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Étude des Conditions Critiques de la Propagation de l'Arc sur les Isolateurs Recouverts de Glace

Study of Critical Conditions of Arc Propagation on Ice-Covered Insulators

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ABSTRACT

In cold regions, atmospheric icing can decrease the electrical insulation strength of outdoor insulators used in power transmission networks. Under certain conditions, this decrease in insulator strength can lead to insulator flashover and the consequent power disruption.

The overall objective of this Master's thesis is to study the flashover phenomenon on ice-covered insulators together with the influencing parameters, allowing to improve the existing mathematical model for predicting the critical flashover voltage of long insulators of up to 4 m (the full scale of post insulator for 735 kV systems). This study contributes to the understanding of the flashover and arc propagation processes, by determining the arc maintenance conditions.

Three post insulators of certain type were used in this study to make an insulator assembly, normally, used to support the high voltage transmission lines of up to 735 kV. A series of tests were arranged at CIGELE high voltage laboratories in the University of Quebec in Chicoutimi (UQAC). These tests were carried out to find the minimum voltage required to maintain an arc across a certain air gap length. The steps of the tests include: (i) to form an ice layer, using the wet-grown ice method, on the insulator (ii) to simulate natural air gaps caused from various origins by cutting out a part of the ice layer close to the high voltage electrode (iii) to produce a white and stable arc across the air gap made (iv) to decrease the voltage until the arc produced extinguishes. The voltage at the arc extinction instant is the minimum voltage required to keep the arc burning. The parameters studied during the tests were: (i) the insulator length (ii) air gap length (iii) and leakage current. The latest was controlled indirectly by varying conductivity level. Also a series of the same type of tests, but limited, were carried out on the post insulators of the same type with greater diameter. It was found that the insulator diameter, *D*, has an influence on arc maintenance condition. Studies also show that the insulator length does not influence the breakdown voltage of the air gap. A nonlinear tendency was found for the relationship between the arc maintaining voltage and the insulator length.

The study results suggested a new mathematical condition to have an arc, potentially able to lead to flashover, which is called arc maintenance condition. This condition comes from the fact that arc may spread as a result of thaw of the ice and of widen air gap.

Based on the study presented in this thesis, several recommendations and further research interests are proposed.

Résumé

Dans les régions froides, les accumulations de glace atmosphérique peuvent diminuer la tenue diélectrique des isolateurs utilisés dans les réseaux de transmission de l'énergie électrique. Cette diminution de la tenue diélectrique peut entraîner, sous certaines conditions, un contournement électrique des isolateurs recouvert de glace qui se traduit généralement par des interruptions plus ou moins longues de l'alimentation en énergie électrique.

L'objectif principal de cette étude est d'étudier les paramètres influençant le processus de contournement électrique des isolateurs recouverts de glace en vue d'améliorer le modèle mathématique statique actuel de prédiction de la tension critique de contournement. L'idée principale est de pouvoir appliquer le modèle mathématique développé à la CIGELE à des longueurs des isolateurs allant jusqu'à quatre mètres correspondant á ceux présents sur le réseau 735 kV d'Hydro-Québec. De plus, les résultats obtenus contribueront à accroître les connaissances sur le processus de contournement et de propagation de l'arc électrique sur des isolateurs recouverts de glace par la détermination des conditions de maintien de l'arc.

Les séries de tests effectuées au cours de cette recherche ont été réalisées sur une colonne isolante qui est utilisée dans le réseau 735 kV de transmission de l'énergie électrique au Québec. Les tests effectués au laboratoire de la CIGELE à l'Université du Québec a Chicoutimi (UQAC) ont permis de déterminer la tension minimale de maintien de l'arc électrique le long d'un intervalle d'air de longueur variable. Pour ce faire, il a été décidé d'utiliser la même procédure expérimentale décrite par les étapes suivantes : (i) réalisation d'une accumulation de glace en régime humide sur la colonne isolante ; (ii) création d'un intervalle d'air artificiel près de l'électrode haute tension en découpant une partie du dépôt de glace ; (iii) établissement d'un arc blanc le long de l'intervalle d'air par application de la tension jusqu'à ce que ce dernier soit stable ; enfin, (iv) diminution de la tension jusqu'à extinction de l'arc. Cette dernière étape permet ainsi de déterminer la tension minimale nécessaire au maintien de l'arc qui correspond à la valeur de la tension appliquée lors de l'extinction de l'arc. Chaque série de tests a été réalisée en ajustant les paramètres suivants : (i) la longueur de la colonne isolante ; (ii) la longueur de l'intervalle d'air et (iii), la valeur du courant de fuite. Ce dernier paramètre a été contrôlé indirectement en faisant varier la valeur de la conductivité surfacique du dépôt de glace. Les résultats ainsi obtenus ont montré que la longueur de l'isolateur ou de la colonne isolante n'a pas de réelle influence sur la valeur de la tension de claquage de l'intervalle d'air. Par contre, une relation non-linéaire a été établie entre la longueur de l'isolateur et la tension de maintien de l'arc. De plus, une série de tests suivant la même procédure expérimentale décrite précédemment a été effectuée sur des isolateurs de poste de même type mais présentant un diamètre plus grand. Les résultats obtenus ont permis de mettre en évidence que le diamètre, D, de l'isolateur ainsi étudié a une influence sur la condition de maintien de l'arc.

Les résultats obtenus au cours de cette recherche ont donc permis d'établir une nouvelle formulation mathématique pour la condition de maintien de l'arc ainsi que de déterminer les paramètres pouvant influencer cette condition. La formulation mathématique proposée a été établie afin de tenir compte de l'allongement de l'arc électrique provoqué par l'élargissement de l'intervalle d'air provoqué par la fonte du dépôt de glace.

Basées sur les résultats obtenus au cours de cette recherche, quelques recommandations et pistes de recherche ont été proposées.

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A	Arc constant
b*	Exponent of AC arc re-ignition condition
b	Exponent of AC arc maintenance conditions
DAS	Data acquisition system
DC+	Positive direct voltage
DC-	Negative direct voltage
d	Insulator diameter
E_{arc}	Voltage gradient along arc
E_c	Critical field stength for corona inception
ESDD	Equivalent salt deposit density
i	Instantaneous leakage current
I_a	Leakage current at arc extinction time
I_b	Leakage current at breakdown
I	Leakage current
I_c	Critical leakage current
I_m	Peak value of ac current
k*	AC arc reignition constant coefficient
k	AC arc Maintenance constant coefficient
L	Insulator length
n	Exponent of arc characteristic
P	Power taken from the supply

$R(x)$ or R_p	Resistance of the part of the ice which is not bridged by arc.
r	Arc foot radius
r_p	Uniform pollution resistance per unit leakage path
T	Temperature
V_e	Voltage drop on electrodes
U_c	Critical voltage
U_{cx}	Critical voltage as a function of x
UQAC	University of Quebec in Chicoutimi, Université du Québec a Chicoutimi
V_a	Applied voltage at arc extinction time
V_b	Applied voltage at breakdown
V	Applied voltage
V_{arc}	Voltage gradiant along arc
V_c	Critical flashover voltage
V_{cx}	Minimum DC voltage to sustain the arc bridging a portion of x/L of the leakage path L
V_{ice}	Voltage across the residual Ice (The part of ice which was not bridged by the partial arc)
V_m	Peak values of AC voltage
w	Width of ice surface
x	Length of arc
x_c	Critical arc length
σ	Freezing water conductivity
δ	Relative air density

ϕ	Function to be determined experimentally
γ_e	Equivalent surface conductivity of the ice sample during flashover

List of Papers Published based on the results of this M.S. Thesis

1) J. Zhang, M. Farzaneh and S.S. Aboutorabi, (2003), "Critical Conditions of Arc Propagation on a Long Insulator Covered with Ice", ISH conference, Netherland.

2) J. Zhang, M. Farzaneh and S.S. Aboutorabi, (2002), "Critical condition of arc propagation on ice-covered insulators", IWAIS conference, Czech Republic.

3) M. Farzaneh, J. Zhang and S.S. Aboutorabi, (2002), "Effects of Insulator Profile on the Critical Condition of AC Arc Propagation on Ice-Covered Insulators", CEIDP conference, Mexico.

Chapter 1

Introduction

1.1 General

Insulators are devices used to support, separate and/or contain conductors at a high voltage. They are widely used in power systems to insulate various electrical parts and connect them mechanically, thus, their degree of performance can directly affect the operation of power systems. Most power system insulators are used in substations and on transmission lines and are subjected to atmospheric conditions or other natural outdoor phenomena, while; a wide range of environmental factors and meteorological conditions influences their electrical performance [42].

1.2 Problem Definition

In cold regions, during winter, atmospheric ice accretion on overhead transmission lines can be considerable, due to freezing rain or drizzle, in-cloud icing, icing fog, wet snow or frost. The normal operation of electric power networks can be affected by this icing phenomenon that tends to produce a multitude of difficulties to clients and public services. A number of published reports are available concerning these problems in Canada [65], China [110], England [54], Japan [55, 85], Norway [45], United States [6, 76], former Yugoslavia [117] and Switzerland [86].

In Canada, the most serious disruption of power to date caused by ice accretion on overhead transmission lines occurred in January 1998 [1, 88]. Ice accretion caused the collapse of over 1000 steel power transmission towers (including 735 kV lines) and 30000 wooden poles. This resulted in an interruption of power service to a large number of clients for periods ranging from one week to one month. The direct economic loss to Hydro-Quebec was over one billion Canadian dollars.

Besides the mechanical damages, the ice accreted on insulators could decrease their insulating strength considerably and may, on occasion, even result in flashover faults in power systems. Some power outages related to this phenomenon have also been reported from several countries [46, 106] subjected to northern climatic conditions.

As an example, in 1986 on the Ontario-Hydro network, 57 successive flashovers took place and were attributed to fog, freezing rain and accumulated icicles. Most of 500 kV power lines underwent interruption at that time [56]. Again in 1988, within the Hydro-Quebec Network, 6 successive flashovers caused an electrical power delivery interruption throughout the greater part of the province of Quebec [65].

Flashover phenomena on ice-covered insulators have attracted much attention from many researchers and a large number of studies were carried out in several laboratories on the subject [8, 13, 22, 45, 55, 57, 89, 108, 110, 117]. Normally, experimental or in-the-field investigation is costly and time-consuming. Therefore, many attempts have been made individually or by research groups to establish a mathematical model for predicting the flashover voltage of ice-covered insulators. As a result, a mathematical model was developed at CIGELE and has been successfully applied to insulators of up to 1 m in length. Due to some difficulties in its application to ice-covered insulators over 2 m in length, it was found necessary to extend the study in order to improve the earlier model.

1.3 Research Objectives

The overall objective of this thesis is to study, the phenomenon of flashover on ice-covered insulators together with the influencing parameters and, to improve the existing mathematical model for predicting the critical flashover voltage of long insulators of up to 4 m (the full scale of post insulator for 735 kV systems). The specific objectives are:

- To study the flashover phenomena on ice-covered insulators when the insulator length is increased.

- To investigate the critical conditions under which an arc of a certain length may occur and persist (maintenance condition), with consideration of parameters such as air gap length, leakage current, and insulator length.

- To contribute in improvement of the existing mathematical model for predicting the flashover voltage of long insulators covered with ice by taking arc maintenance conditions into consideration.

1.4 Methodology

In order to attain the objectives of this study, a series of laboratory experiments was carried out in a climate chamber at CIGELE. The results were subjected to both theoretical and mathematical analyses. The main methods used in this study may be summarized as follows:

- A uniform ice layer in series with a certain length of air gap was formed on a post-type insulator. In order to study the effects of insulator length on arc propagation on iced surfaces, the insulator length was subjected to variations ranging from 50 cm to 310 cm.

- Using a set of AC high voltage sources and a data acquisition system, a test method was designed to determine the minimum level of voltage to be applied for maintaining an arc burning along the air gap.

- Regression analysis was applied to the test results to determine the critical conditions under which the arc burns and extends along the ice surface, namely the arc maintenance conditions.

- By taking into consideration the arc maintenance conditions, the original mathematical methods may be improved upon and a new model may be extracted. This improved model contributes to the studies whose goal is to predict the flashover voltage of long ice-covered insulators.

1.5 Statement of Originality

A physical ice model and a test method based on arc formation and extension along an air gap was designed in order to study arc propagation on iced surfaces and to determine the arc maintenance conditions. This approach was entirely innovative in this context and may be deemed original research. By taking into consideration the parameters of insulator length (from 50 to 310 cm), air gap length (from 7 cm to 56 cm) and insulator diameter, the arc maintenance conditions on ice covered insulators were derived. These maintenance conditions are necessary to improve the new mathematical model established at CIGELE laboratories for predicting the flashover voltage of long ice-covered insulators.

1.6 Organization of Thesis

This thesis is arranged so as to provide the reader with knowledge of a good part of the literature available on the subject and to make it possible for him or her to follow the principles and results of the tests.

In the first chapter, which is the present one, the problem is defined. A innovative methodology in approaching the problem is hereby proposed with a view to the goals and objectives, as are followed through by the author.

In the second chapter, some fundamentals are provided on the electrical breakdown and flashover occurring on polluted surfaces. Then, a relatively detailed overview is provided for ice accretion mechanisms as well as environmental parameters influencing them. This includes ice type, amount of ice, ice uniformity, freezing water conductivity, voltage type, leakage current, insulator type and position, and air pressure, thereby preparing the reader for an understanding of how the parameters in the test are chosen and why. A review of arc and flashover modeling on ice-covered insulators is provided following the prerequisite information, to allow the reader to follow up on the studies already made.

According to our needs and the parameters introduced and selected, the facilities were chosen and then presented in chapter Three. The existing facilities used in the present study such as (i) cooling system, (ii) wind generating system, (iii) water spray system (and the corresponding calibrations on ice accretion rate); (iv) high voltage system and (v) measuring system and method (along with the test circuit and the data acquisition system) are all explained. Details on the test objects and the way they are prepared, are followed by a description of test methods, by way of a review on the literature in the field. At the end of the chapter, the procedure that was applied to choose the test results (raw data) and the mathematical methods used are explained.

The test results processed are presented in Chapter 4. The maintenance condition curves versus air gap change and insulator length were, first, obtained and a comprehensive discussion of the curves follows. The breakdown voltage curves versus air gap length and insulator length are, also, derived, and the various aspects of these derived curves are explained. At the end of this chapter, the application of the arc maintenance conditions is discussed.

Finally, some specific conclusions of this study are provided. These conclusions make it possible to formulate certain recommendations for future research.

Chapter 2

Review of the Literature

2.1 Introduction

The phenomenon of atmospheric ice accretion on power transmission lines has been studied for several decades by various researchers, and their results have been published worldwide [1, 6, 9, 46, 54, 55, 65, 76, 85 and 117]. In order to provide a sound understanding of the background of the present study, a review of the literature concerning the flashover of insulators under atmospheric icing conditions is presented in this chapter. This review will include studies on the mechanisms and development process involved in flashover on ice-covered insulators, the parameters affecting their performance, and the mathematical modeling of an arc on iced surfaces.

The flashover on ice-covered insulators presents similarities to the ones occurring on polluted insulators. For certain studies the ice accreted on the insulator surface was considered to be a special type of pollution [41]. The theories and, particularly, the concept of modeling of flashover on polluted insulators were used in the case of ice-covered insulators [37, 41, 52 and 53]. Therefore, the studies on flashover and arc modeling on polluted insulators are briefly reviewed at the beginning of this chapter.

2.2. Flashover on Polluted Insulators

2.2.1. General Description of Flashover on Polluted Surfaces

When an electrical discharge occurs on the surface of a dielectric substance in a gaseous or liquid medium, it is called surface discharge [79]. In a non-uniform field, there may be a partial discharge with audible and luminous effects, which is called corona discharge. Under certain conditions, the corona discharges may develop to form an arc column. When the arc extends and bridges the distance between two electrodes, flashover occurs.

The 5 steps generally involved in a flashover on polluted insulators are the following: [59, 69 and 101]:

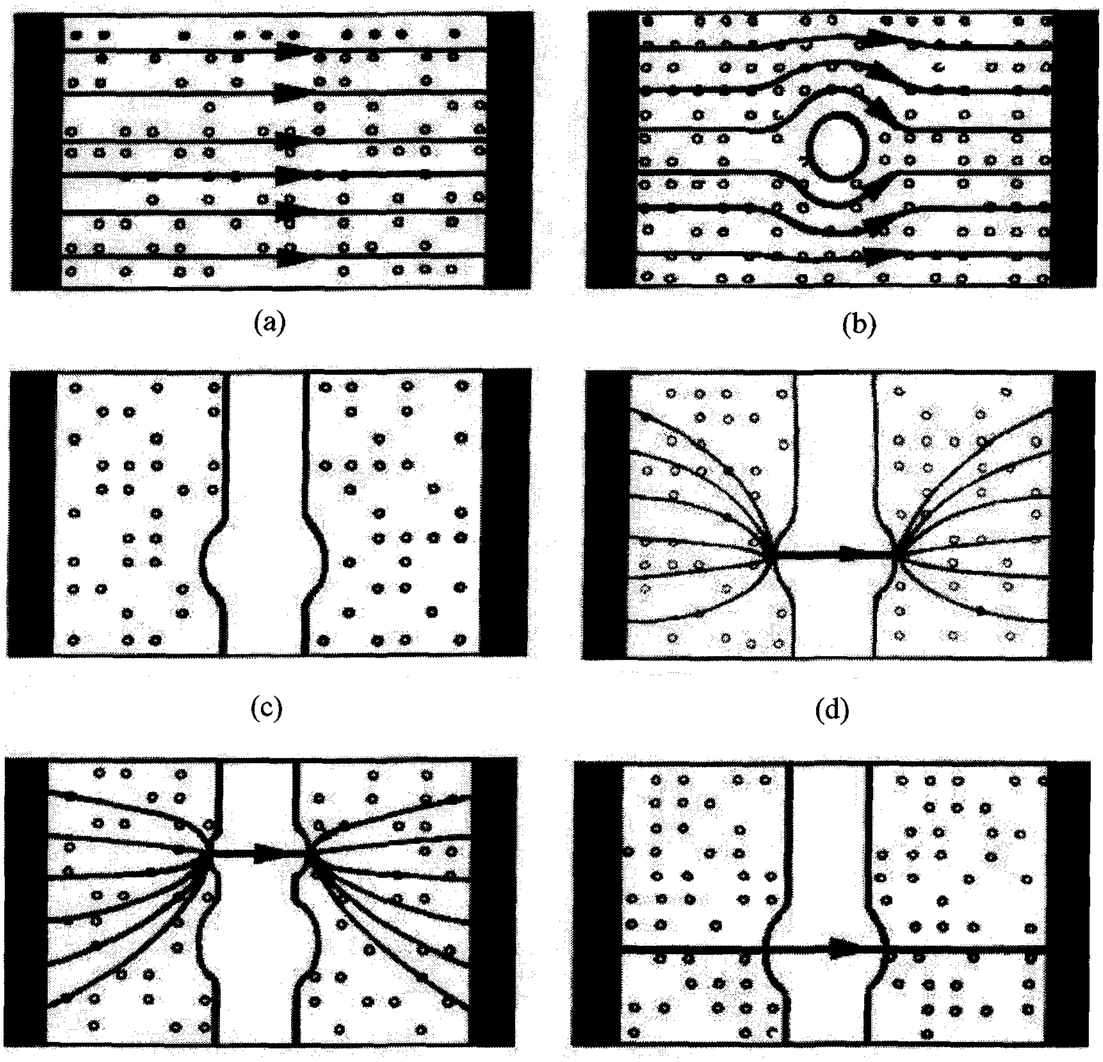
i) Pollutants deposited on the insulator surface: Due to growing industrial development, motorized vehicles, sea salt, as well as dust and chemical particles in the air, a layer of pollution can be deposited on the insulator surfaces.

ii) Wetting of pollution layer: When the pollution layer is dry, it presents high resistivity and has no significant effect on the electrical performance of insulators. When the pollution layer is wetted, however, under certain atmospheric conditions such as fog, drizzle, dew, rain, snow or ice, it will present low resistivity and result in a leakage current flowing on the insulator surface. (Figure 2-1 (a))

iii) The leakage current density on the insulator surface is normally not uniform: The high current density provides a significant heating effect that eventually results in the formation of dry points in certain areas. Such dry points may spread because of the heating effect and ultimately form a dry band. (Figure 2-1 (b) and (c))

iv) The resistivity of the dry band is much higher than the wet pollution layer: Therefore, the voltage distribution changes and becomes non-uniform along the insulator surface. The dry band withstands almost all of the applied voltage. If the voltage level is high enough, a breakdown will occur and a local arc will appear along the dry band. (Figure 2-1 (d))

v) The local arc will move laterally to a more stable position: Depending on the applied voltage level, either it may be extinguished or extend along the wet pollution layer surface without expansion of the dry zone. When the arc reaches its critical length, flashover will occur. (Figure 2-1 (e) and (f))



(a) (b)

(c) (d)

(e) (f)

Figure 2-1 Arc formation process on a polluted insulator

2-1 a) Wetting of pollution layer and leakage current flow.

