If the sample is broken the meter reads very low resistance as high voltage cannot be applied across the short circuited sample. Using this we can separate out broken sample from unbroken samples. The unbroken samples are again placed back into the oven and the system is again restarted.

Figure 6.7 Insulation Tester : Meg Ohm Meter

The accelerated aging are conducted over the 60 Hz ac effective voltage range from 1.5 kV to 3 kV at room temperature of 23^{O}C, and from 1.5 kV to 3 kV at 70 ^{O}C and 190^{O}C, using a minimum of four samples of first kind and second kind at each test condition.

6.5 Accelerating Aging with 10 kV dc voltage

Figure 6.8 shows the experimental test set up used for accelerated aging of insulation of magnet wire. Magnet wire MW 16-C, thermal rating 240^{O}C is used and it is stressed with 10 kV dc voltages at room temperature and at elevated temperature and time-to-breakdown is noted down.

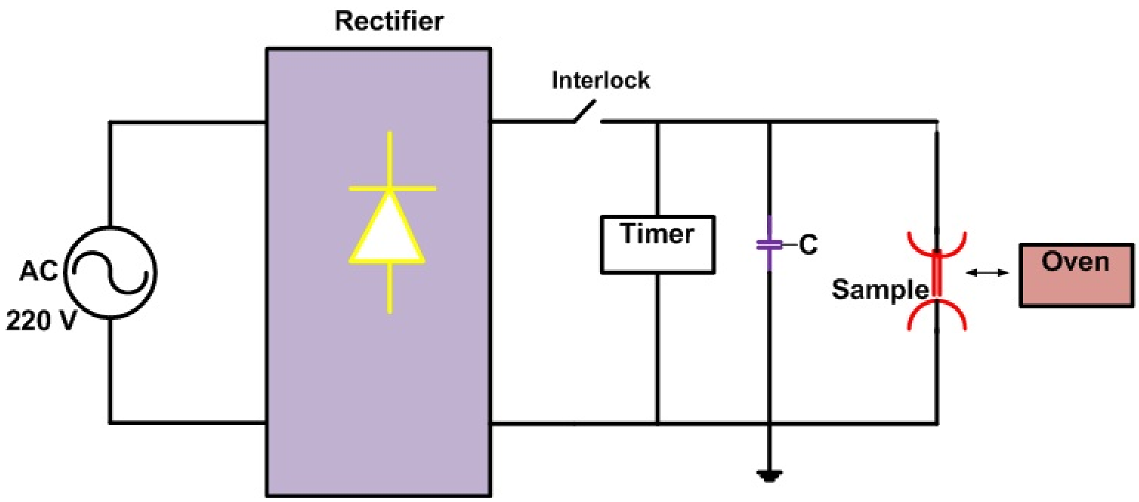

Figure 6.8 Set up diagram for 10 kV dc for accelerated aging of magnet wire

The accelerated aging is conducted at 10 kV dc voltages at room temperature of $23^{O}C$ and $190^{O}C$ using a minimum of four samples of second kind at each test condition.

CHAPTER VII

TEST RESULTS

7.1 Accelerated Degradation with ac 60 Hz Voltage

7.1.1 Weibull Distribution

Two parameter Weibull distributions are used for analysis of time to breakdown. The two parameter Weibull pdf is given as,

$$f(T) = \frac{\beta}{\alpha}\left(\frac{T}{\alpha}\right)^{\beta-1}\exp-\left(\frac{T}{\alpha}\right)^{\beta} \quad (7.1)$$

Where, α is the 63.2% nominal life time, and β is the shape or variance parameter. The time to breakdown value is obtained for a minimum of four samples at the particular voltage level, ranging from 1.5 kV to 3 kV.

The Weibull plots in Figure 7.1 through Figure 7.4 show the plots for the twisted pair of samples of first kind and Figure 7.5 through Figure 7.8 shows the Weibull plots of the twisted pair of sample of second kind. From the graphs, it is obvious that the shape factor β increases with test voltage, while being nearly invariant with respect to temperature. Such voltage dependence indicates a change in the physical aging process when the test voltage is increased from 1.5 kV to 3 kV. Table 7.1 and Table 7.2 represents time to breakdown (63.2% probability) values obtained from the Weibull distribution plot from 1.5 kV to 3 kV for temperatures of 23^{O}C, 70^{O}C, and 190^{O}C, respectively.

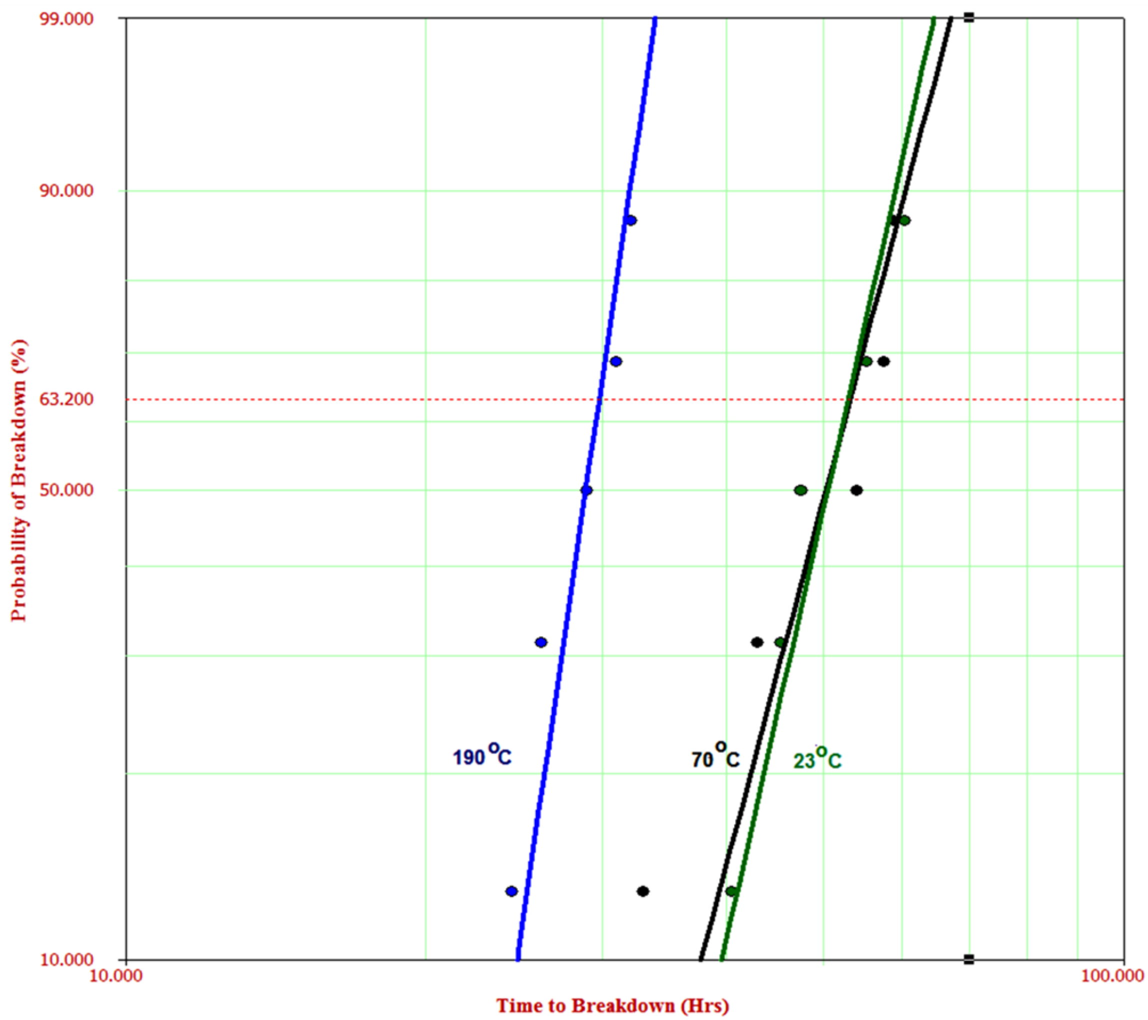

Figure 7.1 Weibull plots of 60 Hz breakdown voltage probability of twisted samples of first kind aged at 1.5 kV at $23^{O}C$, $70^{O}C$ and $190^{O}C$