2-1 b) The leakage current heating effect may form "dry zones".

2-1 c) Dry areas may extend to form "dry bands". The resistivity of the dry band is much higher than that of the wet pollution layer.

2-1 d) The dry band breaks down to form a local arc.

2-1 e) The local arc will move laterally to a more stable position.

2-1 f) Under certain conditions, the arc will extend and propagate and flashover will occur.

2.2.2. Arc Propagation Criteria

Several complexities are involved in arc formation and propagation on real insulators. Therefore, in order to study this phenomenon in detail, several researchers made of use simplified physical models, such as a water channel [5, 69, 84], a triangular plane [68], a flat disc [70, 97] or a cylindrical sample [62].

Although the mechanism of arc propagation is not completely understood, it is generally known that certain external forces are tentatively identified as the reason for arc propagation [12, 59 and 97]. Such possible external forces may include: (i) static-electrical force, (ii) electromagnetic force and (iii) thermal floating force. Using a discharge current of 100 mA, a polluted surface resistance of 50 kΩ, and an arc root radius of 0.5 cm, Jolly [69-72] calculated the forces acting on the arc root. The results show that these forces are not enough to speed up the arc movement to a few hundred m/s. Li [83] calculated the electrical stress around the arc root, and found that it was not strong enough to breakdown the air gap. Therefore, thermal ionization was considered as the main reason for arc root movement along the polluted surface.

[1] "Hampton [59] considered that the necessary condition for flashover is that the voltage gradient in the water column E_p should exceed that in the arc column E_a. Thus, the criterion for arc motion may be expressed:

$$E_a < E_p \tag{2-1}$$

This following criterion was established experimentally by Hesketh [61], who assumed that the arc in series with the wet polluted layer would adjust itself so as to draw maximum current from the supply for all positions along a possible arc path. That is:

$$\frac{di}{dx} > 0 \tag{2-2}$$

If this criterion is satisfied for all positions along a possible arc path, flashover will occur.

---

[1] Texts in quotation marks are derived from the references given at their end. They are marked to respect copy rights.

For a supply with an internal resistance R_s, the flashover criterion according to Hesketh6152] takes the following form for all values of x:

$$E_a + \frac{i*(\frac{dR_p}{dx})}{x*(\frac{dE_a}{di}) + R_p + R_s} < 0 \qquad (2\text{-}3)$$

This criterion, however, does not explain the mechanism and speed by which the arc actually moves. Hesketh assumed that when the arc moves, it is not shunted anywhere by a wet contamination layer.

Näcke [89] proposed an electrical stability criterion. The change of total voltage for the displacement of the discharge root at a constant current is taken into account within this criterion as this can be expressed by the following equation:

$$dV = (\frac{\partial V_{arc}}{\partial x})\partial x + i(\frac{\partial R}{\partial x_p})\partial x_p \qquad (2\text{-}4)$$

where x is the arc length and x_p is the length of the pollution layer. It is assumed that the arc will move if dV is negative (mechanical instability). This will lead to Hampton's criterion for a uniform pollution layer."[101]

2.2.3. Arc and Flashover Modeling

Several researchers have proposed certain models for predicting the flashover voltage of polluted insulators. The first quantitive analysis was made by Obenaus [91]. It was subsequently completed by Neumarker [90], and became known as the extinction theory. The flashover process is modeled as an arc in series with a residual resistance that represents the non-bridged portion of a wet pollution layer as schematically shown in Figure 2-2. The corresponding circuit equation may be expressed as follows:

$$V=V_{arc} + IR + V_e \qquad (2\text{-}5)$$

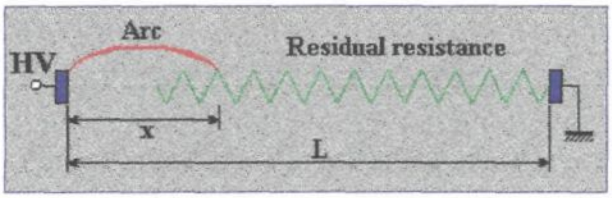


Figure 2-2: Equivalent circuit.

where V is the applied voltage; I is the leakage current; V_{arc} is the voltage along the arc and R is the residual resistance of the pollution layer. The arc voltage, V_{arc}, may be expressed as:

$$V_{arc} = A \cdot x \cdot I^{-n} \tag{2-6}$$

where A and n are the arc constants, and x is the arc length.

Although there are many common aspects and similarities between DC and AC arcs, but they are limited. The zero points of leakage current for AC arcs, however, put end to the similarities and require a significant difference in treatment.

An AC arc is extinguished as the current passes through zero twice every cycle. Arc reignition following current zero can be classified into energy and dielectric breakdown. Energy breakdown takes place when the residual arc gap is no longer able to dissipate the energy injected because of the flow of the post-zero current in the plasma that is still conducting [101]. This type of breakdown normally takes place in the immediate vicinity of current zero and is usually associated with acute rates of increase in recovery voltage. Dielectric breakdown, on the other hand, normally takes place at a later stage, after the residual gap has lost its electrical conductivity and can be treated as a hot gas. Dielectric breakdown then takes place when the instantaneous value of the recovery voltage exceeds the dielectric strength of the gap, and is typical of relatively slow rates of recovery voltage. Energy breakdown may be described by a dynamic equation showing the interaction between the test circuit and the residual arc. This type of dielectric breakdown is based on the temperature decay of the residual hot gas [101].

Several researchers also proposed certain models, which were based exclusively on experimental results. These models are known as "experimentally based" since they do not refer to any specific physical mechanism by which an AC arc is maintained.

"Hurley and Limbourn [64] established an empirical relationship between the minimum voltage necessary to sustain an AC arc over a rod-rod gap, of a length x, in series with a resistance R_p:

$$U_{cx} = const.\ x^{2/3} .\ R_p^{1/3} \qquad (2\text{-}7)$$

Clavier and Porcheron [12, 13] found a further empirical relationship between the minimum arc reignition voltage and the arc current I, under pollution conditions:

$$U_{cx} = 800x \cdot i^{-1/2} \qquad (2\text{-}8)$$

In the case of uniform pollution distribution, and on the assumption that the speed of arc elongation to critical conditions is so slow that it can be analyzed under a quasi-stationary condition [101], the critical flashover voltage of polluted insulators may be calculated as:

$$U_c = 47.6 \cdot r_p^{-1/3} \cdot L \qquad (2\text{-}9)$$

where r_p is the resistance of the water film per unit length and L is the total insulator length. In this case the critical arcing length is:

$$x_c = \frac{2}{3}L \qquad (2\text{-}10)$$

Guan et al. investigated the propagation of an AC arc using a high-speed camera [57, 58] and found that the arc develops only when it approaches the peak values of the applied voltage. In order to complete the flashover, a criterion called the arc recovery condition must be satisfied. The researchers also experimentally determined the arc recovery conditions on polluted surfaces as follows:

$$V_m \geq k^* x/I_m^{b^*} \qquad (2\text{-}11)$$

or

$$V_p \geq k^{*\prime} x/I_m^{b^{*\prime}} \qquad (2\text{-}12)$$

where k^*, b^*, $k^{*\prime}$ and $b^{*\prime}$ are the constants; V_p is the voltage across a gap of a length x cm, V_m is the applied voltage, and I_m is the peak value of arc current."[101]

2.3. Flashover of Ice-Covered Insulators

Atmospheric ice accretion on power transmission lines has been under investigation for many years [15-37]. The problem has been studied for over 25 years [96] at the Research Group on Atmospheric Environment Engineering (GRIEA) and more recently at the NSERC/Hydro-Quebec/UQAC Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE) at the University of Quebec in Chicoutimi (UQAC). The highly useful data obtained by this team and other researchers elsewhere have been published worldwide. Several overviews of these studies have been published from Farzaneh et al. [11, 21, 24, 27 and 40].

2.3.1. General Description of Flashover on Ice Covered Insulators [42]

Flashover on ice-covered insulators consists of a electrical process along with several thermal and electrochemical processes. The mechanism of flashover is not yet fully understood, however, the flashover of ice-covered insulators comprises the following steps [43]:

i) Atmospheric ice is accumulated on the insulator surface due to hoar frost, in-cloud icing, and precipitation icing. Precipitation icing may occur in several ways, including freezing rain, drizzle and wet or dry snow. However, glaze with icicles and wet snow affect insulator electrical performance the most.

ii) The areas of high electrical stress on insulator strings are usually free of ice due to the heating effects of the discharge activities, ice shedding and certain other phenomenon. The ice-free areas on insulators are called air gaps. The distribution of ice on insulators is seldom uniform as ice is usually accreted on the windward side.

iii) If the ice surface is dry, the performance of the insulators is only slightly reduced. However, with a highly conductive water film such as caused by sunshine, a rise in air temperature, condensation, the heating effect of leakage current, the insulator performance will be considerably reduced. This is mainly due to the fact that a large part of the applied voltage is dropped along the air gaps, causing electrical discharges and local arc formations in these areas.

iv) If the applied voltage is high enough, a local arc can change to white arc and extend along the ice surface. When it reaches the critical length, this may result in a flashover arc.

As a result, surrounding condition such as presence of air gaps, water film on the ice surface and the degree of its conductivity play a major role in the process of arc developing to flashover occurrence on ice-covered insulators.

2.3.2. Factors Affecting the Flashover on Ice-Covered Insulators [22, 23]

The complexities arising from the flashover phenomenon on ice-covered insulators derives mainly from a combination of several elements, including the decrease in "effective" leakage distance caused by ice bridging; the increase in surface conductivity resulting from a highly conductive water film and possible pollution on the ice surface; and, the distortion of voltage distribution along the insulators caused by air gaps in the ice layer. Also, each one of these elements itself is influenced by several secondary factors.

2.3.2.1. Type and Density of Ice

Environmental conditions have a major influence on the characteristics of the accumulated ice. Different types of ice may be obtained in the presence of various atmospheric and environmental conditions such as air temperature, wind velocity, water droplet size, and liquid water content. Kuroiwa [80], Imai [67] and Oguchi [92] classified ice into three basic categories: hard rime, soft rime and glaze. The characteristics of these ice types are as follows:

- Hard rime is opaque and has a density of between 0.6 and 0.87 g/cm^3;
- Soft rime is white and opaque with a density of less than 0.6 g/cm^3.
- Glaze is transparent and has a density of approximately 0.9 g/cm^3.

The conditions pre-requisite for producing different types of ice are listed in Table 2-1.

Table 2-1 Conditions promoting the formation of various types of ice [92].

Type of Ice	Density (g/cm^3)	Surrounding Temperature (°C)	Wind Velocity (m/s)	Water Droplet Diameter (μm)
Hard rime	0.6 to 0.87	-3 to -15	5 to 20	5 to 20
Soft rime	< 0.6	-5 to –25	5 to 20	5 to 20
Glaze	0.8 to 0.9	0 to -3	1 to 20	500 to 6000

Under natural conditions, icicles are the most frequently observed type of ice on Hydro-Quebec power networks [23]. The environmental conditions required for this type of ice accumulation is the presence of freezing rain and temperatures ranging between -4 °C and -1°C.

Phan et al. [95] caused various types of ice to form artificially on an energized insulator. For flashover studies, there was no noticeable difference between the results obtained using artificially made ice as opposed to natural ice.

The changes in the insulating strength of a flat insulator, under different ice types (glaze, soft rime or hard rime) were studied by Sato et al. [103] using ice formed by spraying NaCl- contaminated water on an insulator in a cold room. According to their results, soft rime leads to a 20%-reduction in flashover voltage compared to ice free conditions.

At CIGELE, Farzaneh et al. [27] carried out informative tests on ice grown artificially on energized insulators. The researchers divided the ice into two different types, known as wet and dry regimes. The conditions for producing these two types of ice are listed in Table 2-2.

Table 2-2 Experimental conditions for dry-growth and wet-growth ice

Type of Regime	Surrounding Temperature (°C)	Droplet Size (mm)	Wind Velocity (m/s)	Liquid Water Content (g/m^3)
Dry	-12	15	3.3	6.8
Wet	-12	80	3.3	6.8

The ice growth is said to be dry when the ice deposit temperature remains below 0 °C [33]. This is the equilibrium temperature prevailing between ice surface, water droplets and ambient temperature. The density of the accreted ice is mainly a function of impact velocity, average droplets volume and the ice deposit temperature. Dry ice accretion is called soft or hard rime according to its physical appearance and density.

The ice growth is said to be wet when its growth takes place at the melting point [33], resulting in the presence of a water film on the surface, in which case the accreted ice is called glaze. When it is grown without water run-off, no icicles are formed. When the flux of water impingement is high, mostly in connection with freezing rain, icicles are formed, usually on the windward side of the insulators.

Different types of ice have different characteristics and exert a different influence on the insulating strength of insulators. A number of studies have been made on the minimum flashover voltage under soft rime, hard rime and glaze conditions, using short insulator strings [42, 77, and 95]. As a result, glaze with icicles was considered to be the type of ice with the highest probability of producing flashover.

2.3.2.2. Influence of Amount of Ice

The amount of ice, including length and number of icicles [54, 85, 114 and 116], the thickness of the ice layer [95, 27 and 28] and the weight of ice [105], all have considerable influence on the insulator flashover voltage. Different measurement techniques were used in different laboratories.

Under extra-high voltage conditions, even an ice thickness of 0.4 cm is likely to result in flashover [76]. Phan et al. [95] showed that the minimum flashover voltage would decrease with an increase in ice thickness of up to 2 cm, but that thereafter, it would remain constant. It was also found that the thickness of the ice on the shed itself, would decrease the withstand voltage. This decrease, however, is less than the one that occurs when there are icicles of the same thickness on the sheds.

The ice thickness, which is non-uniform, is not easily accessible to precise measurement, thus the ice weight was used as a parameter to determine the amount of ice on the insulators. It was shown that the withstand voltage diminishes with an increase in the weight of accumulated ice on the insulators, and tends towards saturation [55, 105].

Ice weight is easy to measure in the laboratory but less so on power systems. Therefore, the thickness of wet ice grown on a rotary monitoring cylinder was used as a reference to estimate the amount of accumulated ice [22, 23, and 40]. Such an estimate may be made using a predetermined relationship between ice thickness and ice weight per meter on an insulator string. The relationship between the ice thickness and the maximum withstand stress has been investigated for different types of insulators [40]. It was found that the maximum withstand stress decreases with an increase in ice thickness of up to 2 cm for anti-fog insulators, 2.5 cm for IEEE standard and EPDM insulators, and 3 cm for post insulators. Beyond that, the maximum withstand stress will remain constant. Therefore, with about 1.5 cm of ice thickness, the probability of insulator flashover on transmission lines of 230 kV rises considerably [9].

2.3.2.3. Influence of Ice Uniformity

As a general rule, ice accretion along insulators is not uniform. There may be sections of insulator strings that are free of ice and where air gaps are formed [85]. This is due to the heating effect of partial arcs or ice shedding from the insulators during or after ice accretion.

The ice shape depends closely on wind velocity during ice accretion. Farzaneh et al. [22, 23, 27] observed that nearly vertical icicles formed when the wind velocity was below 3.3 m/s, resulting in relatively uniform vertical ice distribution along the insulator string or post insulator. Otherwise, wind causes the ice and icicles, which are formed, to slope toward the insulator axe. In other words, it causes a deviation from the vertical axis toward the insulator. The higher the velocity, the greater the deviation will be. Also, for velocities up to 6.4 m/s, which result in non-uniform ice distribution, the leakage distance will increase.

2.3.2.4. Influence of Freezing Water Conductivity

In nature, the degree of conductivity of atmospheric ice results mainly from environmental pollution. Under voltage, this conductance will result in an increase in insulator leakage current and, consequently, in a decrease in insulating strength. Field studies in Norway show that flashovers in mountainous areas occur because of icing conditions combined with a high ion concentration in the air. These ions come from either salt or combustion of fossil fuels [46].

The resistivity of the water producing the ice has a significant effect on leakage current, particularly, when it drops from 90 Ω·m to 9 Ω·m [75]. Under this condition, leakage current pulses start at the outset of icing and then increase rapidly.

Chisholm et al. [9] considered that surface contamination at a temperature of about 0 °C is a natural case under which 500kV, 230 kV or 115kV power lines, in cold regions, would experience flashover for low, moderate or heavy contamination levels, respectively.

Fujimura et al. reported that, with a constant amount of ice or snow, withstand voltage depends on the conductivity of melted water on the ice surface. The higher the conductivity, the lower the withstand voltage [55]. A surface conductivity level of 800 μS/cm is almost equal to the effect of 0.1 mg/cm^2 of salt [85].

2.3.2.5. Influence of Voltage Polarity

Watanabe [118] carried out a series of DC flashover tests on a vertical insulator covered with ice or snow. The desired test conditions were created using ice which was made at night when the temperature was below 0°C, or by laying down mountain snow on an insulator. The minimum flashover voltage was found to be higher under negative voltage as compared to positive voltage.

However, Fujimura et al. [55], also reported that the flashover voltage under negative polarity for DC voltage is lower than its positive counterpart. Therefore, they carried out experiments exclusively under DC- voltage conditions.

Renner et al. [98] found that the flashover voltages of ice-covered insulators under DC- and DC+ are only marginally different, thus the effect of voltage polarity may be disregarded.

A number of tests were carried out under DC voltage, by Farzaneh et al [17, 27 and 35]. The flashover voltage was considerably lower under DC- than under DC+ voltage for a short string of 4 anti-fog insulators. The flashover voltage of ice-covered insulators decreases by 32% to 47% as compared to that of clean insulators of the same dimensions, when ice thickness goes from 0.5 to 3 cm.

2.3.2.6. Influence of Leakage Current

Under icing conditions, the characteristics of the local arc depend on the leakage current through the arc. The leakage current was occasionally used as a parameter for studying the performance of ice-covered insulators.

Khalifa et al. [77] studied the influence of atmospheric ice accretion on the performance of a high voltage insulator string in 1965. The critical leakage current of an ice-covered insulator was found to be less than the critical leakage current of a polluted insulator.

Hara et al. [60] studied the effects of leakage current on the flashover performance of ice-covered insulators. The threshold value for the current of a white arc was observed to be approximately 18 mA during the flashover. When the leakage current was above this threshold, a white arc occurred on the insulator. The threshold value was independent of either the type of insulator or the type of ice. Furthermore, this value for the current of a white arc remained constant during periods of ice accumulation and de-icing. Transition from a white arc to a flashover occurred when the leakage current was above or equal to 120 mA for a long-rod porcelain insulator, and 180 mA for a post-type porcelain insulator. This flashover threshold current was observed to be virtually equal to the maximum stable white arc current.

2.3.2.7. Influence of insulator type

The insulating properties of an insulator vary with its shape and the materials of which it is made. The performance of these insulators also varies under different icing conditions. To date, no specialized type of insulator has been designed for anti-atmospheric icing.

Cherney [6] reported that, when 5 different types of long-rod transmission insulators are exposed to icing conditions, the insulating performance of the composite insulator is superior to IEEE standard insulators. For the same materials and specifications, the alternative sheds tend to show evidence of more satisfactory performance than uniform sheds.

Wu et al. [120] conducted a large number of flashover tests using different types of insulators ranging from 7 m and 11 m in length. For the composites, SIR (Switched Integrated Rectifiers) and EPDM (Ethylene Propylene, Diene Monomers), the insulating performance was superior to glass cap-pin insulator strings. The researchers also found that the presence of corona rings can improve insulating performance under icing conditions.

2.3.2.8. Influence of Insulator Position

Methods of insulator installation may vary for different engineering reasons. Renner et al. [98] reported that, for suspension insulators, with the same type and amount of ice, installation at a swing angle could lead to higher insulating strength than vertical installation. The same flashover performance, however, is expected when specimens are normalized in terms of the percentage of ice bridging.

Lee et al. [82] and Schneider [103] independently tested an insulator in the vertical, horizontal and V type positions. The V type insulator string displayed superior performance to the one observed for a vertical string under similar ice conditions. The minimum flashover voltage of a vertical insulator string was 20% lower than that observed for a horizontal string under almost the same icing conditions.

Comparable results were obtained by Bui et al [2]. The flashover performance of the horizontal installation was superior both to the V-type installation and the vertical one; also, the V-type installation showed more satisfactory performance than the vertical one.

2.3.2.9. Influence of Insulator Length

The flashover voltage of an ice-covered insulator string depends on its length. Farzaneh et al. [23], Phan et al. [95], Kannus et al. [75] and Su et al. [108] independently studied the flashover voltage of a short insulator string and they found that the minimum flashover voltage of an ice-covered insulator string increased in a more or less linear fashion for insulator strings of up to 1 m in length.

Kawai [76] tested the flashover voltage of both long and short insulator strings covered with ice. No linear relationship between insulation strength and insulator length was revealed under mild icing conditions. The flashover voltage for an insulator unit was considerably lower for a long insulator string of 19 to 25 units than it was for a short insulator string of 5 to 7 units. This disparity was attributed to the non-uniform voltage distribution along the insulator string.

2.3.3. Modeling of Flashover on Ice-Covered Insulators

The highly complex phenomenon of flashover on ice-covered insulators is influenced by several environmental parameters. To date, most published studies have concentrated mainly on determining the flashover performance of ice-covered insulators. The relevant factors involved in this phenomenon are also addressed in detail by such studies. There appears to be a scarcity of research, however, concerning the various aspects of discharge on ice-covered insulators or flashover modeling.

2.3.3.1. Arc Characteristics and Mechanism of Flashover

In 1976, Jordan et al. [74] studied the corona discharge at the tip of an icicle. In addition, Phan et al. [96] measured the corona discharge of water drops over the freezing temperature range. Also, the evolution of the corona discharge of a water drop was studied during its transition from a liquid to a solid phase and vice versa.

Sato et al. [103] investigated the flashover performance of a flat plate insulator covered with the three types of ice (glaze, soft rime and hard rime) formed by spraying a contaminated liquid on an insulator in a cold room. For a given concentration of NaCl-contaminated liquid, the average SDD (Salt Deposit Density) value for an ice state was 5 to 9 times higher than the average SDD value under ice-free conditions. Soft rime conditions lead to a 20% reduction in the flashover stress as compared to ice-free conditions. Thus, the density of Na atoms in the discharge space during flashover was the highest under soft rime conditions.

Using a triangular sample of ice, Farzaneh et al. [37, 38 and 41] carried out a large number of investigations on the characteristics of both dynamic and static arcs on an ice surface under AC and DC conditions. Under AC conditions, the electrode voltage drop, V_e, was not calculated separately. Instead, V_e was included in the calculation of the arc constant A. Hence, when the arc length was less than 7 cm, arc length had a significant influence on the arc characteristics. When the arc was longer than 7 cm, the influence of arc length on arc characteristics was negligible. Under DC conditions, the E-I characteristics, of both the dynamic and static arcs were not affected by the arc length.

There was, however, a slight difference between the characteristics of both types of arcs. Table 2-3 presents the results of this particular study.

Table 2-3 Electrode voltage drops and arc constants obtained at CIGELE using a triangular ice sample [18, 38 and 41]

Arc Type		AC	Positive	Negative
Static Arc	V_e (V)	—	—	502
	A	346.4	—	107.5
	n	0.36	—	0.61
Dynamic Arc	V_e (V)	—	799	526
	A	204.7	208.9	84.6
	n	0.56	0.45	0.77

At CIGELE, Zhang et al. [122] [124] studied the behavior of an arc on an ice surface under both AC and DC conditions, using a high speed-camera. They found that the arc could propagate in two different ways: inside or outside the ice. The arc propagation process may be divided into two stages. The first stage begins at the moment that a violet arc is established with an initial length of 5% of the total ice sample length. This initial stage ends when the arc length reaches approximately 40% of the total ice sample length. The arc extends relatively slowly during the first stage. An arc length of between 40% and 100% of the total ice sample length may make the second stage more distinguishable. During this stage, the arc propagation velocity suddenly increased, and the maximum arc propagation velocity was reached immediately before flashover. Table 2-4 illustrates the arc propagation velocity under different voltage types and polarities.

Table 2-4 Arc propagation velocities under different voltage types and polarities [124]

Arc type		Arc propagation velocity (m/s)		
		First stage	Second stage	Maximum value
Positive arc	outer	0.05 to 0.3	20 to 50	≈ 100
	inner	-	3 to 7	≈ 50
Negative arc	outer	0.05 to 0.3	35 to 60	≈ 100
	inner	-	10 to 20	≈ 50
AC arc	outer	0.04 to 0.15	16 to 30	≈ 440
	inner	-	2 to 7	≈ 260

2.3.3.2 Electric Arc Modeling

Field and laboratory investigations of flashover on ice-covered insulators are costly and time-consuming. That is one of the reasons why so much effort has been forthcoming from many researchers in order to establish a mathematical model for accurately predicting the flashover voltage of ice-covered insulators.

The ice accreted on insulators is considered to be a special kind of pollution. Therefore, a mathematical model based on a series of experiments was established at CIGELE for calculating the flashover voltage of a short ice-covered insulator string [18, 38]. This model is based on the Obenaus concept as illustrated in Figure 2-2. The basic equation, the arc reignition condition, and the equation for calculating the residual resistance are as follows:

$$V = V_e + AxI^{-n} + IR(x) \tag{2-13}$$

$$I = \left(\frac{kx}{V}\right)^{\frac{1}{b}} \tag{2-14}$$

$$R(x) = \frac{1}{2\pi\gamma_e}\left[\frac{4(L-x)}{D+2d} + \ln\left(\frac{D+2d}{4r}\right)\right] \tag{2-15}$$

where V is the applied voltage, I represents the leakage current, V_e is the electrode voltage drop, A and n are the arc constants, k and b are the arc reignition constants, x is the arc length, $R(x)$ represents residual resistance, γ_e is the surface conductivity of the ice layer, L and D are the length and diameter of the insulator respectively, d is the thickness of the ice layer and, finally, r is the arc root radius. .

Using a triangular physical ice model, all the necessary parameters used in equations 2-13, 2-14 and 2-15 were empirically determined at CIGELE [18, 37, 38, 41, 121, 122 and 124]. The results are shown in Table 2-5.

Table 2-5 Parameters for calculating the flashover voltage of an ice-covered insulator under AC and DC conditions [18] [38] [121]

	AC	Positive	Negative
V_e (V)	—	799	526
A	204.7	208.9	84.6
n	0.56	0.45	0.77
k*	1118	—	—
b*	0.5277	—	—
γ_e	$0.0675\sigma+2.45$	$0.082\sigma+1.79$	$0.0599\sigma+2.59$
r	$\sqrt{\frac{I}{0.875\pi}}$	$\sqrt{\frac{I}{0.648\pi}}$	$\sqrt{\frac{I}{0.624\pi}}$

This model was applied to a 5-unit string of IEEE standard insulators covered with ice. The results, calculated from the established model as well as from the tests, are shown in Figure 2-3. It may be observed, here, that there is a satisfactory concordance between them. This particular mathematical model was also successfully applied to an insulator that ranged in voltage from 44 kV to 500 kV (See reference [38]).

At CIGELE, a dynamic mathematical model is currently being established to calculate the flashover voltage, the leakage current, and arc propagation velocity. Initial results have already been published [17, 43, 44, 47-52].

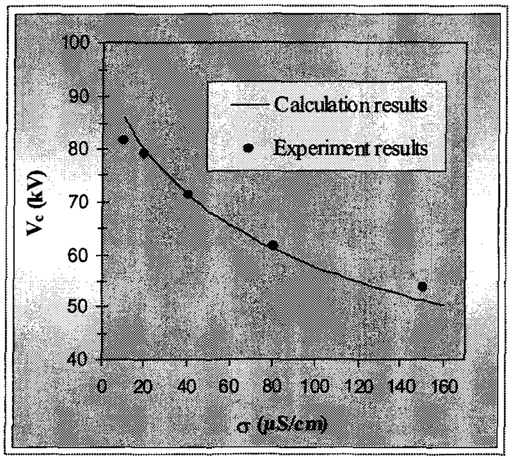


Figure 2-3: Test results on 5 IEEE standard units.

2.3.3.3. Arc Maintenance Condition

When the existing mathematical model was applied to a long insulator string, it was found that the flashover voltage increases linearly with the length of the insulator string [4], as shown in Figure 2-4. Test results for longer insulator strings, however, revealed that on the contrary, the flashover voltage did not increase linearly with an increase in insulator string length [17].

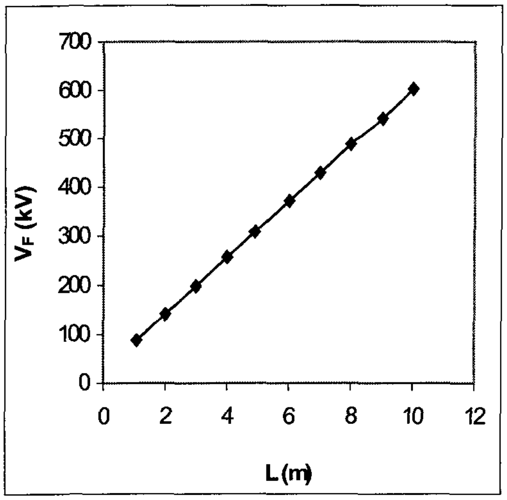


Figure 2-4: Flashover voltage calculated by the existing model, as a function of insulator string length

The discrepancy observed between the calculated and test results may be due to the fact that the arc re-ignition condition was determined using a small triangular ice sample and that this condition was considered to be independent of the insulator length. In order to improve the mathematic model for application to long insulators, recent researches were carried out at CIGELE [4, 124] showed that the local arc had the potential for extending in two different ways: (i) the arc propagates on the ice surface, or (ii) the arc burns along the air gap and spreads as the ice thaws and the air gap widens [125]. In either case, when the arc reaches its critical value, flashover will occur. The researchers were, therefore, convinced that the minimum applied voltage for maintaining an arc burning steadily along an air gap constitutes the critical condition of arc propagation on ice-covered insulators. The minimum applied voltage for maintaining an arc burning steadily along an air gap of a certain length was then determined, using a cylindrical ice sample. The equation describing the tendency of these minimum voltages is called the "Arc

Maintenance Condition" [126]. The results show that the minimum applied voltage, V_m, for maintaining an arc burning steadily along an air gap is a function of the arc length, x, the leakage current, I_m, and the insulator length, L. Thus, the arc maintenance condition may be expressed as:

$$V_m = f(x, I_m, L) \tag{2-16}$$

Due to the inconvenience of creating long cylindrical ice samples however, the investigation was limited to an ice sample length of up to 83 cm [125]. In order to complete this investigation and to improve the mathematical model, it will be necessary to make further studies of the arc maintenance condition using a full-scale insulator string.

2.4. Conclusion

The flashover of ice-covered insulators has attracted a great deal of attention from researchers worldwide. A large number of studies have been carried out in several laboratories on this subject. These studies include observing the ice accretion process, experimentally determining the flashover performance of ice-covered insulators, and the modeling of flashover on ice surfaces. A mathematical model was established at CIGELE for predicting the flashover voltage of ice-covered insulators and was successfully applied to a short insulator string of up to 1 m.

By the review of the literature as presented above, a gap in the studies on the modeling of flashovers of long ice-covered insulators is revealed. This lack of information has prompted the writing of the present MS thesis.

Chapter 3

Experimental Facilities and Test Procedures

3.1 Introduction

In order to achieve the objectives laid out at the beginning of this study, a series of tests was carried out in the high voltage laboratory at CIGELE. For this purpose, certain facilities were used in order to simulate the environmental conditions of cold regions and to accumulate an ice layer artificially on an insulator surface.

The present chapter provides a detailed description of the facilities and equipment used in this study, followed by a discussion of test methods.

3.2. Facilities

3.2.1. Test Objects

The electrical performance of insulators depends on a number of factors including insulator parameters and environmental conditions. To study the effects of insulator length and diameter on the arc maintenance conditions, two types of post insulators, of different diameters, but of the same shape and shed distance, were used. The insulator dimensions are shown in Figure 3-1. Insulator length was considered as a parameter of the study. Therefore, three insulator units were installed vertically in a climate room and an electrode was placed at the desired position on the insulator in order to obtain insulator lengths of 59, 103, 161, 206, 259 or 309 cm (see Figure 3-2).

As mentioned in the previous chapter, the presence of glaze with icicles is the most critical condition for ice-covered insulators. Thus, for the study glaze ice with icicles was artificially formed on the post insulators by spraying super-cooled water droplets on the insulator surface (Figure 3-3). In order to eliminate problems arising from randomness of location and length of the air gaps, the ice was accumulated without voltage application. Once the ice thickness reached the desired value, the icing process was halted and then an artificial gap of a given length was made near the high voltage electrode by removing a part of the ice (Figure 3-3).

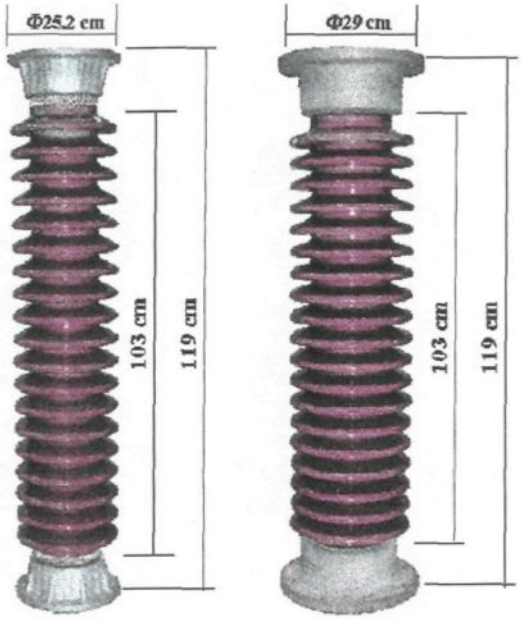


Figure 3-1 Post insulators

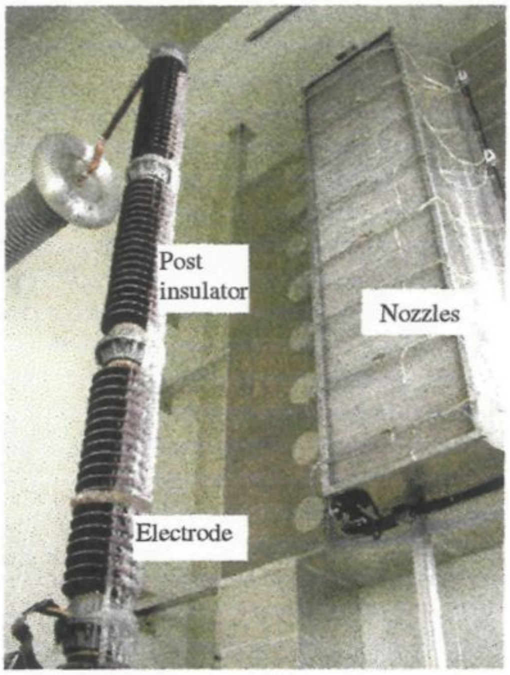


Figure 3-2 CIGELE large climate room and insulator setup with an electrode in the desired position

Figure 3-3 Test insulators covered by ice and with an artificially created air-gap

3.2.2. Climate Room and Facilities

In order to simulate and control the environmental conditions, all tests were carried out in two climate rooms at CIGELE laboratories. The smaller one measures 6.4 × 6 × 3.9 m^3 (for the insulator of less than 161 cm in length) and the larger one measures 6 × 6 × 9 m^3 (for the insulator of more than 161 cm in length). Both rooms are equipped with a cooling system, a water spraying system, and a wind producing system (Figure 3-2).