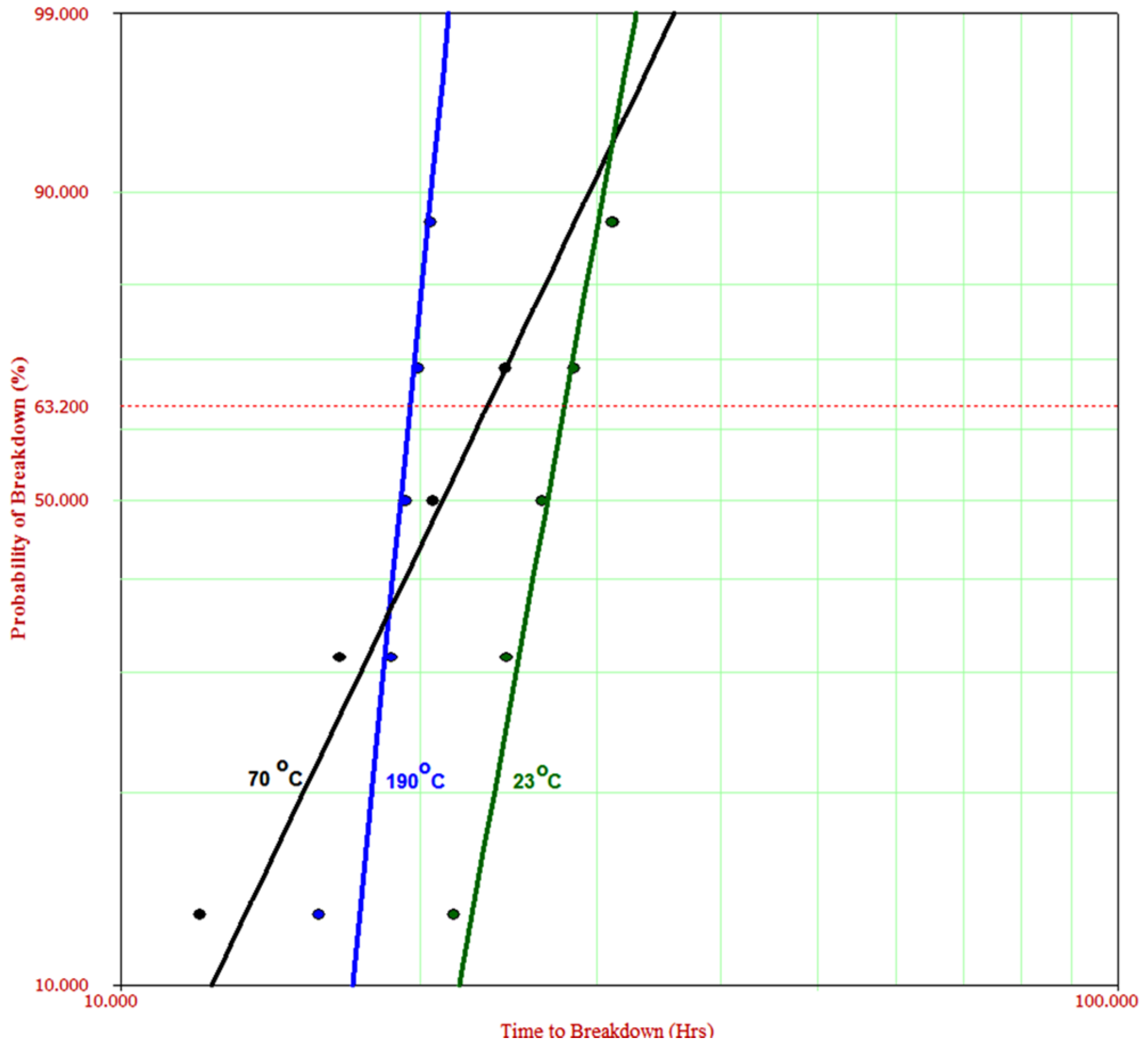

Figure 7.2 Weibull plots of 60 Hz breakdown voltage probability of twisted samples of first kind aged at 2 kV at $23^{O}C$, $70^{O}C$ and $190^{O}C$

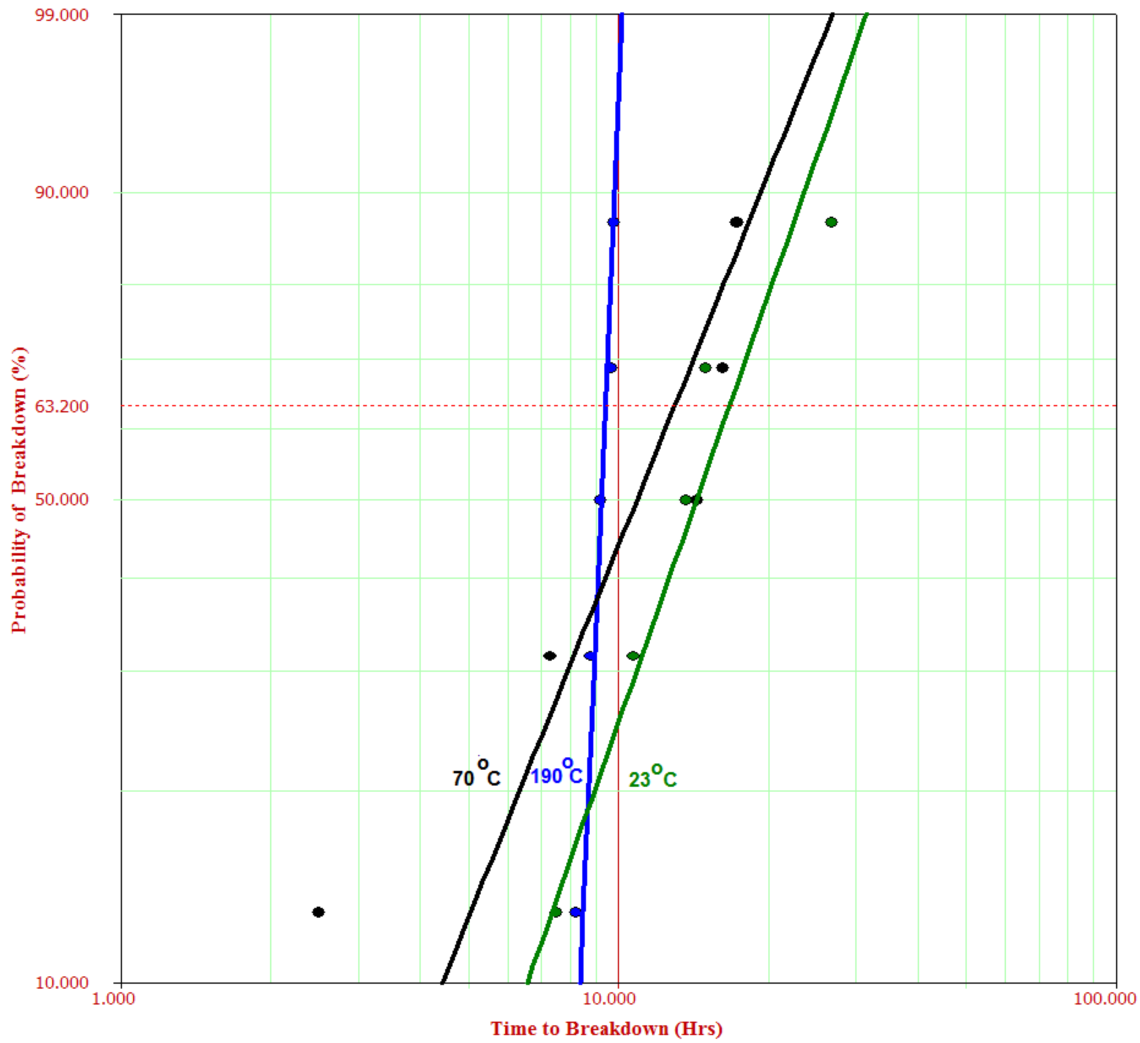

Figure 7.3 Weibull plots of 60 Hz breakdown voltage probability of twisted samples of first kind aged at 2.5 kV at $23^{O}C$, $70^{O}C$ and $190^{O}C$