Cooling System

To simulate cold atmospheric conditions as prevail outdoors, the climate rooms are provided with a cooling system was used. It consists of a powerful 316.5kJ/min compressor and temperature PID controller making it possible to alter the temperature inside the climate room between -30 °C and room temperature (~20 °C). By using a PID controller, the accuracy of temperature control is ±0.1 °C. In this study, it was necessary to accumulate glaze with icicles on the insulator surface. Based on previous studies at CIGELE, the temperature was set at -12 °C during the ice accumulation period.

Water Spraying System

The ice was accumulated on the insulator surface by spraying supercooled water droplets onto the insulator surface. Type No. SU12A Nozzles made by Spraying Systems Co were used to produce the water droplets (Figure 3-4). The spray angle was 15°, and the size of the water droplets depended on the pressure of the air and water fed into the nozzle. In this study, pressures of 10 psi for air and 80 psi for water were used. Under these pressures, the mean diameter of water droplets was 80 μm. Liquid-water content (LWC) is another parameter that affects the ice accumulation. Its value depends on a number of factors such as the wind speed, water droplet diameter and the water quantity. In this study, LWC was set at 6.8 g/m^3 to produce the glaze. The water quantity was set at 250 cm^3/min per nozzle.

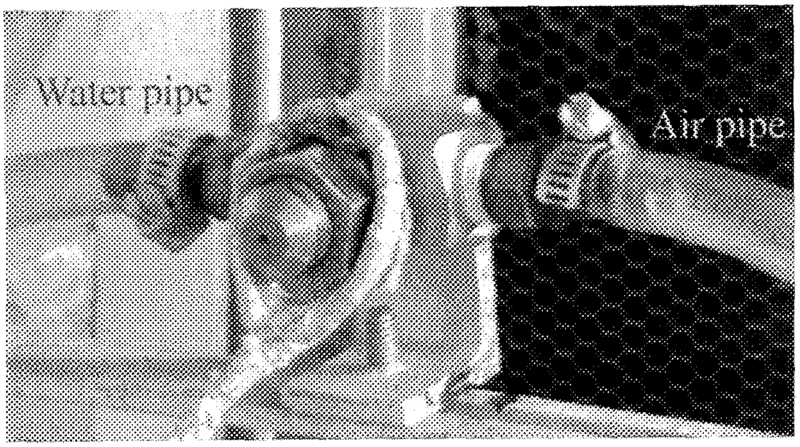


Figure 3-4 Nozzles used to produce water droplets

Wind Producing System

Wind speed may also affect the ice accumulation on an insulator surface. In order to simulate natural wind as found in cold regions, the cold climate rooms are equipped by several electric fans are installed behind the nozzles to produce different air-flow speeds (Figure 3-5). By using a PID controller, the wind speed may be adjusted to within a range of 0 to 15 m/s. A honeycomb grid panel is installed in front of the fans to cause the wind to flow uniformly. In this study, the distance between the insulators being tested and the nozzles is greater than 1.8 m. The results measured showed that the wind along the insulators was relatively uniform. A wind speed of 3.3 m/s was set to form a uniform ice layer on the insulator surface.

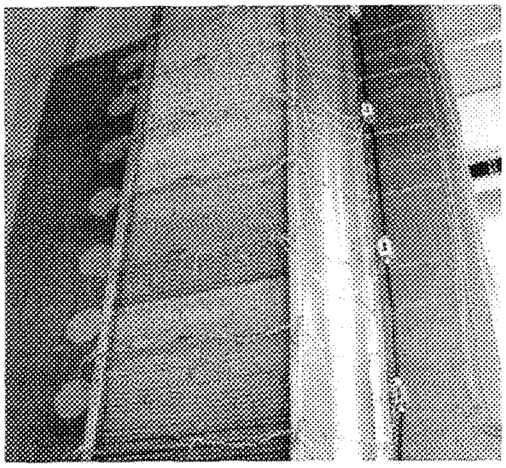


Figure 3-5 Wind-producing system

3.2.3. High Voltage System

For insulator lengths under 161 cm in the smaller climate room, an AC high voltage was supplied by a 120 kV/240 kVA transformer (Figure 3-6) and a 240 kVA regulator. The output voltage may be adjusted from 0 to 120 kV. The short circuit current is about 28 A at the rated voltage of 120 kV. The rate of increase in output voltage is about 3.9 kV/s.

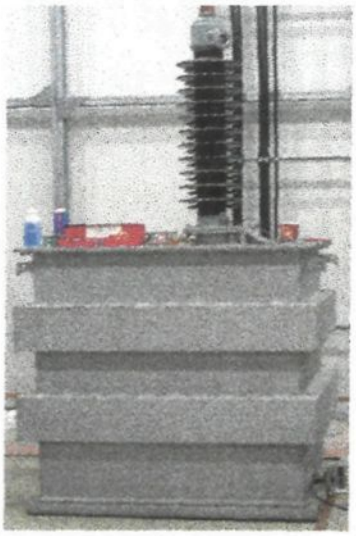


Figure 3-6. 120 kVA transformer

For insulator lengths over 161 cm, the tests were carried out in the larger climate room. A 350 kV/700 kVA transformer and a 700 kVA regulator were used to supply the high voltage to the test sample (Figure 3-7).

Figure 3-7. 350 kV/700kVA AC high voltage system

The output voltage of this system may be adjusted from 0 to 350 kV with a control unit (Figure 3-8). The voltage increase rate may be set at 5 different levels, where the maximum level is 12kV/s. On this unit, the over-current and over voltage protection may also be adjusted. The short circuit current is in the range of 10 to 20 A, depending on the output voltage level. The short circuit current of both the 120 kV and the 350 kV systems satisfies the requirements of the international standard for tests under high leakage currents, namely, tests on polluted insulators [IEC507].

Figure 3-8. Control unit for 350 kV Transformer.

3.2.4. Test Circuit and the Measuring System

The test circuit is shown in Figure 3-9. After the ice was accumulated on the insulator surface and the air gap was created, an AC high voltage was applied to the top electrode of the insulator. A voltage divider and a shunt were used to measure the voltage and the leakage current.

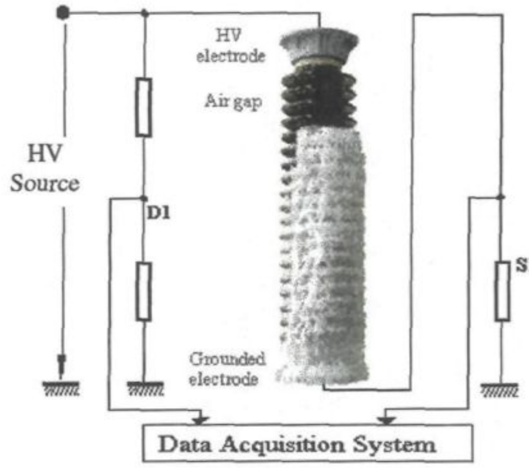


Figure 3-9: Test circuit

A computer-based data acquisition system (DAS) was used to record and analyze the waveforms of the applied voltage and the leakage current during the tests. This DAS system consists of a 16 bit high precision PCI data acquisition card and the widely used software, LABVIEW. Figure 3-10 shows the data acquisition interface as designed for this study.

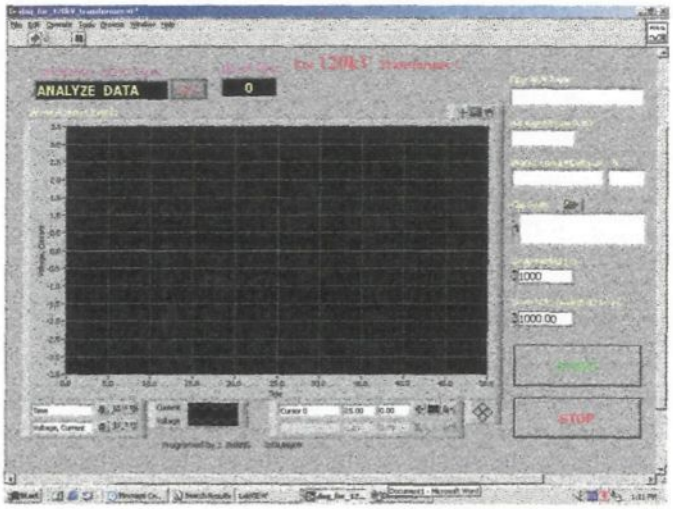


Figure 3-10: Interface designed for data gathering

3.3. Test Procedures

The objective of this study is to determine the minimum arc maintenance voltage as a function of the leakage current, the air gap length and the insulator length. To achieve this objective, a series of tests was carried out at the CIGELE laboratory. The test procedures under discussion consist of two phases: the ice accretion period and the voltage application period. The details of the procedure may be summarized as follows:

3.3.1. Ice Accretion

This period includes the preparation of the climate room, the accretion of ice on the insulator surface and the creation of an air gap.

The surface temperature of the insulators will influence the ice accretion process. Therefore, before starting the accretion, the insulators were installed in the climate room and the cooling system was turned on so as to lower the temperature to the desired value. In this study, a ambient temperature of -12 °C was set for ice accretion. This value was maintained for at least 3 hours to ensure that all the objects in the room, particularly the insulator to be tested, were at the same target temperature.

Spraying the super-cooled water droplets on the insulator surface formed the ice layer. Depending on the environmental conditions, the ice formed could be of different types. The ice type called glaze with icicles was selected for the purposes of this study and the corresponding environmental conditions are listed in Table 3-1.

Table 3-1 Conditions for wet-grown ice accretion

Temperature (°C)	Water Droplet Size (μm)	Wind speed (m/s)	Liquid Water Content (g/m^3)
-12	80	3.3	6.8

The ice amount was checked by measuring the ice thickness on a monitoring conductor 3.8 cm in diameter, installed in front of the insulator, and rotating at a speed of 1 rpm (Figure 3-11). Another fixed conductor was also installed to investigate the difference between the ice accretion on rotating and non-rotating conductors (Figure 3-11).

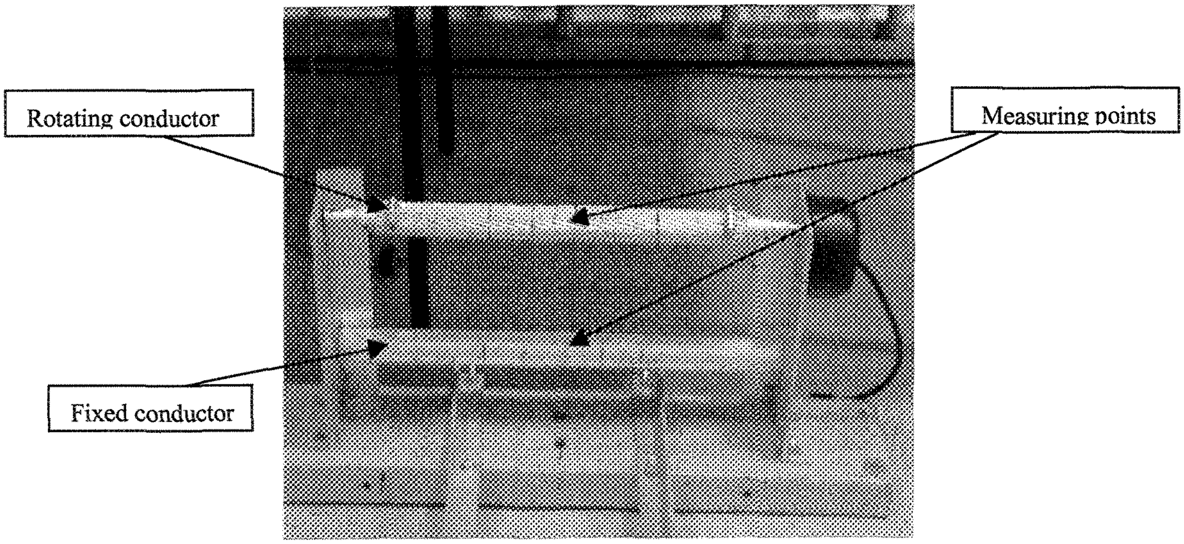


Figure 3-11. Rotating and fixed monitoring conductors

Figure 3-12 shows the monitoring conductors after ice accretion. The ice accretion on the conductors was not absolutely uniform. Therefore, the average ice layer thickness, as measured at 5 equally spaced points, was used to indicate the amount of accumulated ice on the insulators (Figure 3-12).

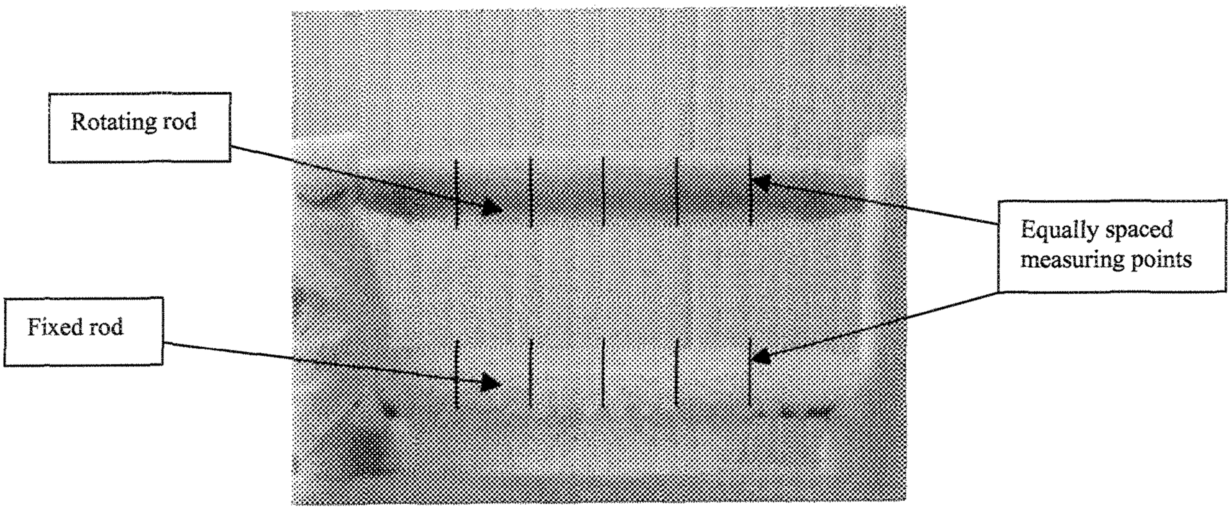


Figure 3-12. The device used to calibrate ice accretion after ice deposition

The dependency of ice thickness growth on time is shown in table 3-1.

Table 3-2 Variations in the ice layer thickness on the conductors as a function of time

Measuring Positions Time (min)		Diameter of ice rod (mm)					Average Ice Thickness (mm)
		1	2	3	4	5	
Rotating conductor	20	40	43	44	45	41	2.3
	40	43	53	55	54	46	6.1
	60	46	60	61	60	51	8.8
	80	50	68	71	68	55	12.2
	90	55	78	72	77	58	15
Fixed conductor	20	42	44	45	45	42	5.6
	40	43	53	55	54	46	12.2
	60	47	61	63	63	54	18.6
	80	50	68	71	68	55	24.4
	90	55	78	73	77	58	31

It should be noted that the average ice layer thickness of 15 mm was obtained on the rotating conductor after 90 minutes of accretion time, as selected for this study. These conductors were removed in later tests in order to reduce the effects of monitoring conductors on the ice accretion. To ensure that test conditions remain constant for each test the ice layer thickness was maintained to 15 mm.

After the required ice thickness was obtained on the insulators, the ice accretion period was halted and an air gap was artificially created close to the high voltage electrode.

3.3.2. Voltage Application and the Determination of Arc Maintenance Voltage

After the ice and the air gap were formed on the insulator surface, the door of the climate room was opened to cause the temperature inside to rise to 0 °C. At this temperature, a water film appears on the ice surface. Because of the high resistivity of ice, the leakage current will not be so strong and the arc will be unstable. Thus, the water film is necessary for higher leakage current. The higher the leakage current, the lower the voltage required to maintain the arc.

In order to determine the arc maintaining voltage, an arc must be established across the air gap. For this purpose, an AC voltage was applied to the ice-covered insulator, and increased at a constant rate until the air gap was broken down and an arc appeared (Figure 3-13). A waiting is required for the arc-color to change to white, and then voltage is decreased at a constant rate until the arc is extinguished. Figure 3-14 shows the schematic of the voltage application process during the test.

Figure 3-13 The arc was established across the air gap

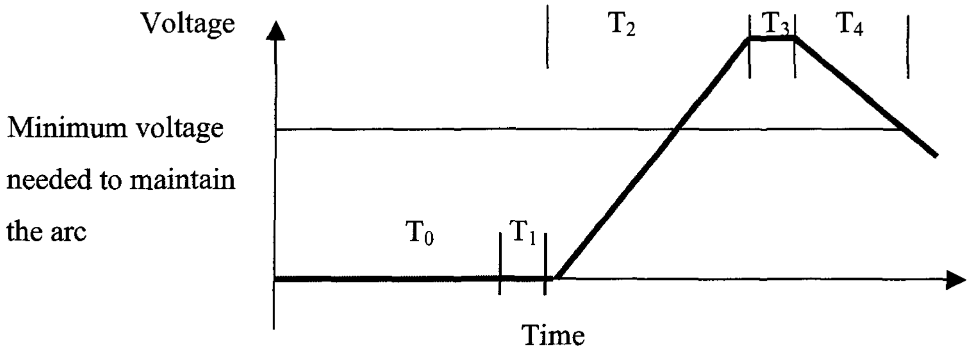
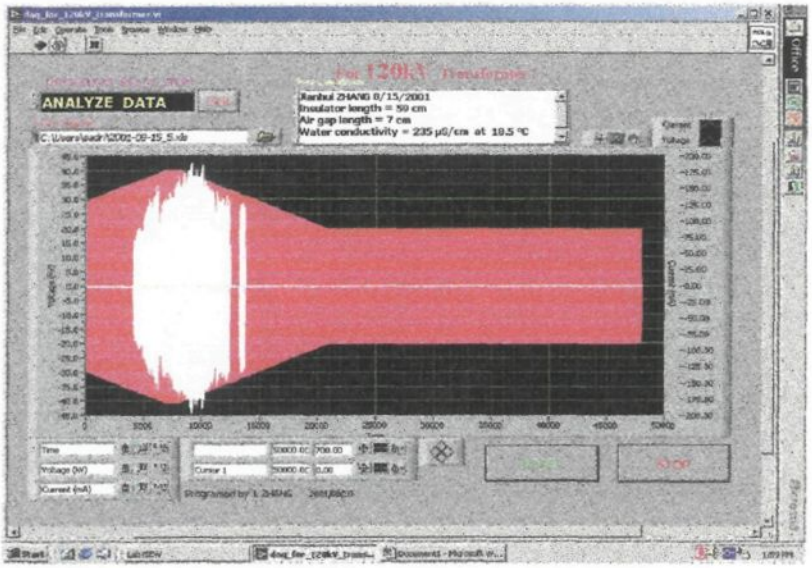


Figure 3-14 Voltage application process

In figure 3-14, T_0 is the time of cooling and ice accretion period; T_1 is the time for creating the artificial air gap; T_2 is the time for applying and increasing the voltage to obtain an arc; T_3 is the time for reaching a white arc; T_4 is the time for decreasing the voltage until the arc is extinguished.