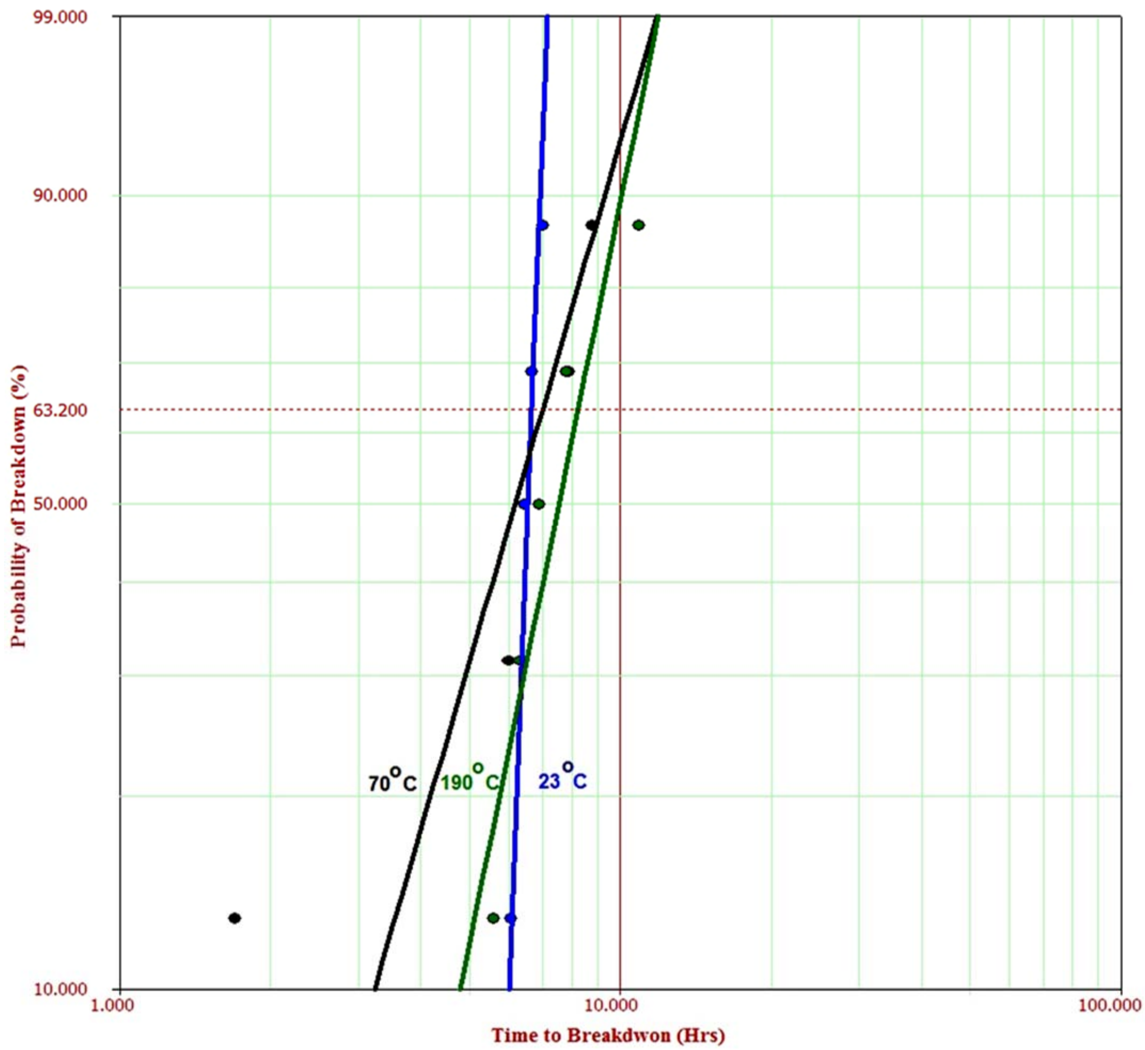

Figure 7.4 Weibull plots of 60 Hz breakdown voltage probability of twisted samples of first kind aged at 3 kV at 23^{O}C , 70^{O}C and 190^{O}C

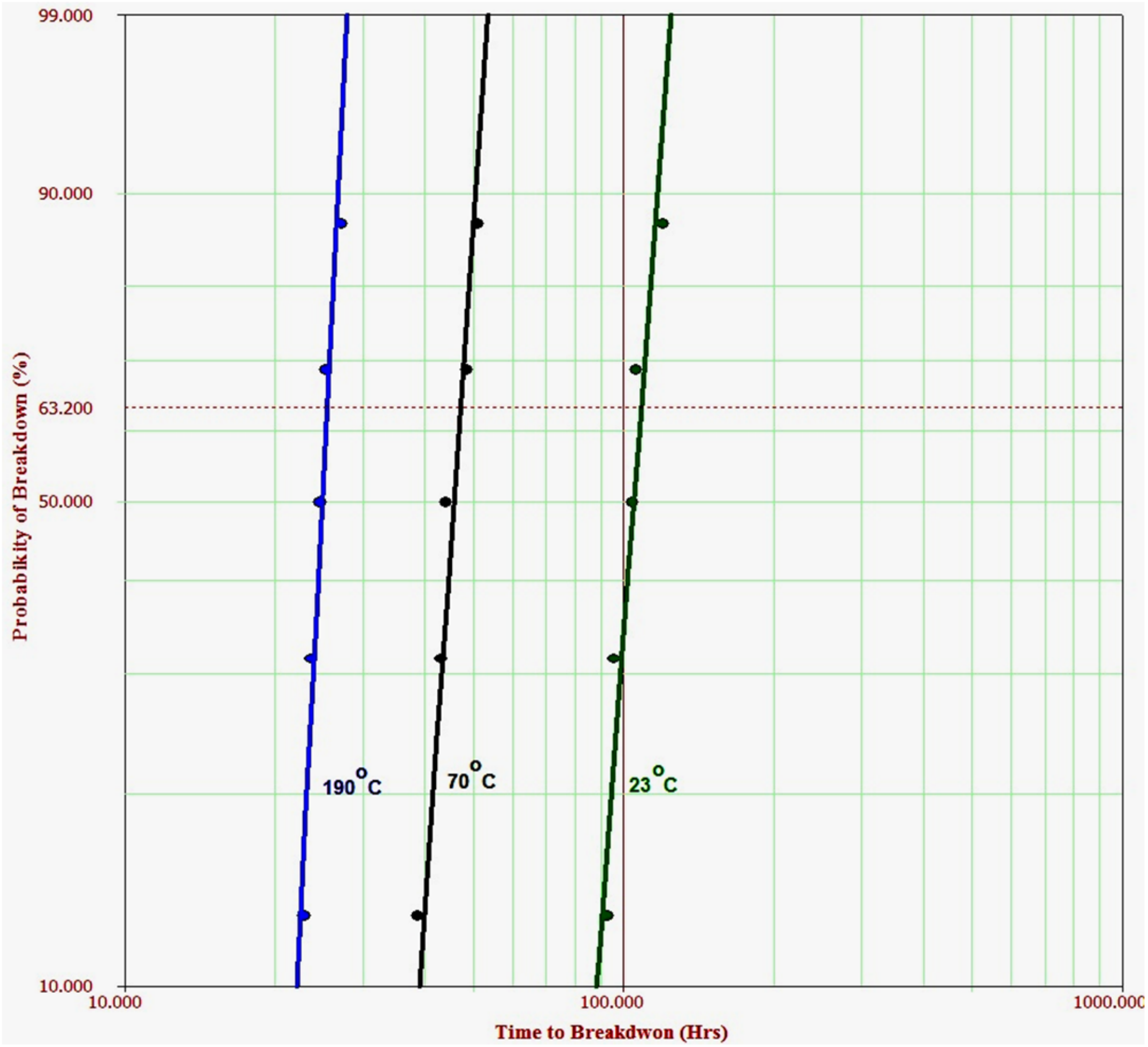

Figure 7.5 Weibull plots of 60 Hz breakdown voltage probability of twisted samples of second kind aged at 1.5 kV at 23^{O}C , 70^{O}C and 190^{O}C

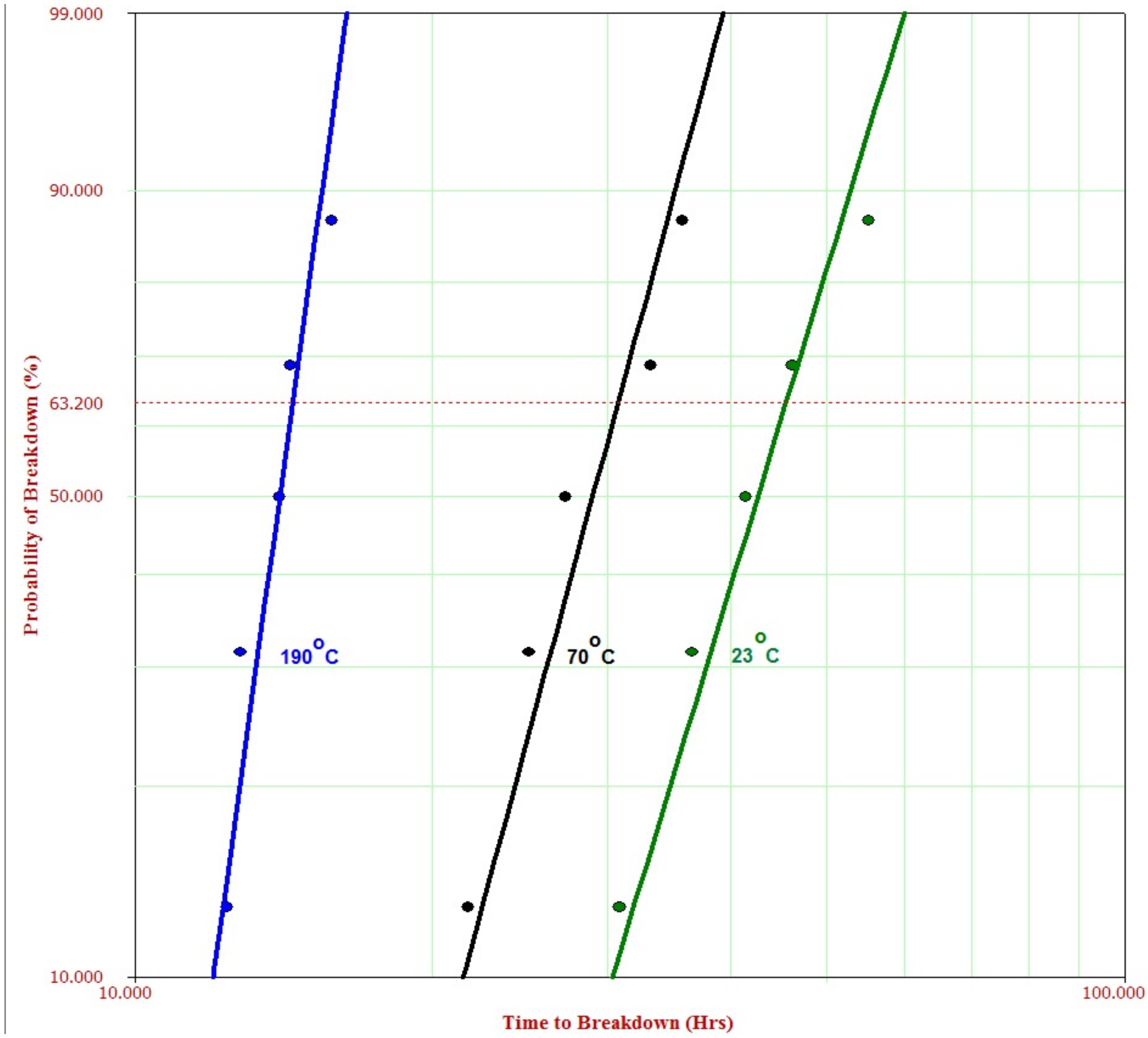

Figure 7.6 Weibull plots of 60 Hz breakdown voltage probability of twisted samples of second kind aged at 2 kV at 23^{O}C , 70^{O}C and 190^{O}C

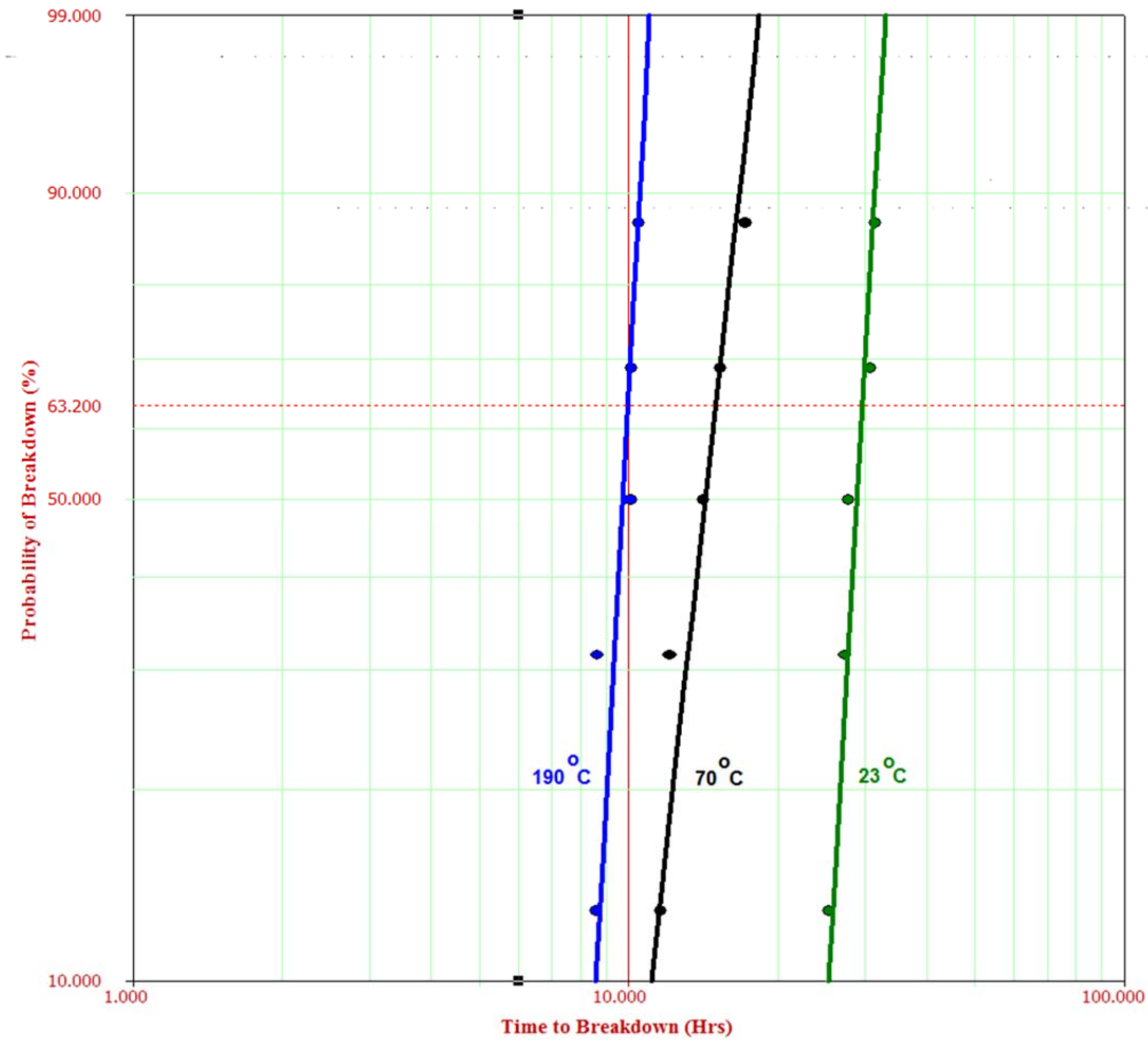

Figure 7.7 Weibull plots of 60 Hz breakdown voltage probability of twisted samples of second kind aged at 2.5 kV at 23^{O}C , 70^{O}C and 190^{O}C

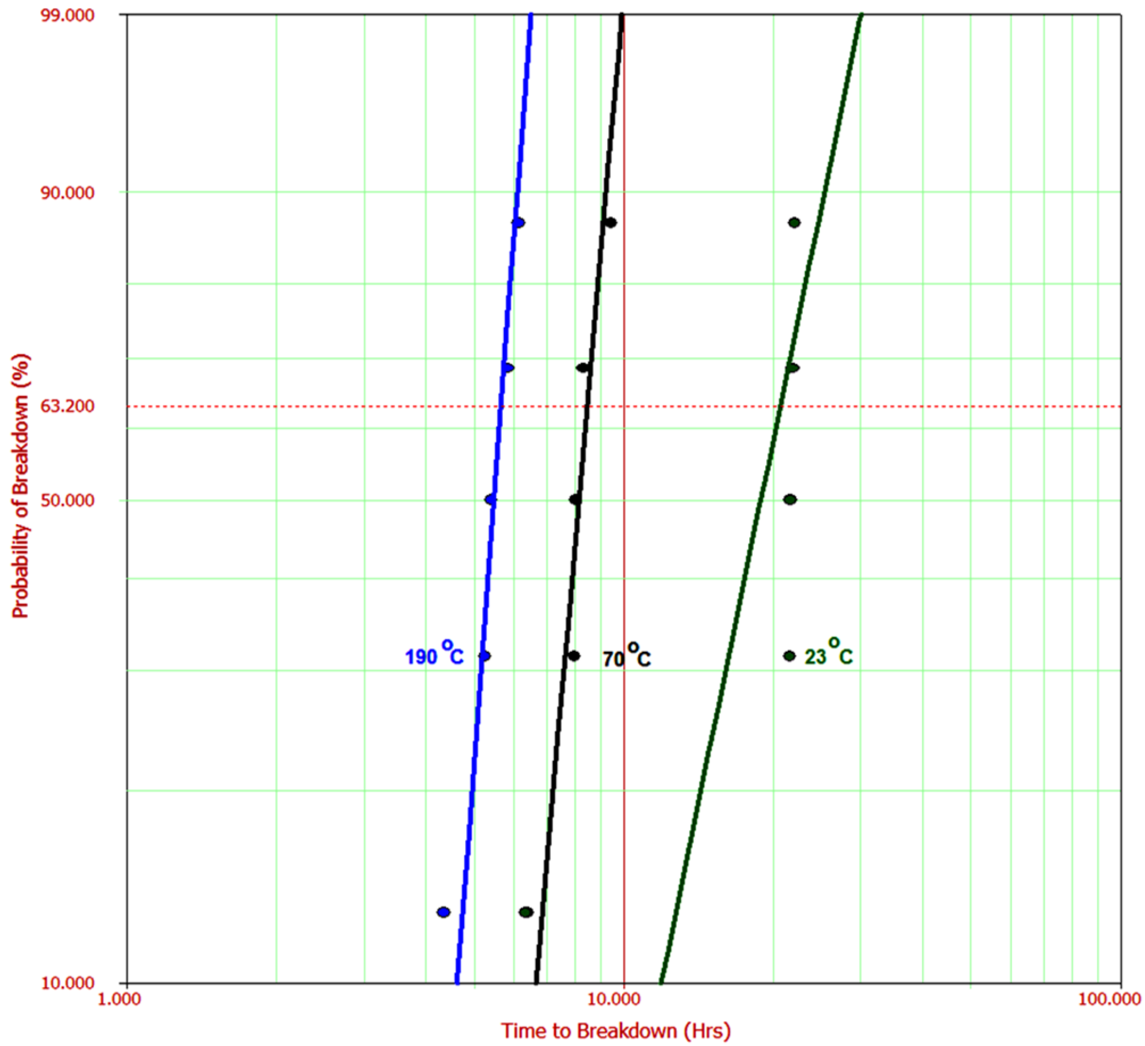

Figure 7.8 Weibull plots of 60 Hz breakdown voltage probability of twisted samples of second kind aged at 3 kV at $23^{O}C$, $70^{O}C$ and $190^{O}C$

The time to breakdown for different probability of breakdown voltage are calculated from the given Weibull distribution plot at each voltage stress for different temperatures. Changes in the aging process with changes in voltage levels are also shown by the summarized V-t lifetime graphs and are plotted according to the inverse power law and Arrhenius equation. The life time of the samples decreases with increase in the stress levels.