During the voltage application period, the waveforms of the applied voltage and the corresponding leakage current were recorded by the DAS system. Figure 3-15 shows an example of typical waveforms displayed in LABVIEW. It may be observed that, as the voltage increased, the leakage current appeared at a certain instant, which means that an arc was established across the air gap. The arc may become stable and turn white after a period of time in which the voltage level is kept constant. If this does not occur, the voltage may be increased to achieve the desired conditions. At this point, as shown in figure 3-5, the voltage is decreased, followed by a decrease in leakage current, until the arc disappears at a certain voltage value.



Xianhui ZHANG 8/15/2001
Insulator length = 59 cm
Air gap length = 7 cm
Water conductivity = 235 µS/cm at 18.5 °C

Figure 3-15. Typical waveforms of the applied voltage (red) and the leakage current (white)

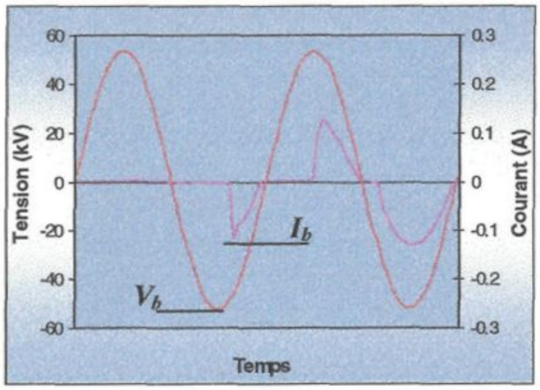


Figure 3-16 Voltage and current when the arc appeared

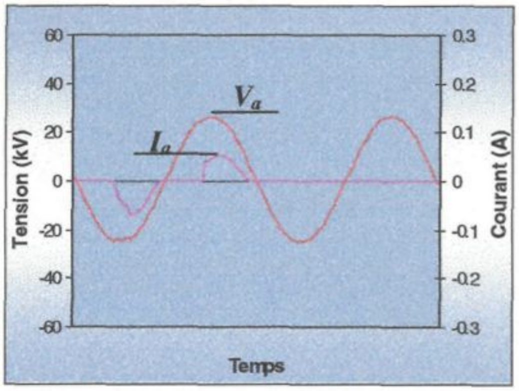


Figure 3-17 Voltage and current when the arc extinguished

By amplifying the waveforms at the moments of arc appearance and extinction, the details of the applied voltage and leakage current were obtained as shown in Figures 3-16 and 3-17. From these waveforms, the air gap breakdown voltage, V_b, and the current after breakdown, I_b, as well as the minimum voltage maintaining the arc, V_a, and the corresponding current, I_a, may be determined. A block diagram, as shown in Figure 3-18, summarizes test procedures.

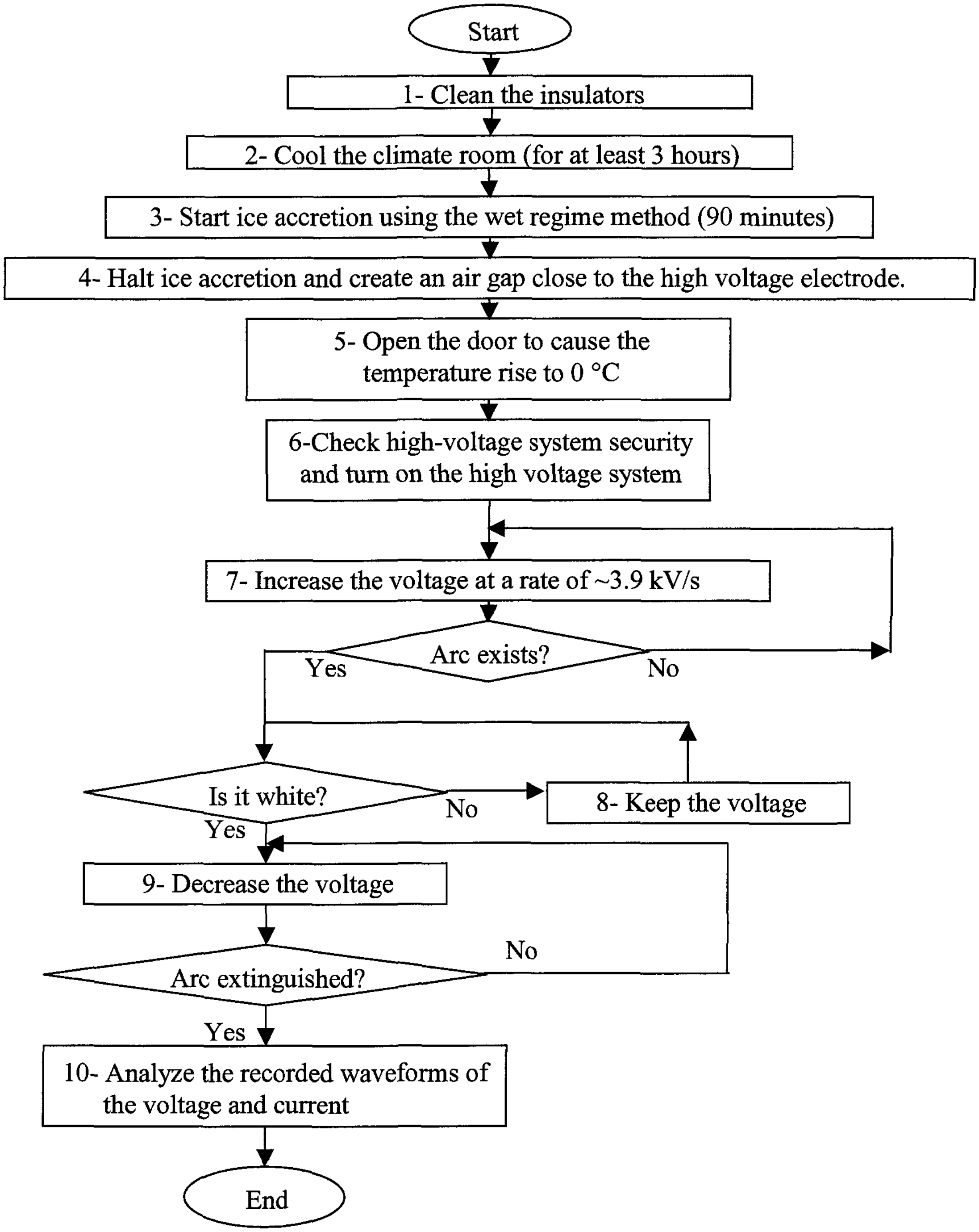


Figure 3-18. Block diagram of test procedure

Chapter 4

Arc Maintenance Conditions

4.1. Introduction

By using the test facilities and the procedures as defined in the previous chapter, a series of tests was carried out to determine the minimum applied voltage required to maintain a white arc across an air gap, i.e. the arc maintenance conditions. The test results are presented and discussed in this chapter. Also, a mathematical expression is proposed here to describe the arc maintenance conditions on ice-covered insulators based on the experimental results.

4.2. Introducing of the Experimental Parameters

The minimum arc maintaining voltage is a function of the leakage current, the arc length and the insulator length, as described in a previous work carried out at CIGELE [50] . It is necessary to investigate the relationship between the arc maintaining voltage and these parameters in order to determine the arc maintenance conditions. Therefore, in this study, the conductivity of the water used to form the ice was adjusted within a range of 10 to 350 μS/cm, in order to change the arc leakage current. The range of the air gap length was chosen according to insulator length.

The range of these parameters was chosen based on the requirements for a stable white arc burning across an air gap. If the leakage current is too weak, a violet arc and not a white arc will form. This occurs because of the low conductivity level or the small ratio of air-gap length to the insulator length. In such a case, we need to increase the water conductivity or increase the ratio of the air gap length to the insulator length in order to increase the leakage current. This causes the violet arc to pass to the white arc stage. Flashover will occur immediately after the arc is established across the air gap and no stable arc can be obtained, if the water conductivity is too high or the air gap is too long. Table 4-1 shows the experimental status for an insulator length of 206 cm. It should be noted that, for a given insulator length, the larger the air gap is, the lower the water conductivity should be, to avoid flashover.

Table 4-1 Test status for an insulator length of 206cm

x(cm) Water Conductivity (μS/cm)	16	26	36	46	56
10	OK	OK	OK	OK	
30	OK	OK	OK	OK	F.O.
80	OK	OK	OK	OK	F.O.
150	OK	OK	OK	F.O.	
250	OK	F.O.	F.O.		
350	F.O.				

Note: F.O. = Flashover ; O.K = Violet arc passes to a stable white arc

Similarly, the ranges of air gap length were chosen according to insulator length and are listed in Table 4-2.

Table 4-2 Air gap length (*x*) chosen for different insulator lengths (*L*)

L(cm) *x*(cm)	59	103	161	206	259	309
7	▲	▲	▲			
12	│	│	│			
16	▼	│	│	▲	▲	▲
26		▼	▼	│	│	│
36				│	│	│
46				▼	▼	│
56						▼

4.3. Minimum Arc Maintaining Voltage as a Function of Leakage Current

The leakage current will change with a change in the water conductivity. The relationship between the minimum arc maintaining voltage and the leakage current was investigated for different air-gap and insulator lengths, using an insulator of 25.2 cm in diameter. Figures. 4-1 to 4-3 show the results obtained for a given air gap length of 12 cm and different insulator lengths ranging from 59 cm to 161 cm.

It may be observed that the minimum arc maintaining voltage decreases with an increase in leakage current. The tendency of the voltage variation obeys a power curve, that is to say, the relationship between the minimum arc maintaining voltage, V_a, and the leakage current, I_a, can be expressed as a power equation.

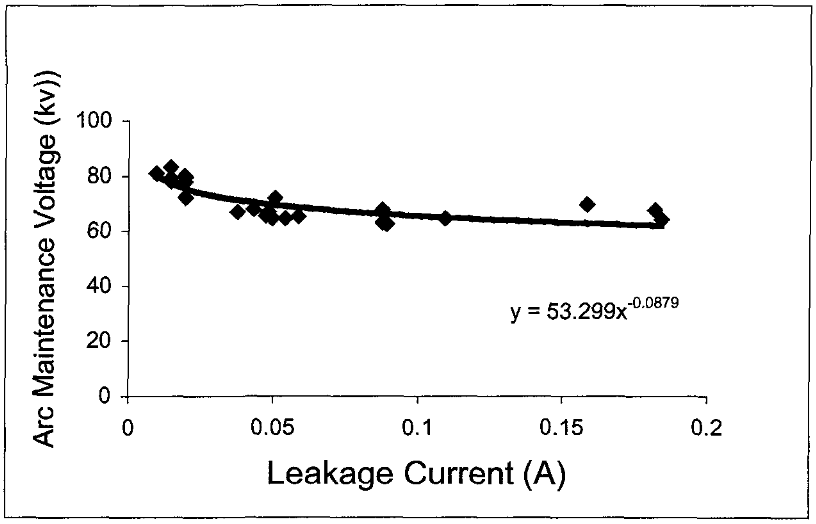


Figure 4-1. Minimum arc maintaining voltage for x = 12 cm and L = 59 cm

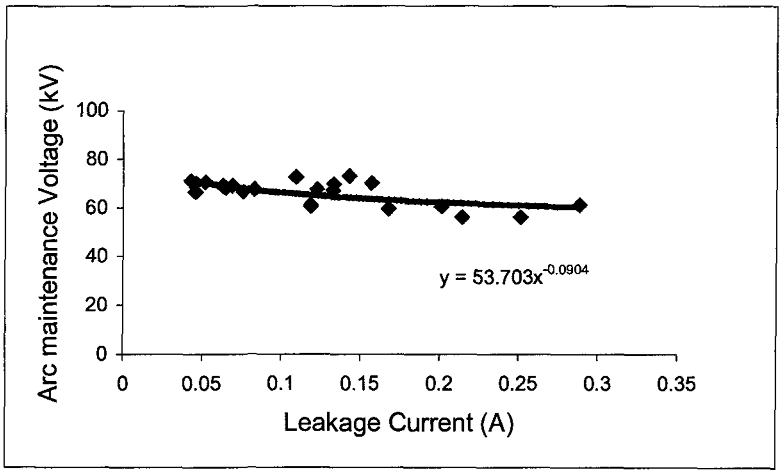


Figure 4-2. Minimum arc maintaining voltage for x = 12 cm and L = 103 cm

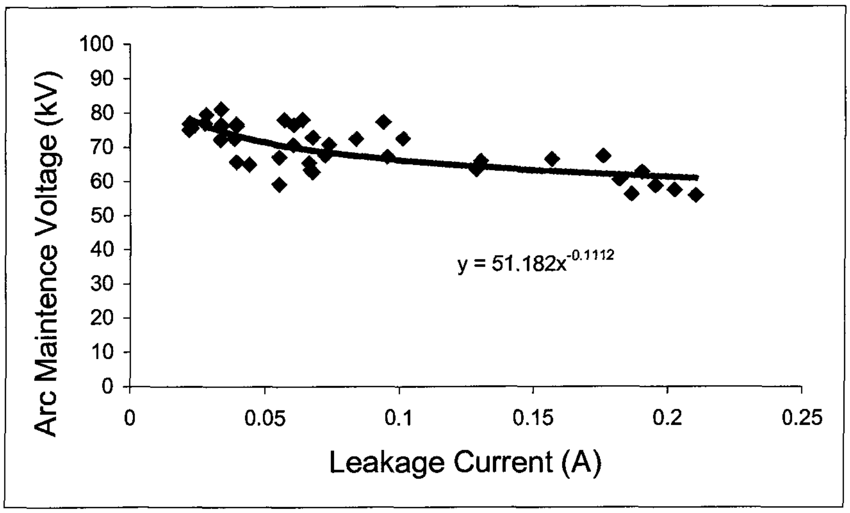


Figure 4-3. Minimum arc maintaining voltage for x = 12 cm and L = 161 cm

For Figures 4-1 to 4-3, the equations are:

$$V_a = 53299 I_a^{-0.0879} \quad \text{when } L = 59 \text{ cm and } x = 12 \text{ cm} \tag{4-1}$$

$$V_a = 53703\ I_a^{-0.0904} \quad \text{when } L = 103 \text{ cm and } x = 12 \text{ cm} \tag{4-2}$$

$$V_a = 51182\ I_a^{-0.1112} \quad \text{when } L = 161 \text{ cm and } x = 12 \text{ cm} \tag{4-3}$$

For all the combinations of air gap and insulator length shown in Table 4-2 the minimum arc maintaining voltage can be expressed in the following form:

$$V_a = \mathrm{K} \cdot I_a^{-\mathrm{b}} \tag{4-4}$$

where K and b are coefficients and their values depend on the combination of the air gap length and insulator length.

4.4. Minimum Arc Maintaining Voltage as a Function of Insulator Length

Figures 4-4 and 4-5 show the minimum arc maintaining voltage for the same air gap length but different insulator lengths. The voltage for maintaining the same arc length increases with an increase in insulator length. This effect can be explained by the fact that the residual resistance of an ice layer increases with increase in the insulator length. Therefore, a higher voltage is needed to maintain the same leakage current as the one for the shorter insulator length. That is, the value of the coefficient K in Equation (4-4) depends on insulator length.

Also, it may be observed that, for a shorter air gap, the difference between the minimum arc maintaining voltages for different insulator lengths is greater than it is for longer air gaps.

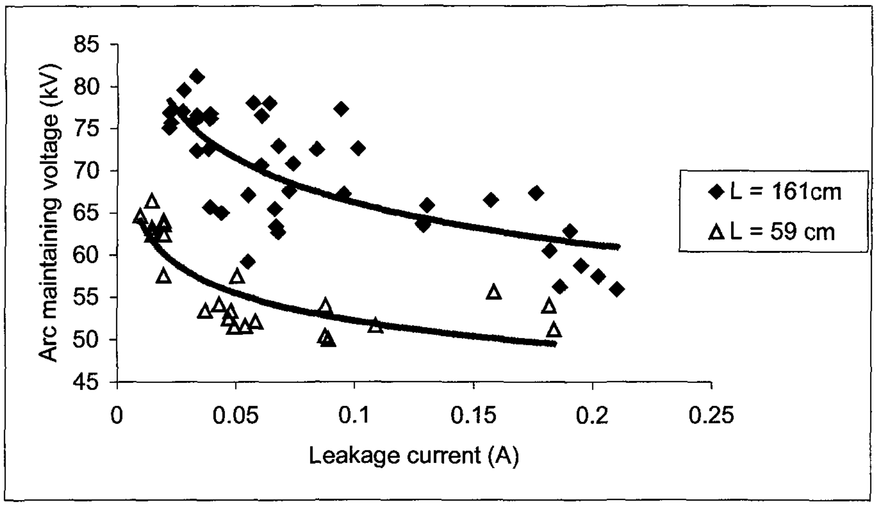


Figure 4-4. Minimum arc maintaining voltage for different insulator lengths (x =12 cm)

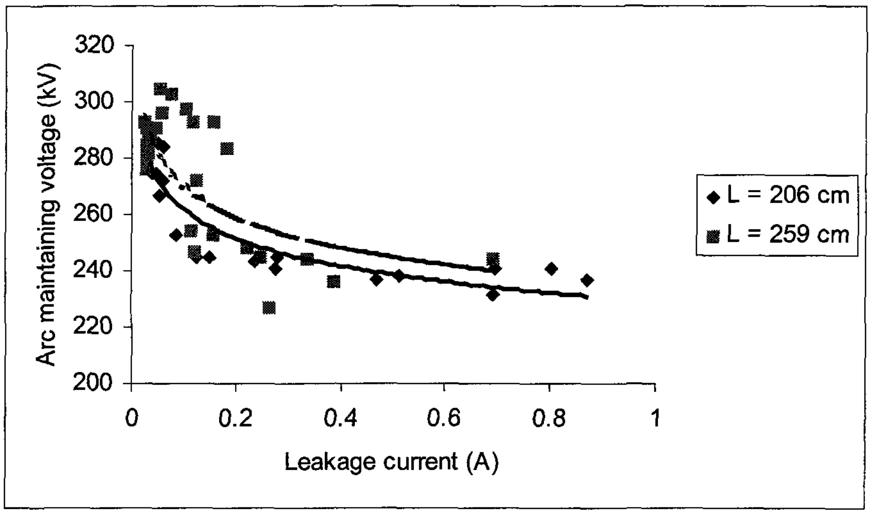


Figure 4-5. Minimum arc maintaining voltage for different insulator lengths (x =46 cm)

4.5. Minimum Arc Maintaining Voltage as a Function of Air Gap Length

The minimum arc maintaining voltage is the applied voltage for maintaining an arc burning across an air gap. Therefore, changing the air gap length will also change the arc length. The longer the arc, the more energy the arc absorbs from the power source. Thus, the minimum arc maintaining voltage is a function of arc length. Figures 4-6 to 4-10 show the results obtained for different air gap lengths, i.e. arc lengths.