Table 7.1 Time to breakdown (63.2 % probability) for MW 16-C insulation at different voltages level of First kind of samples

Applied Voltage(kV)	Time to Breakdown (63.2 % Probability)		
	23 ^{O}C	70 ^{O}C	190 ^{O}C
1.5	52.95	53.2	29.81
2	27.86	23.31	19.50
2.5	16.70	12.96	9.40
3	8.23	6.99	6.65

Table 7.2 Time to breakdown (63.2 % probability) for MW 16-C insulation at different voltages level of Second kind of samples

Applied Voltage(kV)	Time to Breakdown (63.2 % Probability)		
	23 ^{O}C	70 ^{O}C	190 ^{O}C
1.5	108.36	47.08	25.44
2	45.50	30.76	14.43
2.5	29.61	14.97	9.96
3	20.66	8.44	5.66

7.1.2 Inverse Power Law

Using values of Table 7.1 and Table 7.2 the graph is plotted and it fits the inverse power law; Inverse power law is given as,

$$L(V) = k\,V^{-n} \tag{7.2}$$

Where, L is the time -to-breakdown and is usually a Weibull scale parameter α at 63.2 % probability, or any other percentile, V is applied voltage, and k,n are constants to be determined for the magnet wire MW 16-C for Polyimide insulation.

The results of time to breakdown fit very well to inverse power law as shown Figure 7.9 and Figure 7.10, and the value of exponent n shows the effect of stress on the insulation.

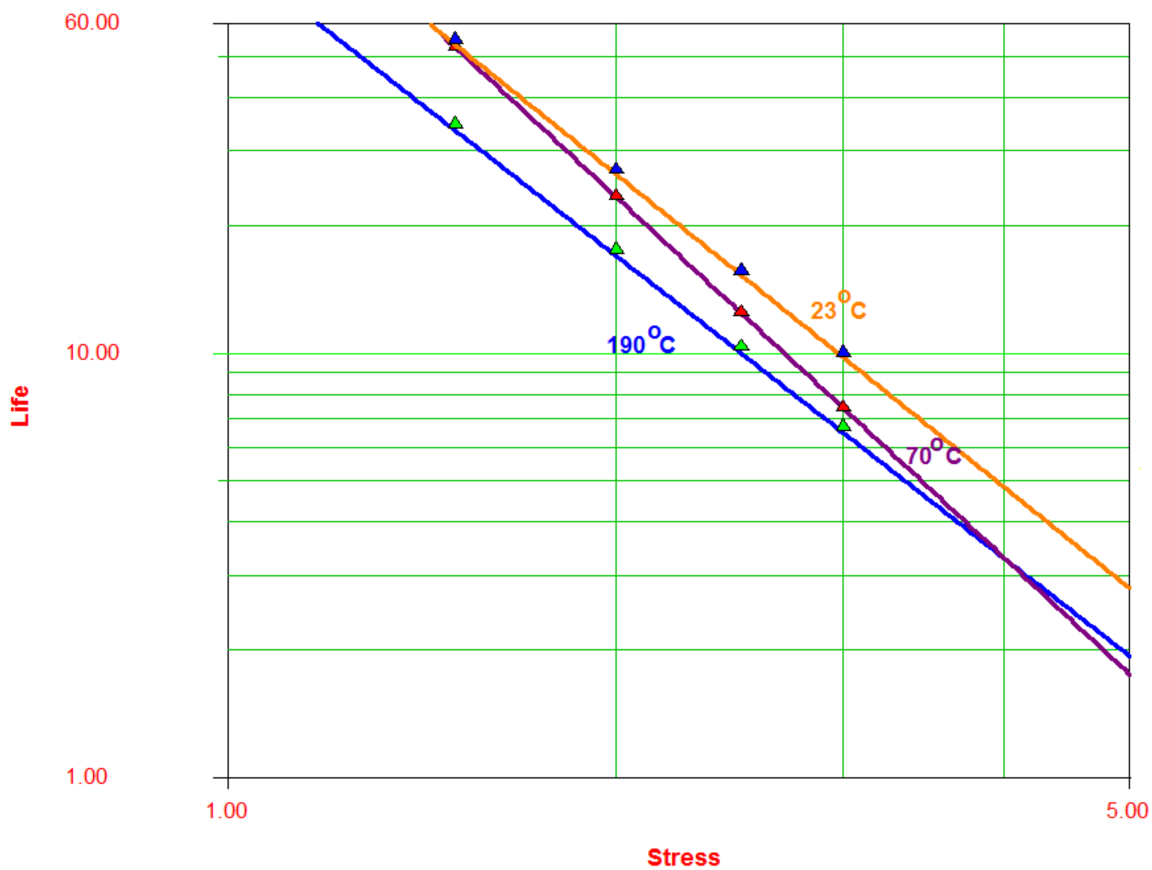

Figure 7.9 Measured time to breakdown (Hrs) at 63.2 % probability of breakdown voltage at each voltage stress , plotted according to the inverse power law for First kind of Twisted pair samples

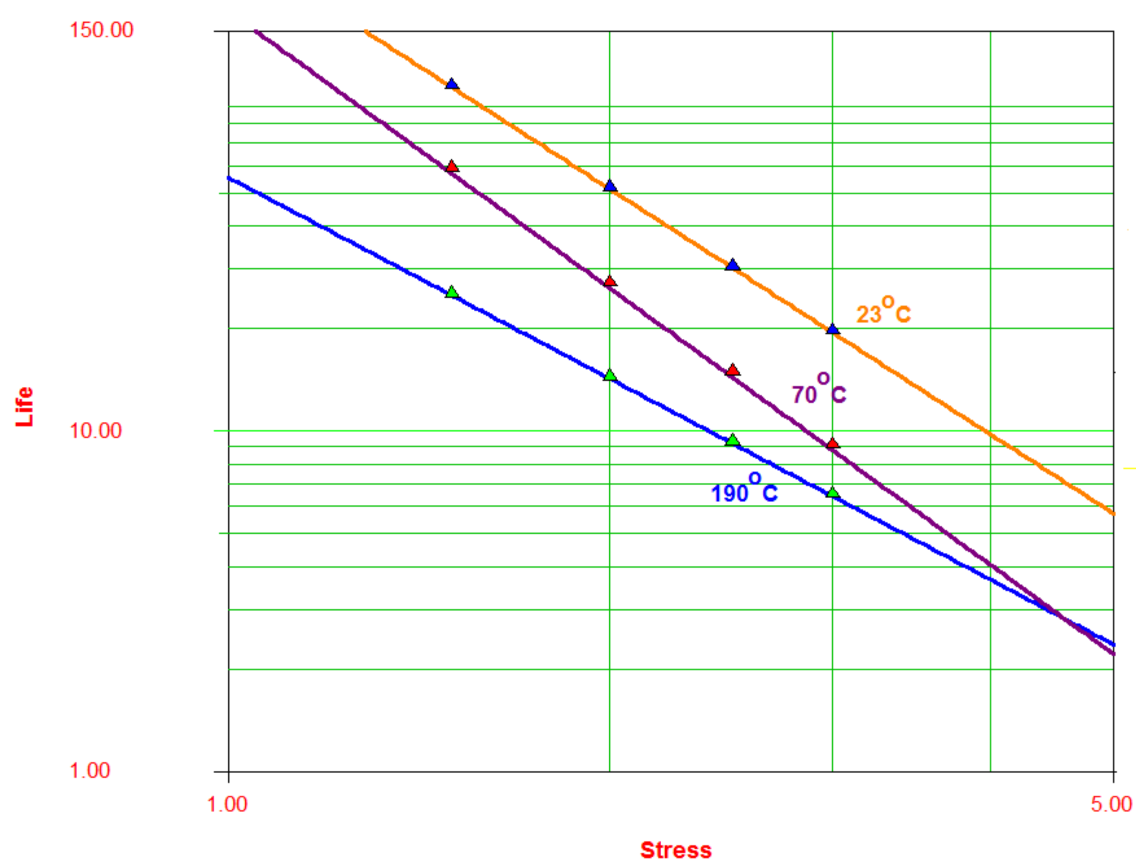

Figure 7.10 Measured time to breakdown (Hrs) at 63.2 % probability of breakdown voltage at each voltage stress , plotted according to the inverse power law for Second kind of Twisted pair samples

From the graph, using the inverse power law, the lifetime model of MW 16-C insulation is obtained, which is presented in Table 7.3.

Table 7.3 Inverse power model of MW 16-C at different temperature

Aging Temperature	Inverse Power Model	
	First Kind of Sample	Second Kind of Sample
23 ^{O}C	$L(V) = 149.25\, V^{-2.44}$	$L(V) = 277.77\, V^{-2.39}$
190 ^{O}C	$L(V) = 96.15\, V^{-2.36}$	$L(V) = 57.14\, V^{-1.96}$

7.1.3 Arrhenius Relation

The aging mechanism is also shown by Arrhenius plots and Arrhenius equation is given as,

$$L(T) = A \exp\left(\frac{B}{T}\right) \tag{7.3}$$

Where, L is time-to-breakdown, T is temperature in K, A, and B are constants determined by the activation energy of the reaction. It is confirmed that the test voltage from 1.5 kV to 3 kV is to reduce the apparent thermal activation energy from 5.17kJ/mole to 1.84kJ/Mole. In general, the temperature dependence of dielectric properties of polyimide films, as permittivity and dc conduction, is usually governed by activation energies in the range of 100 to150 kJ/mol. It means that, in this case, thermally-activated processes of polyimide seem to have a minor effect on the rate of degradation [16].

Figure 7.11 and Figure 7.12 shows that the results of accelerated aging test fit in an Arrhenius relation. And Arrhenius relation model is shown in Table 7.4.

Table 7.4 Arrhenius relation model for MW 16-C

Agin g Voltage	Arrhenius Relation Model	
	First Kind of Sample	Second Kind of Sample
1.5 kV	$L(T) = 7.6 \exp\left(\frac{623.32}{T}\right)$	$L(T) = 0.64 \exp\left(\frac{1514.54}{T}\right)$
3 kV	$L(T) = 3.8 \exp\left(\frac{222.51}{T}\right)$	$L(T) = 0.20 \exp\left(\frac{1352.18}{T}\right)$

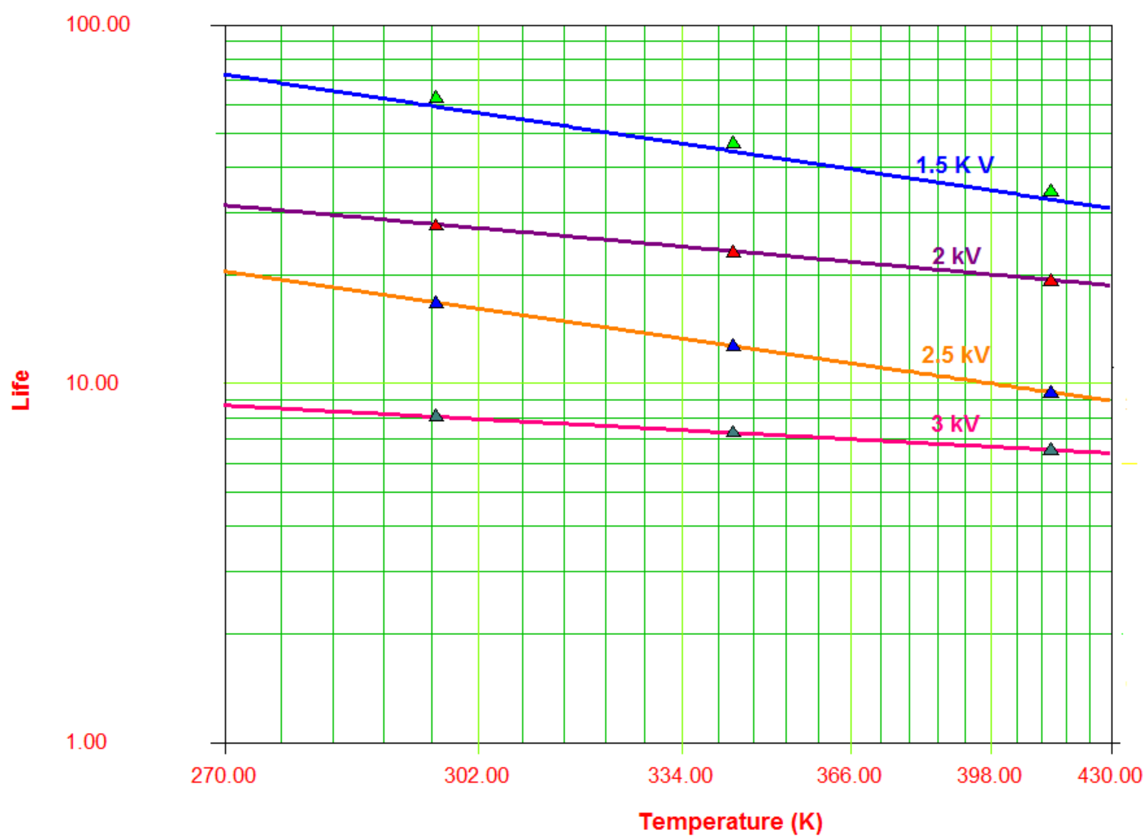

Figure 7.11 Measured time to breakdown (Hrs) at 63.2 % probability of breakdown voltage at each temperature stress , plotted according to the Arrhenius relation for First kind of Twisted pair samples

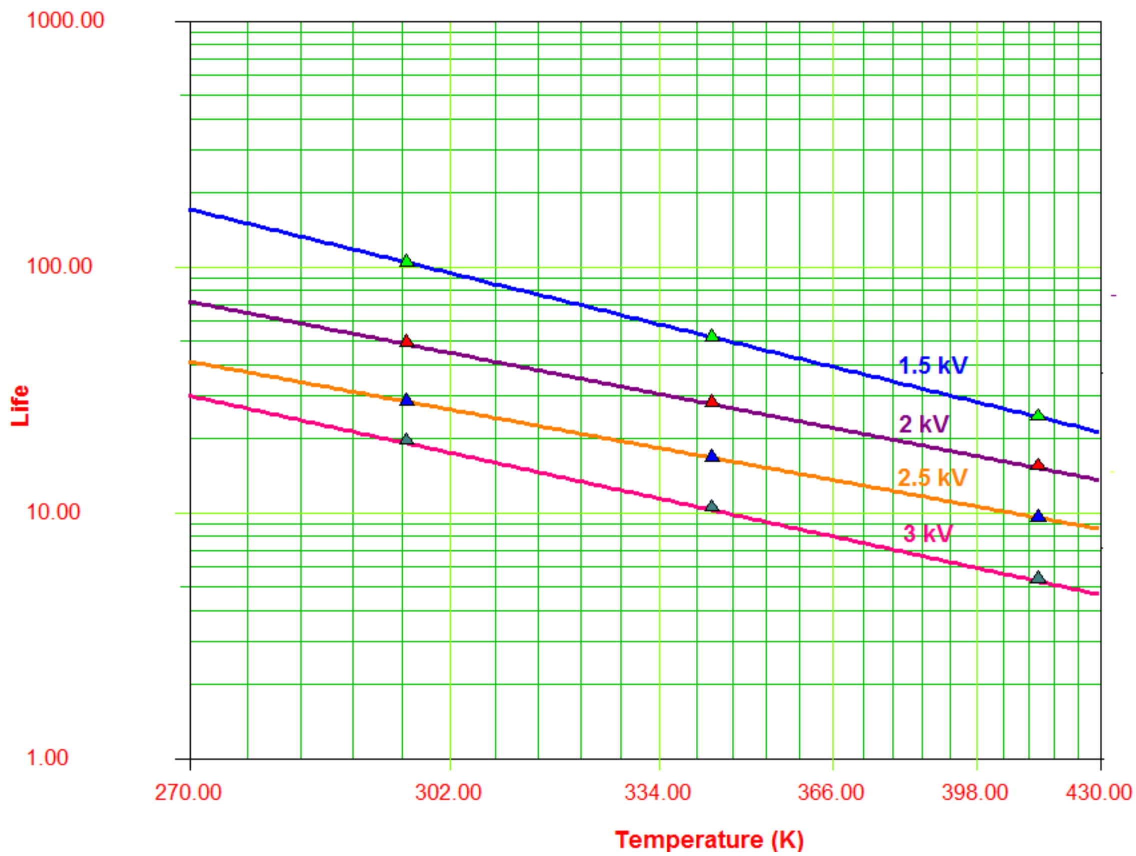

Figure 7.12 Measured time to breakdown (Hrs) at 63.2 % probability of breakdown voltage at each temperature stress , plotted according to the Arrhenius relation for Second kind of Twisted pair samples

7.1.4 Electrical Thermal Model

The new Electrical-Thermal model shown here is yield by combining Arrhenius and the inverse power law models for magnet wire MW 16- C.

The model for MW 16-C is given as,

$$L(V,T) = \frac{C}{V^{n}\, e^{\frac{-B}{T}}} \qquad (7.4)$$

Where, L is the lifetime (in hours) at 63.2% of probability of breakdown, V is the applied voltage, T is the temperature and B, C, and n are the parameters to be determined for magnet wire MW 16- C.

The model is plotted using ALTA software and the Electrical Thermal model plot is shown in Figure 7.13 with constant stress as Voltage.