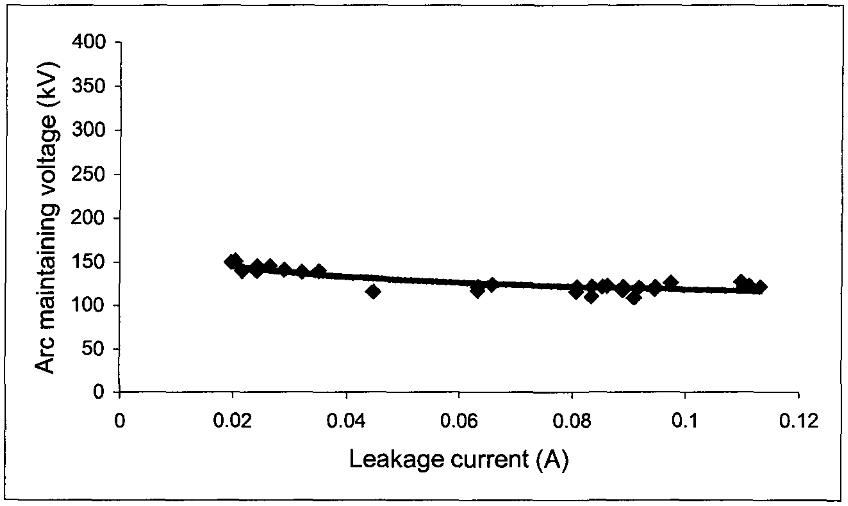


Figure 4-6. Minimum arc maintaining voltage for $L = 309$ cm and $x = 16$ cm

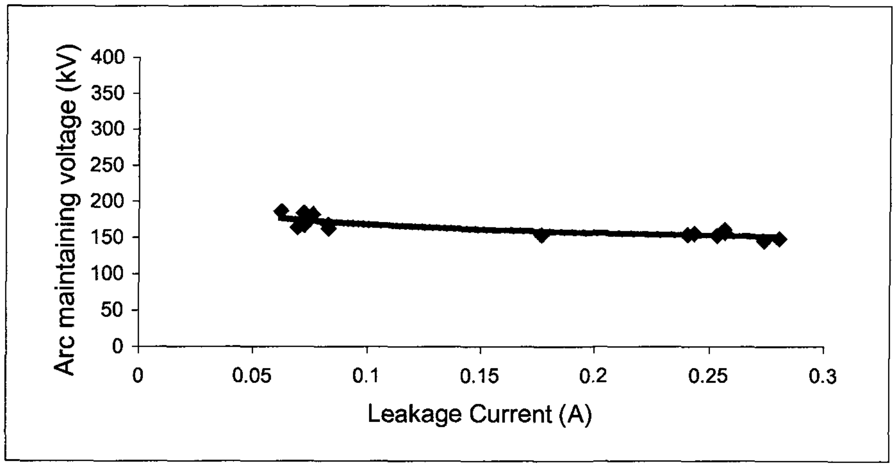


Figure4-7. Minimum arc maintaining voltage for $L = 309$ cm and $x = 26$ cm

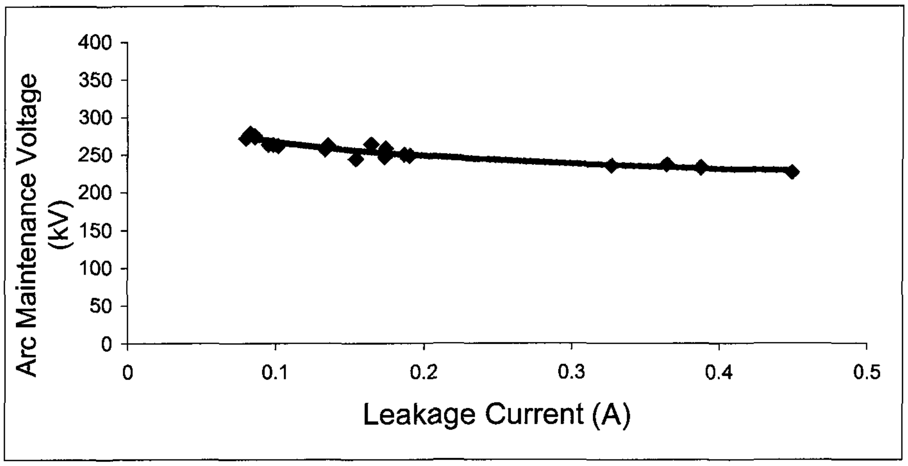


Figure 4-8. Minimum arc maintaining voltage for $L = 309$ cm and $x = 36$ cm

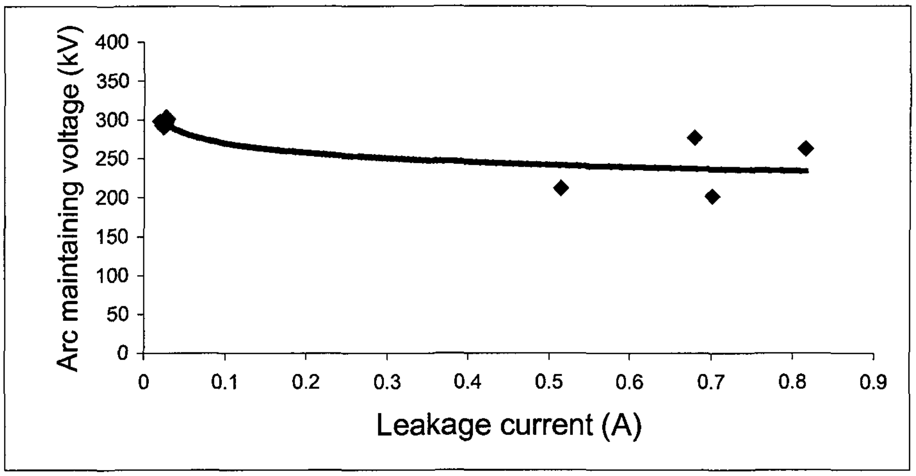


Figure 4-9. Minimum arc maintaining voltage for $L = 309$ cm and $x = 46$ cm

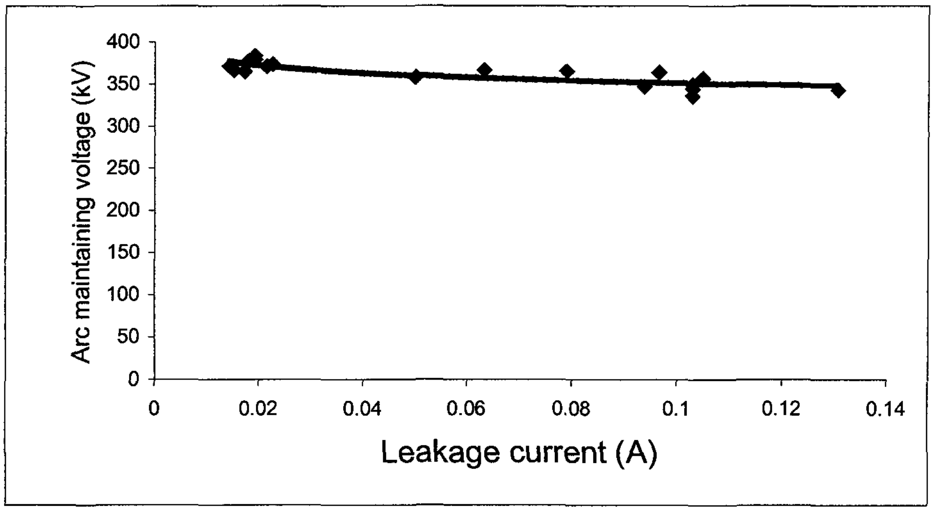


Figure 4-10. Minimum arc maintaining voltage for $L = 309$ cm and $x = 56$ cm

By comparing Figures 4-6 to 4-10, it may be observed that, for a given insulator length, the arc maintaining voltage increases with an increase in arc length. Therefore, the value of the coefficient K in Equation (4-4) also depends on the arc length. Figure 4-11 makes it easy to compare between the resulted curves.

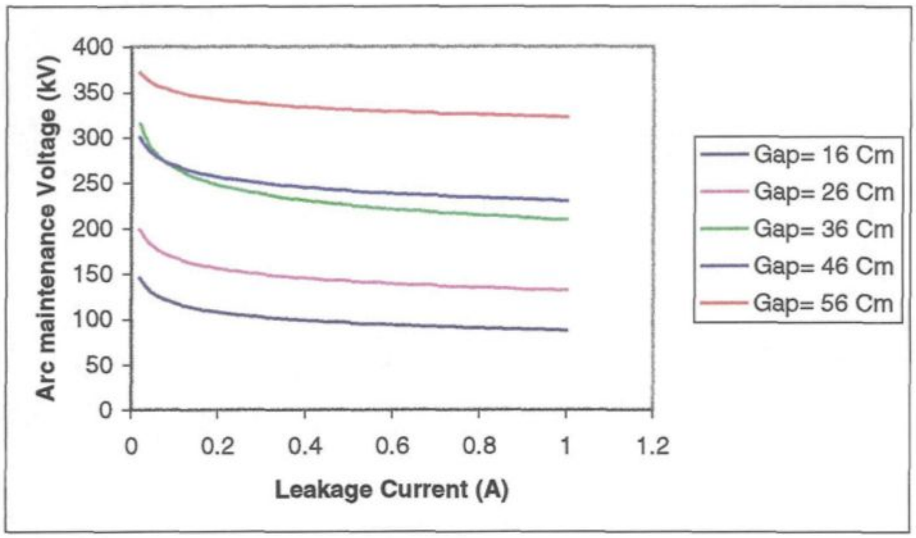


Figure 4-11. Resulted curves for L=309 Cm and different air gap length

4.6. Determining Coefficient K

Provided that the coefficients K and b have been determined, Equation (4-4) may describe the arc maintenance conditions for various combinations of air-gap length, insulator length and leakage current. As presented in the Equation (4-5), both these coefficients, and particularly K, are functions of the insulator length and air gap length. Therefore, in general, Equation (4-4) may be expressed as follows:

$$V_a = \mathrm{K}(L, x)\cdot I_a^{-\mathrm{b}(L,x)} \qquad (4\text{-}5)$$

In order to determine the values of coefficients K and b, a series of tests and analyses were carried out for all combinations of insulator length and air gap length. By applying the regression method to the results obtained, the values of coefficient K were determined and are shown in Table 4-3.

Table 4-3 Values of coefficient K

L (cm) *x* (cm)	59	103	161	206	259	309
7	23758	29891	38338			
12	53299	53703	51182			
16	46724	58312	80735	95552	74814	88034
26		67441	121329	146349	132462	131943
36				176364	199126	209767
46				229273	234651	230606
56						322863

It may be seen that the value of K is influenced by the insulator length, *L*, and the air gap length x. That is, K is a function of *L* and *x*. K increases first and then decreases as the insulator length, *L*, increases with a constant value of *x*. Therefore, K reaches a maximum value as *L* increases. Figure 4-12 shows the tendency of K with an increase in *L*.

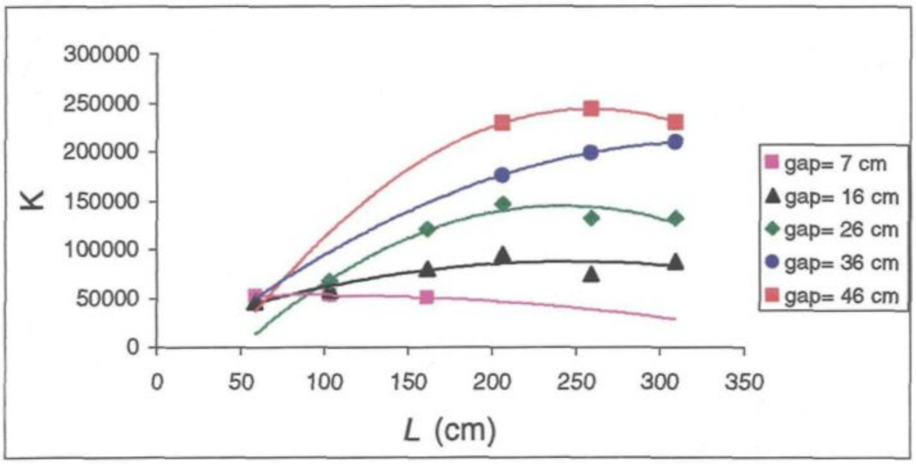


Figure 4-12. K as a function of *L*

For a longer air gap, i.e. a longer arc, the maximum value of K appears at a greater insulator length. The non-linearity of the variations in K indicates that the arc maintaining voltage for an arc increases nonlinearly with an increase in insulator length. This may be one of the reasons for the non-linearity of the flashover voltage curve of ice-covered insulators as a function of insulator length. On the other hand, K increases with an increase in *x* for a given value of *L*. The tendency is shown in Figure 4-13.

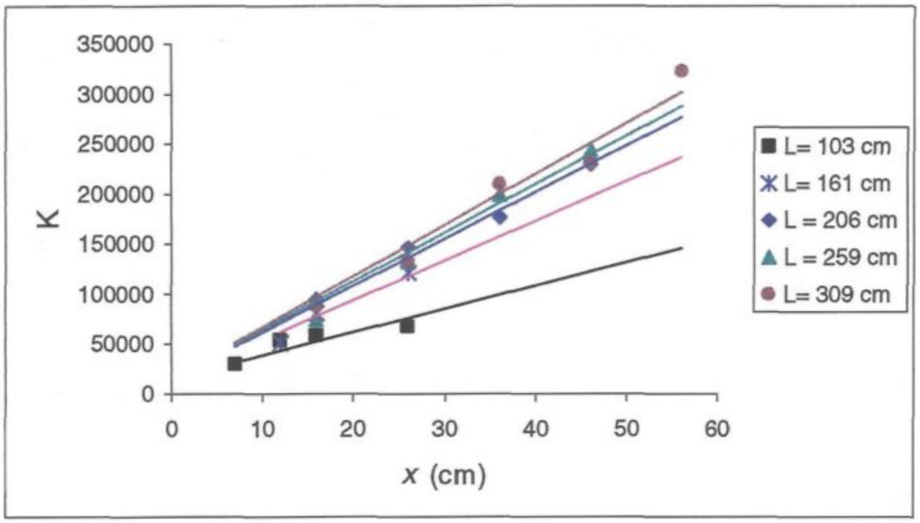


Figure 4-13. K as a function of air gap length, *x*

K increases almost linearly as the air gap length, i.e. the arc length *x*, increases. In order to determine the relationship between K, *L* and *x*, a regression method was applied the points on the curve. Thus, a series of linear equations and the corresponding correlative coefficient, r, were obtained based on these regression results and are listed as Equations (4-6) to (4-10).

$K = 2333.4\,x + 15000$ and $r = 0.8450$ for $L = 103$ cm (4-6)

$K = 3950.3\,x + 15000$ and $r = 0.9703$ for $L = 161$ cm (4-7)

$K = 4688.6\,x + 15000$ and $r = 0.9905$ for $L = 206$ cm (4-8)

$K = 4870.5\,x + 15000$ and $r = 0.9844$ for $L = 259$ cm (4-9)

$K = 5130.9\,x + 15000$ and $r = 0.9804$ for $L = 309$ cm (4-10)

In order to unify the form of the equations, a constant of 15000 is used in each one. Thus, the insulator length, *L*, only affects another coefficient which may be defined as K', where K' is a function of *L*.

$$K = K'(L).\,x + 15000$$

The effect of L on the coefficient K' is shown in Figure 4-14. From this figure, a nonlinear equation may be determined as follows:

$$K' = -0.0816 \cdot L^2 + 45.987 \cdot L - 1294.5 \qquad (4\text{-}11)$$

Thus

$$K = (-0.0816 \cdot L^2 + 45.987 \cdot L - 1294.5) \cdot x + 15000 \qquad (4\text{-}12)$$

From Fig. 4-14, it may be seen that the experimental data can be fit by a polynomial curve. In order to simplify the equation, order 2 of *L* was chosen. The results show a good concordance between the experimental data and the curve.

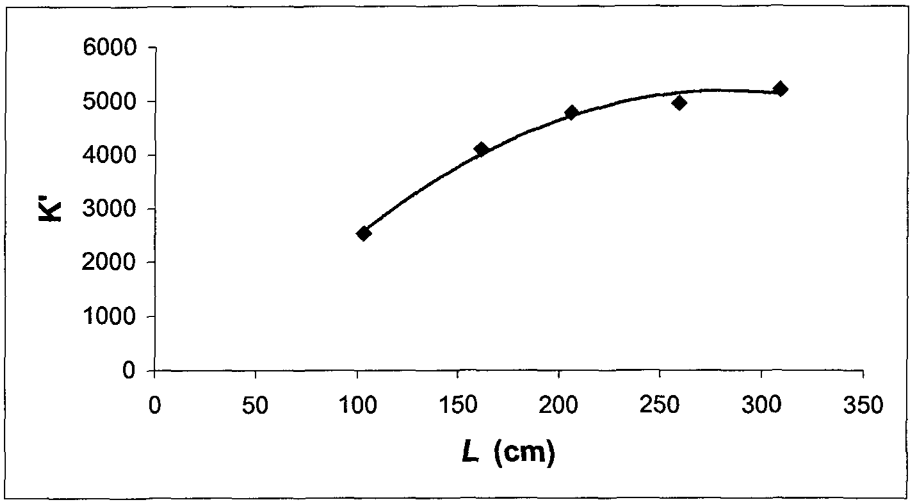


Figure 4-14 Effect of insulator length, *L*, on the coefficient K'

4.7. Determining Coefficient b

Coefficient b(L, x) is the second coefficient introduced in Equation(4-3) to describe the arc maintenance conditions. Its values were also determined in the tests for various combinations of *L* and *x*. The results are listed in Table 4-4.