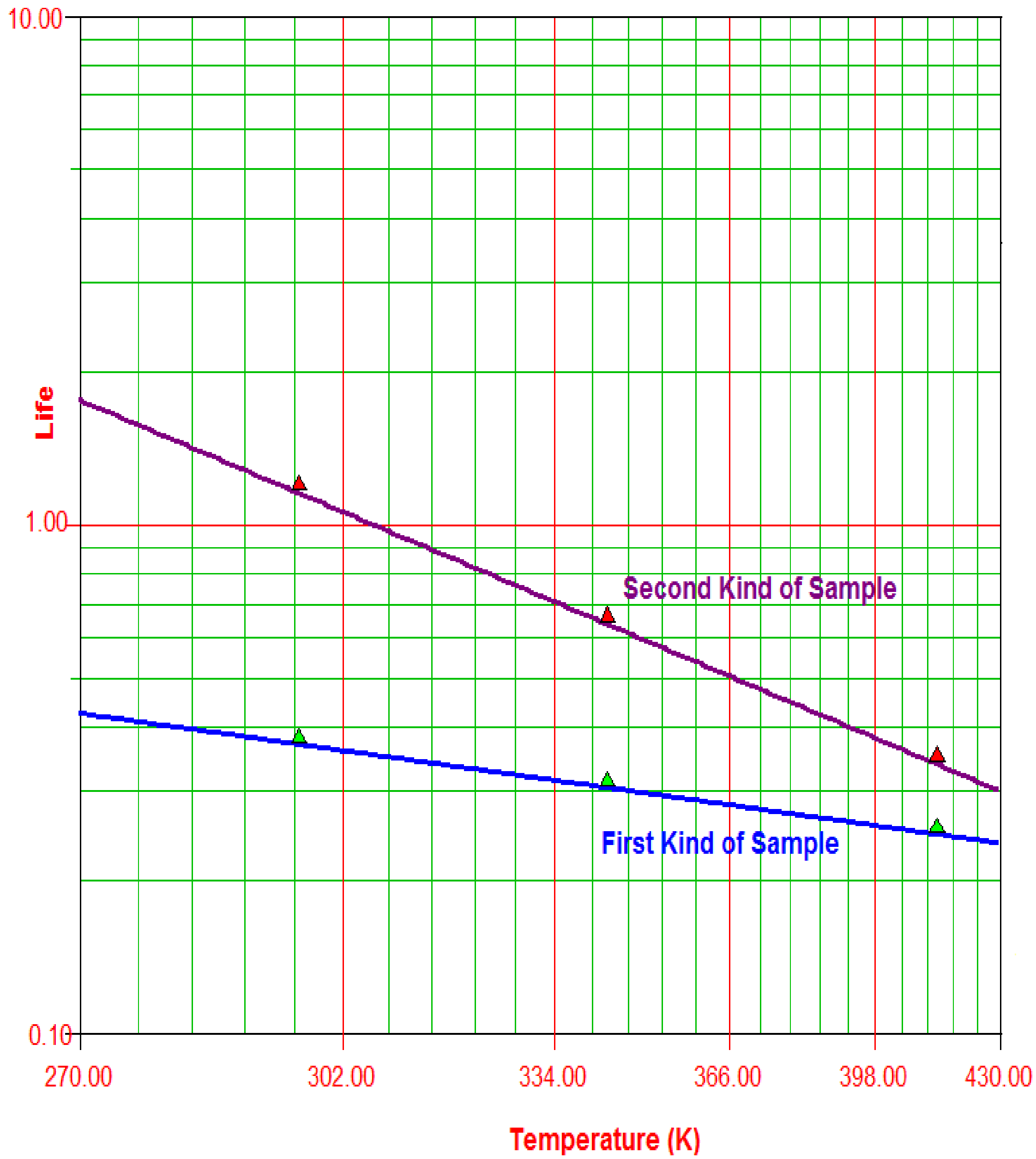

Figure 7.13 Electrical-Thermal Model (Plot of Life vs. Temperature (K) keeping voltage stress constant)

Estimates of the parameters for twisted pair of samples of First kind and Second kind is given in Table 7.5

B shows the slope of the life line in a Life vs. temperature plot. It means that B is the measure of effect of the temperature on the life and n measures the effect of voltage has on the life. We can see that, higher the value of B, higher the dependency of the life on the temperature.

Table 7.5 Electrical Thermal Model for MW 16-C

Model Parameter	Electrical Thermal Model	
	First Kind of Sample	Second Kind of Sample
β	12.7	10.5
C	42.57	3.39
n	2.66	2.32
B	425.60	1283.33

7.2 Accelerated Degradation with dc Voltage

The accelerated aging test is conducted on magnet wire MW 16-C when subjected to 10 kV dc voltages with temperatures 23^{O}C and 190^{O}C The experiment is carried on Second kind of samples alone. The result of test data is plotted with Weibull Two parameter Distribution. The Weibull plot is as shown in the Figure 7.14.

The time to breakdown for 10 kV dc is calculated from the given Weibull distribution plot for different temperatures

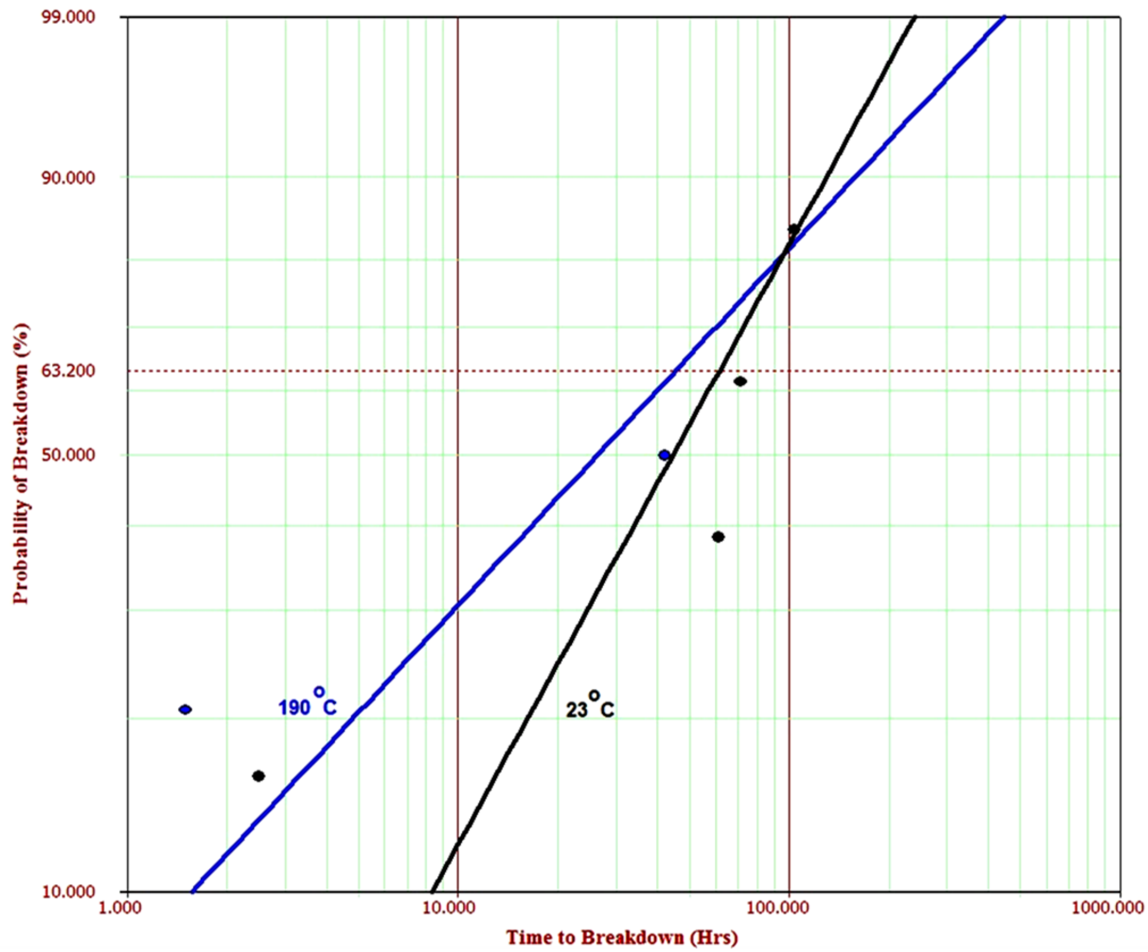

Figure 7.14 Weibull plots of dc breakdown voltage probability of twisted samples of second kind aged at 10 kV at 23^{O}C ,and 190^{O}C

Table 7.6 Time to breakdown (63.2 % probability) for MW 16-C insulation at 10 kV dc voltage

Applied Voltage(kV)	Time to Breakdown (63.2 % Probability)	
	23 ^{O}C	190 ^{O}C
10	61.60	45.43

7.2.1 Arrhenius Relation

Also for the 10 kV dc voltages, the results of time to breakdown fit very well to Arrhenius relation as shown in Figure 7.15.