Table 4-4 Values of coefficient b

L (cm) *x* (cm)	59	103	161	206	259	309	Average value
7	0.0958	0.0232	0.1169				0.0786
12	0.0879	0.0904	0.1112				0.0965
16	0.0673	0.0716	0.0738	0.0826	0.1	0.1277	0.0872
26		0.0632	0.0642	0.0777	0.0875	0.1047	0.0795
36				0.0554	0.0517	0.1045	0.0705
46				0.0577	0.061	0.0676	0.0621
56						0.0364	0.0364

It may be seen that, for a given value of x, b increases generally with an increase in L. However, due to its small value, the effect of the change on the voltage maintaining the arc is not significant. In order to simplify the expression of arc maintenance conditions, this effect may be disregarded and an average value of b may be used for all insulator lengths. These average values for different arc lengths are also listed in Table 4-4.

The effect of arc length x on b, however, is noteworthy. Figure 4-15 shows the variation of the average value of b with the increase in x. As x increases, b decreases almost linearly. The relation between b and x, as well as the corresponding correlative coefficient r, may be obtained as follows:

$$b = 0.1104 - 0.0012 \cdot x \qquad \text{and} \qquad r = 0.9696$$

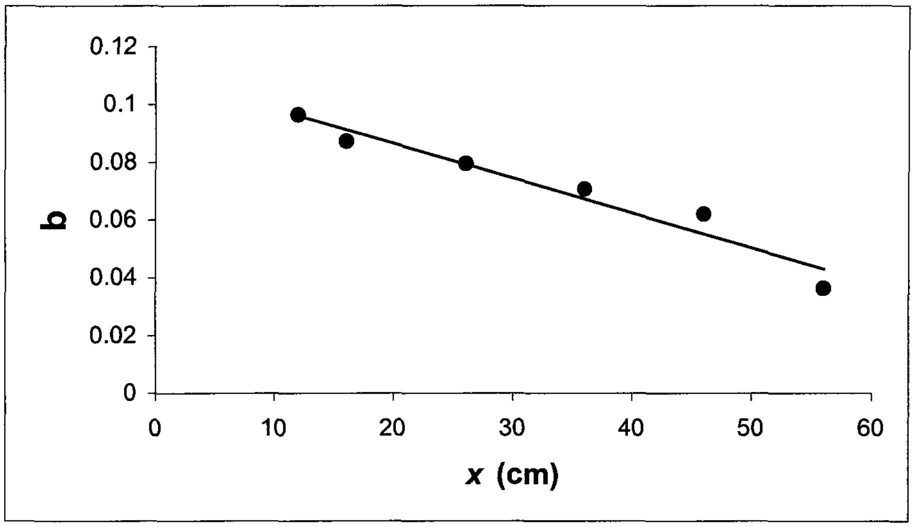


Figure 4-15 Variations of b with respect to air gap length

Having obtained the expressions for coefficients K and b, represented by Equations (4-12) and (4-13), the arc maintenance conditions for an insulator of 25.2 cm in diameter under icing conditions may be expressed as follows.

$$V_a = [(-0.0816L^2 + 45.987L - 1294.5) \cdot x + 15000] \cdot I_a^{-(0.1104 - 0.0012.x)} \qquad (4\text{-}14)$$

4.8. Effects of Insulator Diameter on Arc Maintenance Conditions

Like insulator length, the diameter of the insulator is a further parameter which may influence the shape of the ice layer, and so its consequent resistance [3]. Thus, it is likely to have an influence on arc maintenance conditions. In order to investigate this effect, two different types of insulators of different diameters (see Figure 3-1) were used in this study. A series of tests was carried out on these two types of insulators. Figures 4-16 to 4-18 show the results obtained on the larger insulator (D = 29 cm).

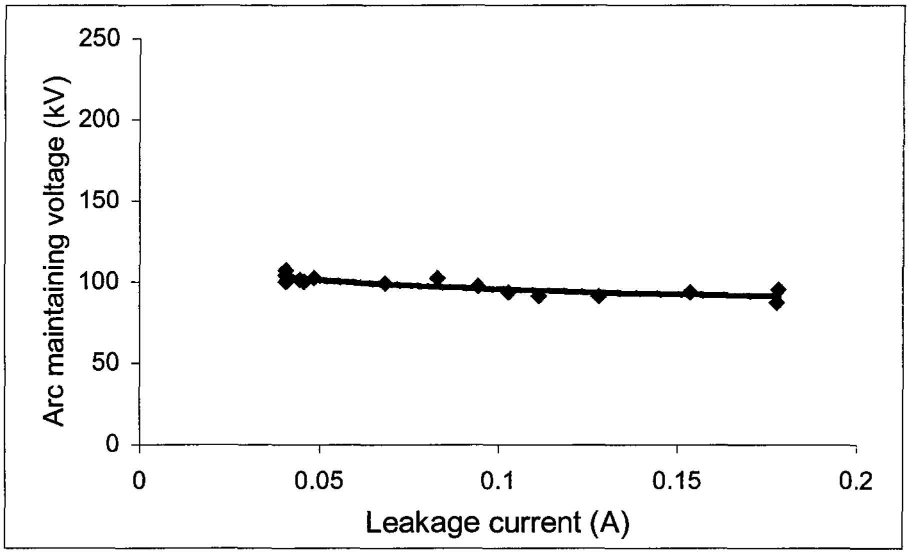


Figure 4-16. Minimum arc maintaining voltage (*L* = 259 cm, *x* = 16 cm, D=29 cm)

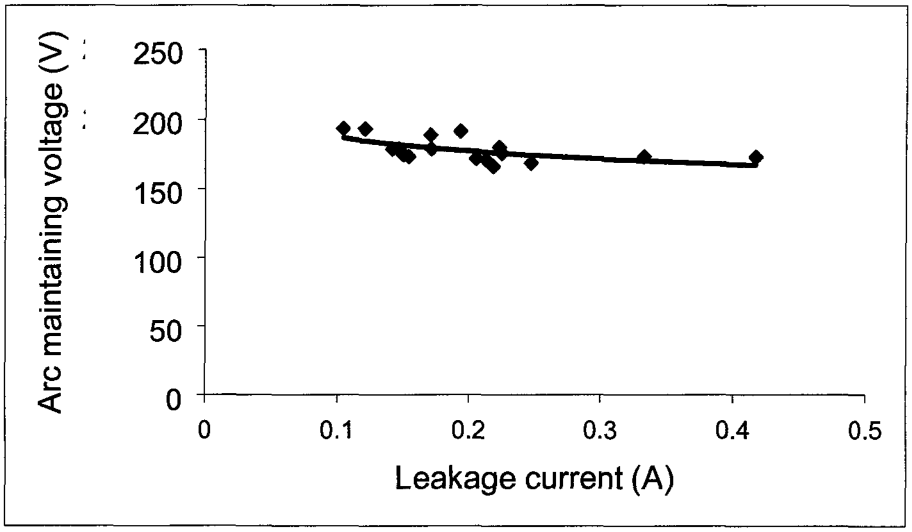


Figure 4-17. Minimum arc maintaining voltage (*L* = 259 cm, *x* = 26 cm, D=29 cm)

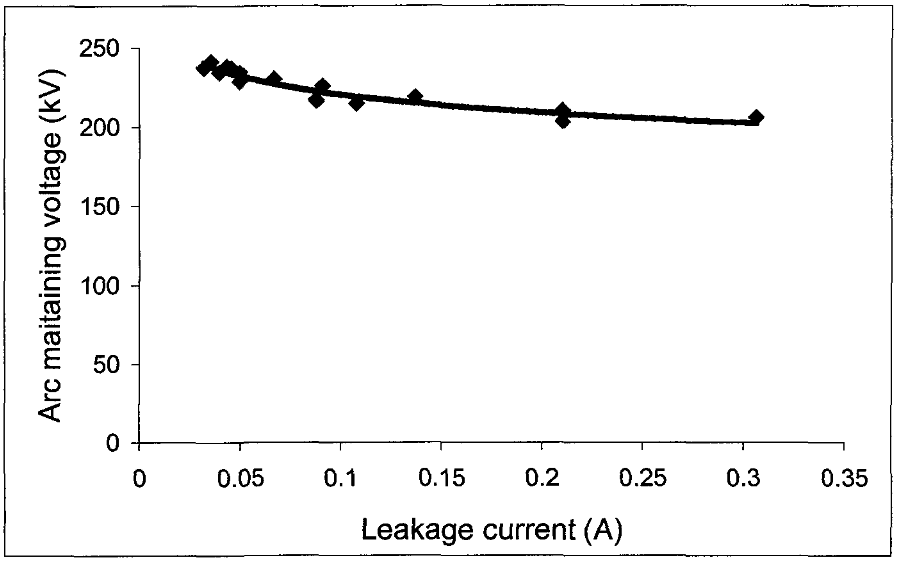


Figure 4-18. Minimum arc maintaining voltage (L = 259 cm, x = 36 cm, D=29 cm)

Similarly, by applying the regression method to the results obtained, the arc maintenance conditions, as well as the values of coefficients K and b, were obtained. Table 4-5 shows a comparison between the values of coefficients K and b for insulators of different diameters.

Table 4-5 Comparison between the values of K and b for insulators of different diameters.

x (cm)	K		Δ	b		Δ
	D = 25.2 cm	D = 29 cm		D = 25.2 cm	D = 29 cm	
16	74814	78483	4.09 %	0.1	0.0841	-15.9 %
26	132462	156176	17.9 %	0.0875	0.0798	-8.8 %
36	199126	184568	-7.31 %	0.0517	0.0761	47.2 %

As in the results obtained from the insulator of a smaller diameter, K increases while b decreases with an increase in air gap length.

The insulator diameter thus has an influence on the values of K and b. As D increases, K increases and b decreases, for arc lengths of less than 26 cm. For arc lengths greater than 36 cm, the variations of K and b are the inverse. In this study, however, only two diameters are used and the difference in diameter between these two insulators is only 13%. Therefore, further experimental investigation is necessary to determine the effects of insulator diameter on the arc maintenance conditions.

4.9. Breakdown Voltage of Air Gaps

During the tests, the voltage distribution was not uniform when the voltage was applied to the ice-covered insulators. Because the air gap displays high resistivity as compared to the ice layer, the greater part of the voltage appears along the air gap. If the voltage is high enough, a breakdown will occur and an arc will be established across the air gap. In this study, the breakdown voltage of an air gap was also investigated under various combinations of the water conductivity, with air gap and insulator lengths. Figs. 4-19 to 4-24 show the breakdown voltage of an air gap, V_b, as a function of air gap length, x.

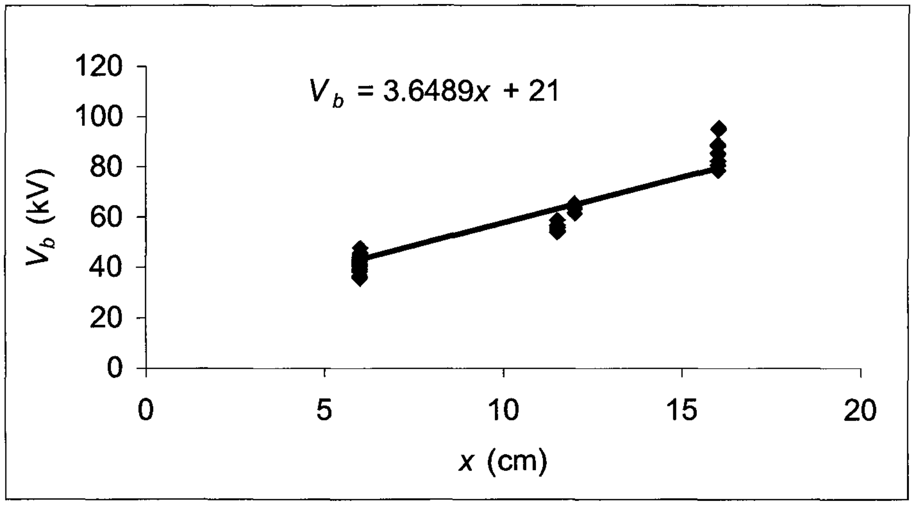


Figure 4-19. Breakdown voltage, V_b, as a function of air gap, x. ($L = 59$ cm)

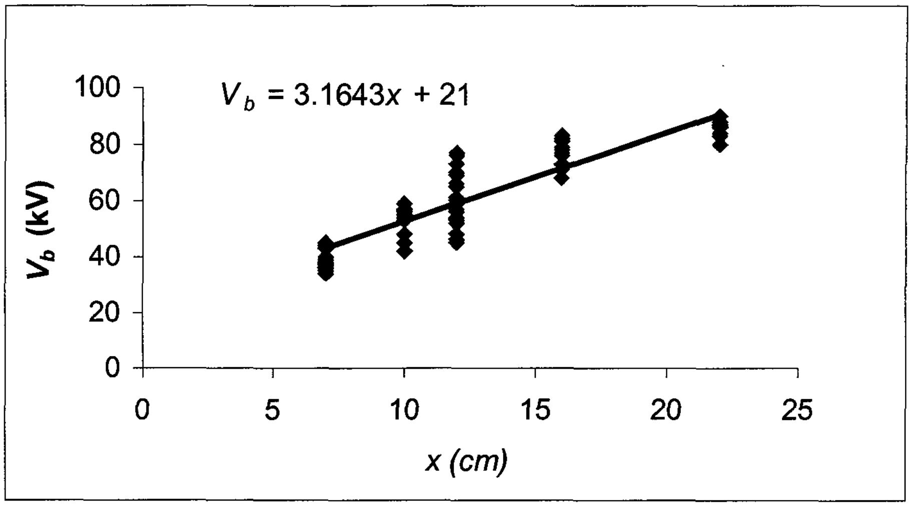


Figure 4-20. Breakdown voltage, V_b, as a function of air gap, x. ($L = 103$ cm)

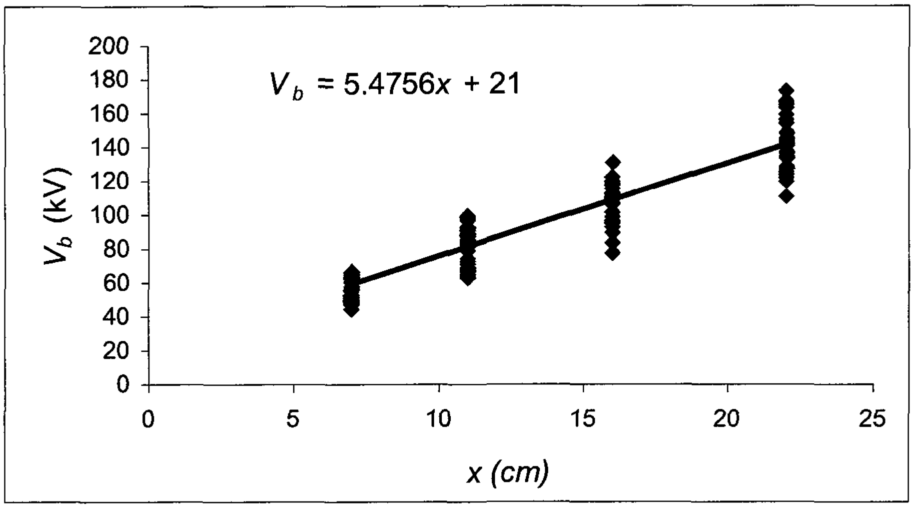


Figure 4-21. Breakdown voltage, V_b, as a function of air gap, x. (L = 161 cm)

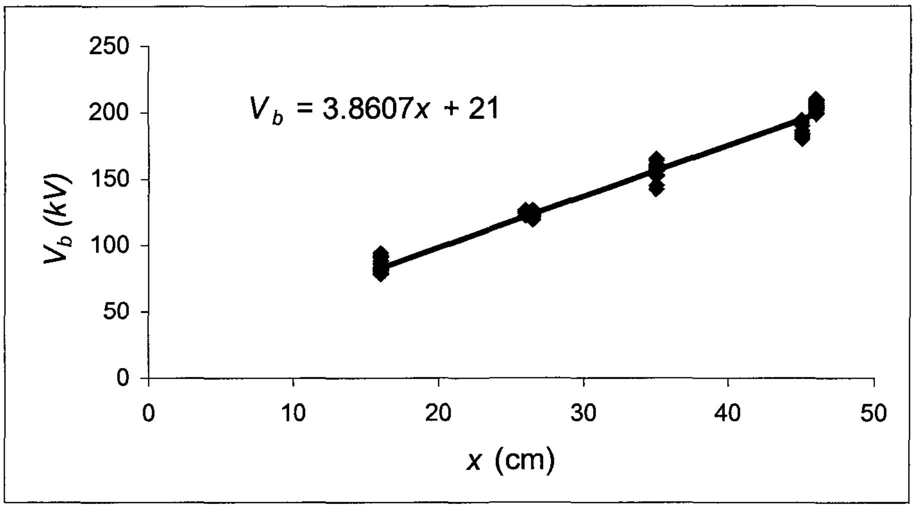


Figure 4-22 Breakdown voltage, V_b, as a function of air gap, x. (L = 206 cm)

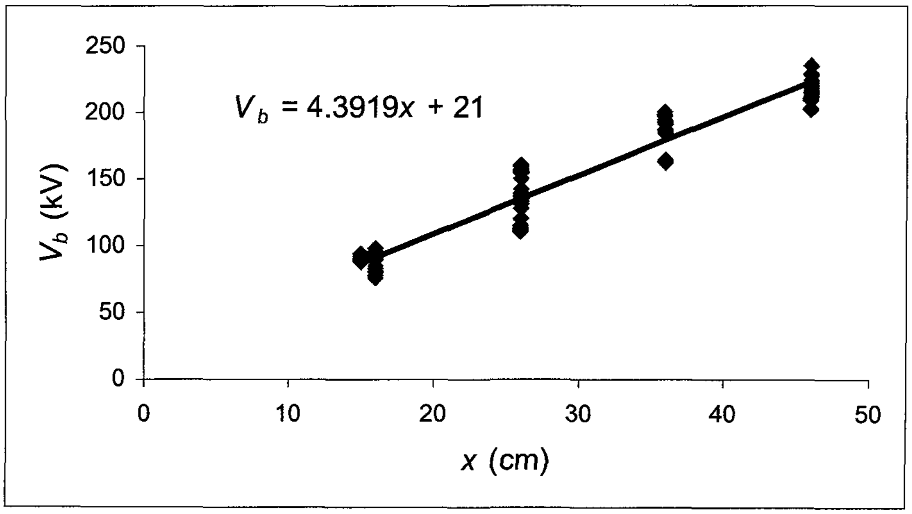


Figure 4-23 Breakdown voltage, V_b, as a function of air gap, x. (L = 259 cm)

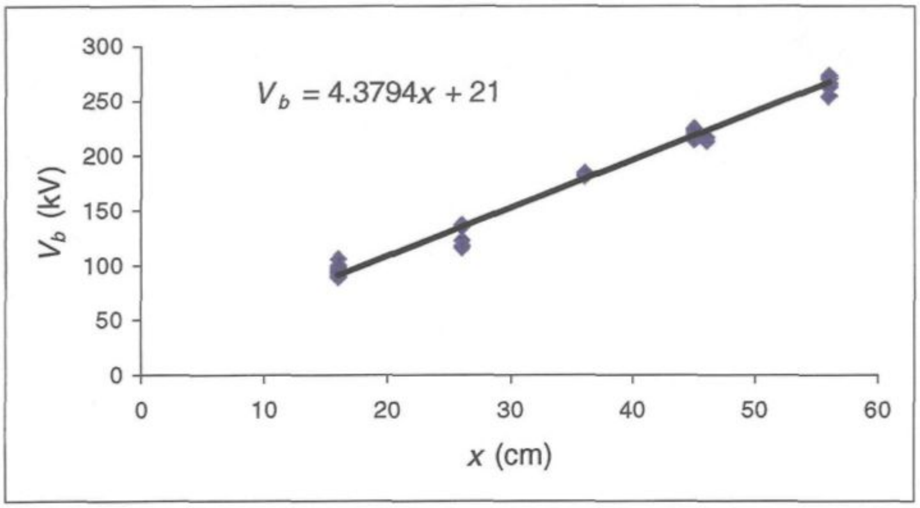


Figure 4-24 Breakdown voltage, V_b, as a function of air gap, x. ($L = 309$ cm)

It may be noted that, the breakdown voltage increases linearly as the air gap increases. The slope of the line is so not affected by insulator length and it lies in the range of 3.1 to 5.5 kV/cm. The deviation observed is caused by the surface conditions of the insulator and the air gap shape, among others.