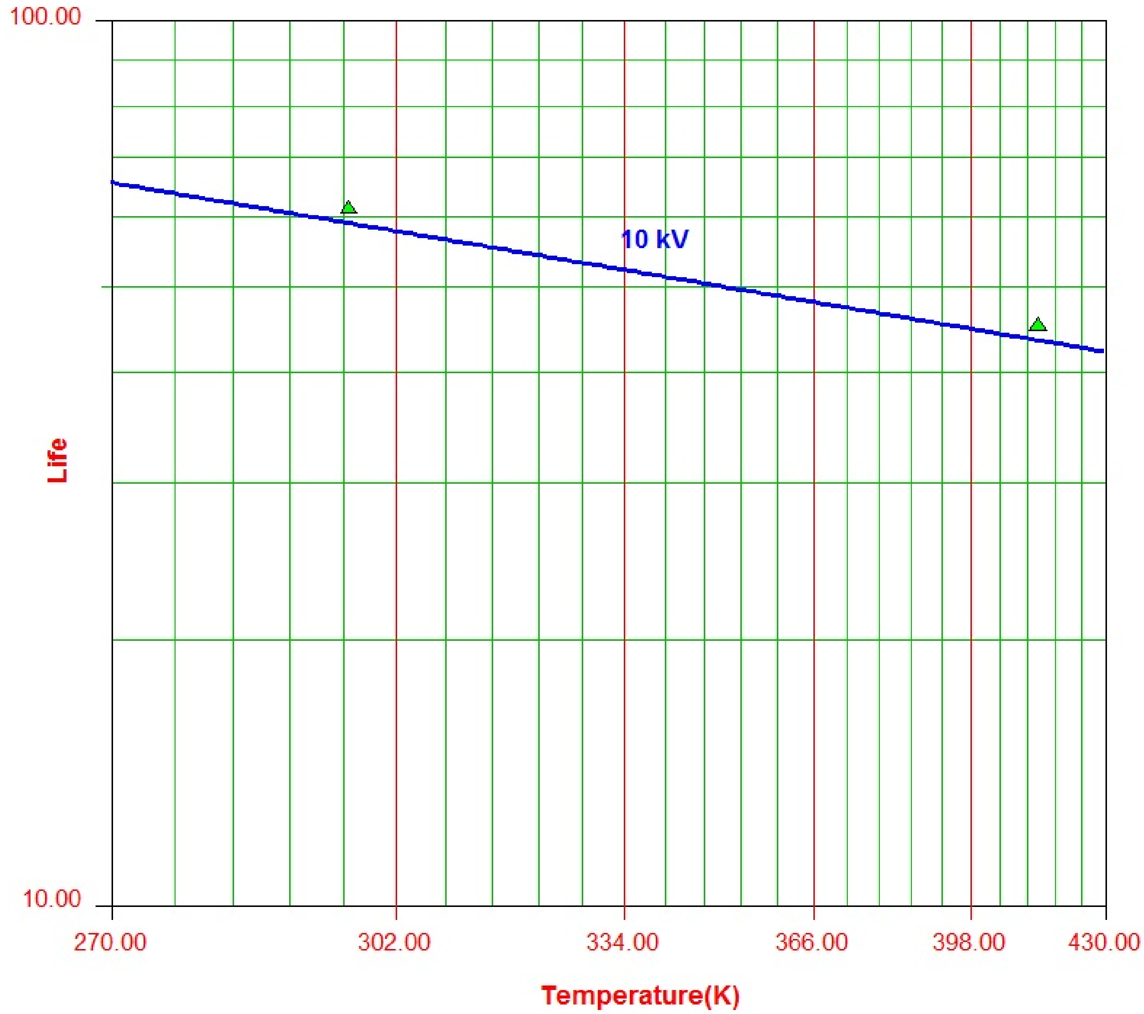

Figure 7.15 Arrhenius model for MW 16-C when subject to 10 kV dc voltage

The Arrhenius model for MW 16-C is given as,

$$L(T) = 21.01 \exp\left(\frac{318.42}{T}\right) \tag{7.5}$$

7.3 Comparison between ac and dc breakdown mechanism

The aging behavior of MW 16-C Polyimide insulation is investigated at ac and dc voltages. The statistical distribution of the time-to-breakdown was represented by the Weibull cumulative probability distribution. The lifetime of the insulation under both ac and dc electrical stresses with room and elevated temperatures are evaluated using the Arrhenius relation.

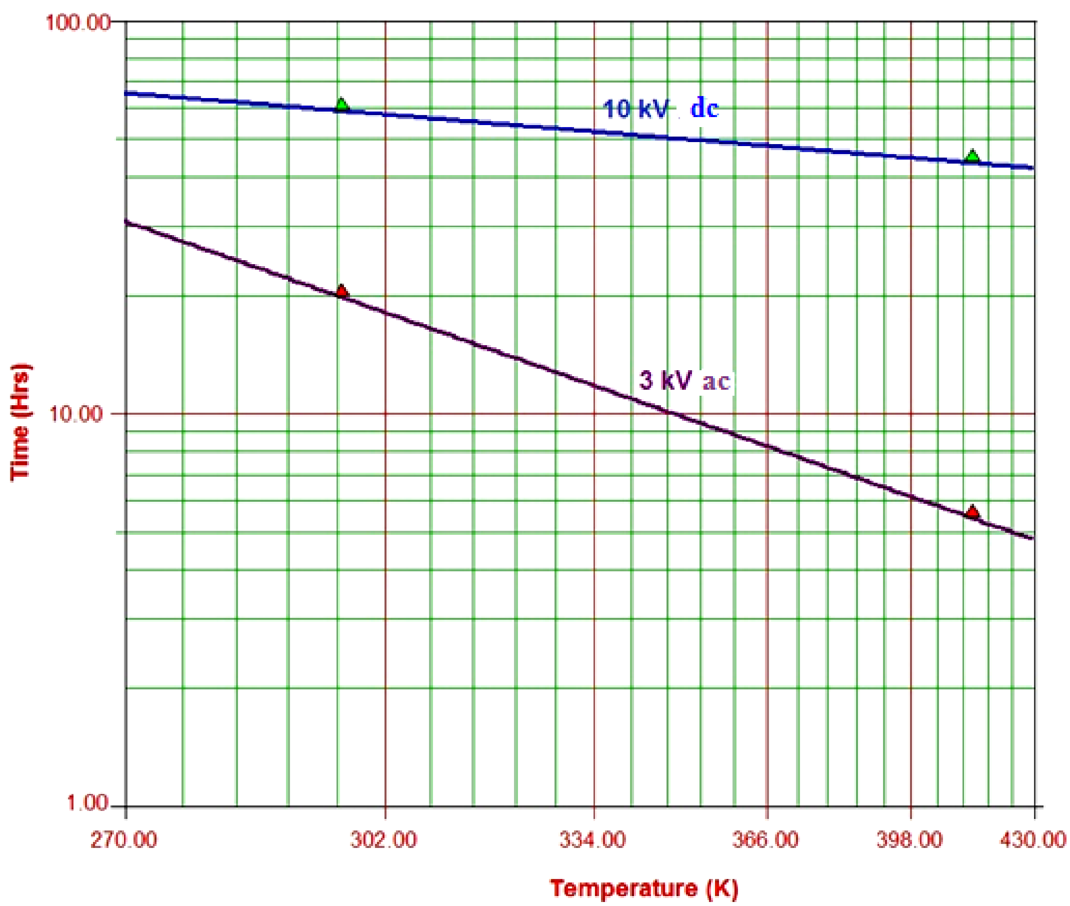

Figure 7.16 Comparison of ac and dc voltages for Arrhenius relation model

The study shows the effect of the temperature on the chemical reaction rate in the ac voltage and the dc voltage degradation. As value of B is greater in ac than dc, excessive heat is produced in ac than dc; and also effect of temperature is high on life dependency in ac voltages than dc voltages.

Table 7.7 Comparison of time to breakdown (hrs) between ac and dc voltages

Applied Voltage(kV)	Time to Breakdown (63.2 % Probability)	
	23 ^{O}C	190 ^{O}C
10 kV dc	61.60	45.43
3 kV ac	40.66	5.66

The study shows that insulation aging under ac voltage is much earlier than that under dc voltage. This is recognized to the extreme heat generated by dielectric losses and partial discharges in the micro voids. However, under dc voltage the aging process is sluggish and breakdown results from the reduction of the insulation resistivity due to ohmic losses [39].

7.4 Comparison between First kind of twisted pair sample and Second kind of twisted pair sample used under ac voltage

From Figure 7.1 through Figure 7.8, it is clear that the Time-to-Breakdown of the Second kind of twisted pair samples is greater when compared with the Time-to-Breakdown of the First kind of twisted pair of samples.

In the first and second kind of samples, on one side, one leg is energized with high voltage and other is grounded. The other side of the first kind of sample is kept open as shown in Figure 6.4 and in the second kind of sample, the other side of sample is turn round as shown in Figure.6.5. In the first kind of sample as the legs on other side are sharp points, so they are more prone to more electrical stress at the end. In second kind of samples, electrical stress is reduced by making the ends of the legs round shaped. To achieve the highest strength the sample is so designed that stress is in the center of the dielectric and lower at the edges to cause discharge in medium. In the first kind of samples, sample broke at the edge of the sample where as in the second kind of sample, it broke at middle of the sample. The second kind of twisted sample is superior to that of the first kind of samples.

CHAPTER VIII

CONCLUSION

The idea behind this work is to verify the electrical thermal model for the magnet wire MW-16 C when stressed under ac voltage and high temperature. In the thesis, 60 Hz ac breakdown measurement and dc breakdown measurements are performed on the NEMA MW-16 C insulation. The accelerated test is carried out for ac voltages ranging from 1.5 kV to 3 kV and under different temperatures (23^{O}C, 70^{O}C and 190^{O}C).The main conclusion from measurement are as follows

- The time to breakdown for 60 Hz ac is modeled with combining the Weibull distribution of failure data with the inverse power law and the Arrhenius relation with respect to test voltage and temperature.
- Electrical Thermal life model is verified for 60 Hz ac voltage

$$L(V,T) = \frac{C}{V^n e^{\frac{-B}{T}}} \tag{8.1}$$

- The estimated parameters for MW 16-C are given in Table 7.5
- The time to breakdown for 10 kV dc is modeled with combining the Weibull distribution of failure data with the Arrhenius relation with respect to temperature.
- The insulation aging under ac voltage is much earlier than that of under dc voltage for MW 16-C.

- Breakdown in ac is due to partial discharge and aging caused by electrical stress, and in dc breakdown is due to thermal and electro-thermal breakdown.
- Second kind of samples are much superior than that of first kind as they are designed such that the stress is in the center of the dielectric and lower at the edges to cause discharge in medium.
- The possible future work could be;
  - Accelerated degradation test under dc voltage with more than 10 kV dc voltage applications to find out Electrical-Thermal model under dc voltage.
  - The accelerated aging of MW 16-C with ac superimposed on dc voltage.

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