By plotting all the results in one figure (Figure 4-25), it may be seen that the breakdown voltage, V_b, is not influenced by the insulator length, L. Therefore, the relationship between the breakdown voltage (in kV) and the air gap length (in cm) may be determined as follows for all insulator lengths:

$$V_b = 4.22 \cdot x + 22.9 \qquad \text{(kV)} \tag{4-13}$$

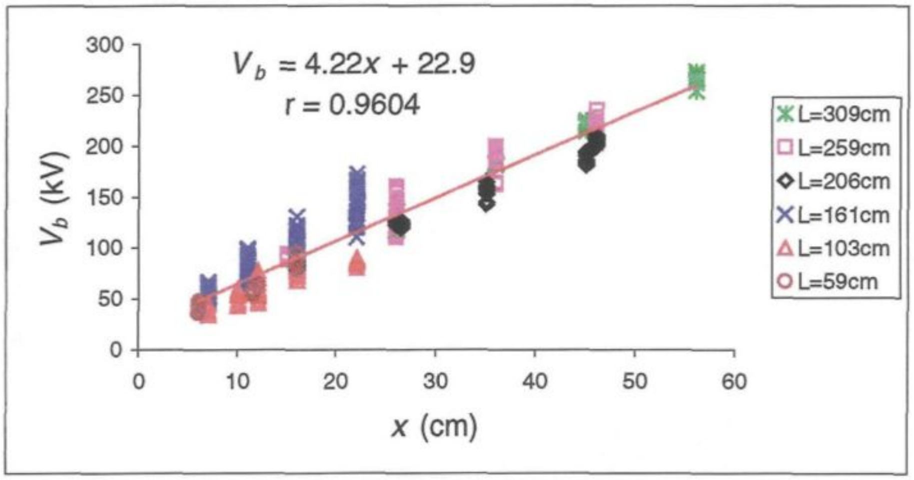


Figure 4-25 Relationship between the breakdown voltage and the air gap length

4.10. Discussion

4.10.1. Observation in Tests and Criteria for Choosing the Test Results

Throughout the tests, the observable phenomena were scrutinized. As soon as the voltage was applied to the insulator, a very weak, but measurable, current was recorded on the measuring instruments. Up to that point, there was no obvious discharge around the insulator. With an increase in voltage, there was a breakdown in the air gap at a certain voltage level. At this juncture, depending on the freezing water conductivity σ, the air gap length, x, and the insulator length, L, two possibilities could manifest themselves: i) if the combination of σ, x and L resulted in a leakage current which exceeded the critical value, a white arc would be established across the air gap; ii) if the leakage current was less than the critical value, a violet arc would be established across the air gap and would change to white as the voltage increased to a certain level. During the tests, it was found that the critical value of the leakage current for a white arc to form was ~15 mA.

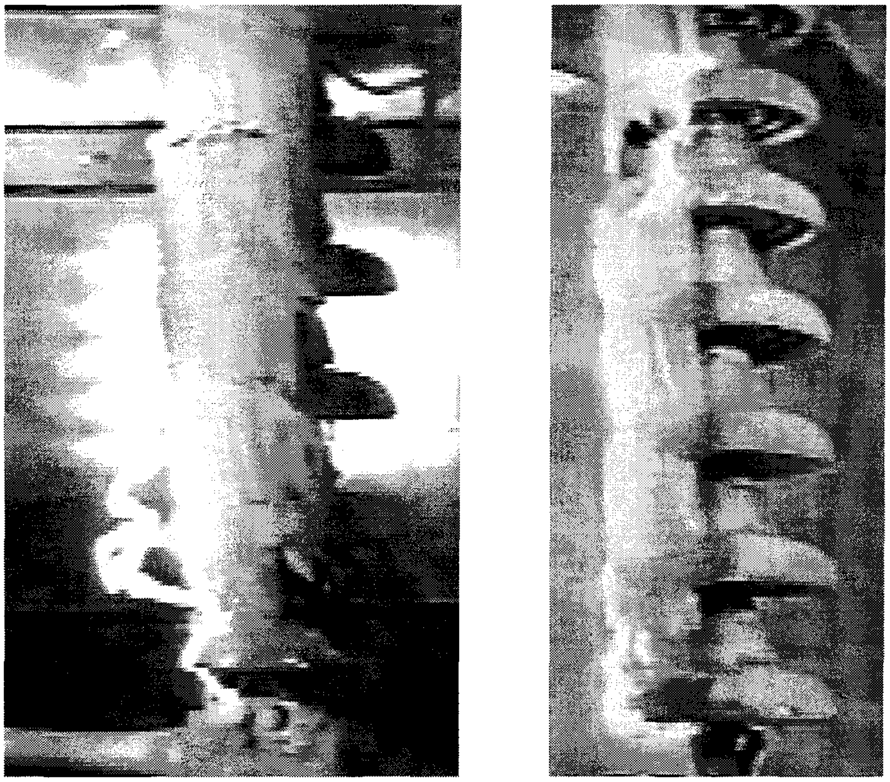
The arc loses its brightness gradually by decreasing the voltage and the leakage current, also, decreased. Depending on the combination of σ, x and L, the arc would extinguish at a certain voltage level. Sometimes, after the arc extinguished, it might be re-ignited and then extinguished again.

It was observed that the voltage needed to maintain an arc across an air gap, increases with the decrease in the leakage current (see test result diagrams in this chapter). It was, also, observed that the current required to produce a violet arc is lower than that of a white arc. Consequently, the voltage required to maintain a violet arc is higher than that of a white arc. In fact, the flashover of ice-covered insulators happens just if, and only if, there is a stable white arc through the entire flashover process. Therefore, in this study, the minimum voltage for maintaining a *stable white arc* was determined.

Also, if arc reignition occurred after the arc extinguished, only the first extinction and the corresponding voltage and current were considered as the results.

4.10.2. Practical Applications of Arc Maintenance Conditions

As mentioned in Chapter 2, the flashover of ice-covered insulators is caused by the formation and propagation of an arc. A mathematical model based on the concept of polluted insulators was proposed earlier by CIGELE laboratory for predicting the flashover voltage of ice-covered insulators. It is valid for insulator strings of up to 1 m in length. For insulators of over 2 meters in length, the calculated results show a linear relationship between the flashover voltage and insulator length (see Figure 2-5). There may be a discrepancy between the calculated and experimental results. This is because the arc reignition condition was obtained using a small ice sample, and was assumed to be independent of insulator length.



(a) (b)

Figure 4-26. Two types of arc propagation on ice-covered insulators

The tests revealed that there are two different types of arc propagation on ice-covered insulators (see Figure 4-26). Figure 4-26(a) shows an arc propagating on an iced surface, which occurred when the applied voltage was high enough to result in immediate flashover. Figure 4-26(b) shows an arc burning along an air gap. In the latter case, the applied voltage was not so high as to cause an immediate flashover, but it was high enough to maintain an arc along the air gap. The arc spread as the ice melted and the air gap widened. When the arc reached its critical length, flashover occurred. It is clear that the voltage required in case (b) is lower than the one required in case (a). Therefore, case (b) is the critical state for flashover on ice-covered insulators.

This study examined the relevant aspects of the minimum voltage for maintaining an arc on an ice-covered insulator, or the "Arc Maintenance Condition". The results obtained showed a nonlinear tendency in the relationship between the arc maintaining voltage and insulator length. It would, therefore, be possible to improve the mathematical model for application to long insulators by introducing the arc maintenance condition into the model.

Further studies, however, are needed in order to investigate the above-mentioned non-linearity in greater detail and for standing CIGELE created model to the EHV (Extra High Voltage) insulators.

Chapter 5

Conclusions and Recommendations

5-1 conclusions

A wet-grown ice layer and an artificial air gap were formed on an insulator, using two types of post insulators. A test method was designed for examining the arc burning along the air gap. The critical conditions required for an arc to extend on an ice-covered insulator, that is, the arc maintenance conditions, were investigated under AC voltage. On the basis of the experimental results and their analysis the following conclusions may be drawn:

1). On the ice-covered insulator, when the applied voltage is not high enough to cause flashover immediately, but high enough to maintain an arc along the air gap, the arc will extend as the ice thaws and the air gap will widen. When the arc reaches its critical length, the flashover will occur. This is the critical situation for flashover on ice-covered insulators. The minimum voltage needed to maintain a white arc burning along the air gap appears to bear a relationship to the parameters of leakage current, arc length, and insulator length. This relationship is defined as the arc maintenance condition.

2). The minimum arc maintaining voltage, V_a, is a function of leakage current, I_a. It decreases with the increase in the leakage current. The relationship between V_a and I_a can be expressed as a power equation:

$$V_a = K \cdot I_a^{-b}$$

where K and b are functions of the air gap length and insulator length.

3). For a given length of arc, the arc maintaining voltage increases with an increase in insulator length. For a given insulator length, the arc maintaining voltage increases with the increase in arc length. That is, the insulator length, L, and the arc length, x, influence the value of the coefficient K. As L increases, K increases at first and then decreases revealing a maximum value. K, however, increases almost linearly with an increase in x.

4). For a given value of x, the effect of L on b is not significant and can be disregarded. An average value of b can be used for all insulator lengths. The effect of arc length x on b, however, is striking. As x increases, b decreases almost linearly.

5). The arc maintenance conditions for an insulator, 25.2 cm in diameter, under icing conditions can be expressed as follows.

$$V_a = [(-0.0816L^2 + 45.987L - 1294.5)\cdot x + 15000]\cdot I_a^{-(0.1104 - 0.0012x)}$$

6). The insulator diameter, D, has an influence on the values of K and b. As D increases, K increases and b decreases, for arc lengths of less than 26 cm. For arcs longer than 36 cm, the variation of K and b is the inverse. Further investigation is necessary to determine the effects of insulator diameter on arc maintenance conditions.

7). The insulator length does not have a significant effect on the breakdown voltage of the air gap, V_b. It increases linearly with the increase in the air gap length, x. The relationship between V_b (in kV) and x (in cm) can be expressed as follows for all insulator lengths:

$$V_b = 4.22\cdot x + 22.9$$

8). A nonlinear tendency was found for the relationship between the arc maintaining voltage and the insulator length. It is possible to improve the mathematical model for application to long insulators by introducing the arc maintenance conditions into the model. For this purpose, further studies are recommended.

5-2 Recommendations

In this Master's thesis study, the critical conditions of an arc propagating on an ice-covered insulator were investigated. The arc maintenance conditions and the corresponding mathematical expression were proposed. The results are useful for understanding and modeling the flashover phenomena on an ice surface. However, due to the limitation of time, the model for predicting the critical flashover voltage of ice-covered insulators is not complete. In order to achieve this objective, further studies are needed.

1). The mathematical expression for the arc maintenance conditions has been established in this study. However, it cannot be introduced into the existing model by simply replacing the arc reignition conditions. Therefore, further studies are needed to complete the mathematical model for predicting the critical flashover voltage of EHV insulators covered with ice, based on the "Arc Maintenance Conditions".

2). The effect of insulator diameter on the arc maintenance condition has been investigated in the present study. The results showed that the insulator diameter has an effect on the arc maintenance conditions. However, the test data were not sufficient for summarizing a general conclusion for this effect. Therefore, studies are needed to determine the effects of the insulator profile, including insulator type, shape, dimension, and configuration, on the arc maintenance conditions.

3). The concepts of "white arc" and "violet arc" were used in the present study to describe qualitatively the aspects of local arcs on ice-covered insulators. More studies may be needed for investigating in detail their characteristics and function in the flashover of ice-covered insulators.

4). The critical length of local arc is an important parameter in the modeling of flashover. In the modeling of flashover on ice-covered insulators, it was calculated, not measured. In order to validate the mathematical model and to better understand the flashover mechanism, an experimental study on this parameter is not only interesting, but also necessary.

Chapter 6

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Appendix

Original Test Results

Insulator Length = 59 Cm					
Gap Length = 7 Cm		Gap Length = 12 Cm		Gap Length = 16 Cm	
Maintenance Voltage (volt)	Current (Ampere)	Maintenance Voltage (volt)	Current (Ampere)	Maintenance Voltage (volt)	Current (Ampere)
29000	0.03944	50400	0.08761	56950	0.03463
28000	0.03183	54000	0.08761	60060	0.02964
35000	0.03408	51600	0.10901	59530	0.03961
37500	0.02394	51600	0.10901	57950	0.03463
36500	0.05944	51200	0.18394	63000	0.0162495
34500	0.06761	50000	0.08901	64000	0.017526
28500	0.03915	54000	0.18169	62000	0.022149
38000	0.02803	55600	0.15831	59000	0.022149
32000	0.06451	64640	0.0097	60500	0.020838
26000	0.11579	66400	0.01468	59600	0.019803
26500	0.11053	62400	0.01468	59000	0.016353
31500	0.08947	63200	0.01468		
36000	0.01025	62400	0.01967		
39500	0.01025	64000	0.01967		
33500	0.01967	63600	0.01967		
32500	0.02465	57600	0.01967		
31000	0.02465	53360	0.048015		
32500	0.01967	54160	0.043076		
33500	0.01967	57520	0.050556		
34500	0.02521	51462.4	0.049533		
36500	0.02465	52096	0.05841		
38500	0.02465	53433.6	0.037466		
33000	0.02465	52465.6	0.047146		
32000	0.02521	51576.8	0.054043		
29000	0.09061				
29000	0.0856				
30000	0.1234				
30000	0.1362				
30000	0.115				
30000	0.1623				
27500	0.1894				
26500	0.1462				
30000	0.1531				
28500	0.1346				

Insulator Length = 103 Cm							
Gap Length = 22 Cm		Gap Length = 16 Cm		Gap Length = 12 Cm		Gap Length = 7 Cm	
Maintenance Voltage(volt)	Current (Ampere)	Maintenance Voltage volt)	Current (Ampere)	Maintenance Voltage volt)	Current (Ampere)	Maintenance Voltage volt)	Current (Ampere)
71500	0.15113	71500	0.06842	69500	0.13296	32000	0.01486
74000	0.48845	68500	0.13878	60500	0.11859	33500	0.01424
71500	0.49521	67500	0.18033	67000	0.13296	33000	0.01524
79000	0.11859	64000	0.14349	70000	0.1569	32000	0.01524
78500	0.07549	67500	0.18615	61000	0.11859	33000	0.019
75000	0.10648	69000	0.17036	73000	0.14282	31000	0.0637
83500	0.08197	70000	0.06451	67500	0.12254	31500	0.01524
73500	0.263	71500	0.06225	72500	0.10901	32000	0.01524
75000	0.22	69000	0.115	56000	0.21408	34500	0.02022
74000	0.212	69000	0.095	59500	0.16789	34500	0.02022
76500	0.193	68500	0.119	56000	0.25127	32500	0.02853
77800	0.213	68000	0.153	60500	0.20113	34000	0.01967
73000	0.251	63000	0.19	61000	0.28845	30500	0.02909
70000	0.329	63000	0.195	69000	0.063	33500	0.02465
68000	0.31	66000	0.21	70500	0.0521	32000	0.0374
		67000	0.133	70000	0.046	32000	0.03352
		65500	0.122	71000	0.043	31000	0.03296
				68000	0.065	33000	0.0374
				67500	0.083	34000	0.03296
				66500	0.076	32500	0.04626
				66500	0.046		
				69000	0.069		

Insulator Length = 161 Cm							
Gap Length = 7 Cm		Gap Length = 12 Cm		Gap Length = 16 Cm		Gap Length = 22 Cm	
Maintenance Voltage (volt)	Current (Ampere)	Maintenance Voltage (volt)	Current (Ampere)	Maintenance Voltage (volt)	Current (Ampere)	Maintenance Voltage (volt)	Current (Ampere)
52000	0.03269	78030	0.06366	79000	0.24488	0.13241	146090
53500	0.03269	78030	0.0569	78000	0.2072	146090	0.13241
57000	0.04044	65650	0.03934	93000	0.24709	115180	0.4964
54000	0.03934	76540	0.06039	90000	0.25817	134290	0.1723
53000	0.03934	70640	0.06039	93500	0.27147	134130	0.32022
57500	0.04709	70800	0.07368	90700	0.23158	112690	0.241
62000	0.04598	77290	0.09363	95000	0.03906	129140	0.28476
55500	0.05374	64930	0.04404	98000	0.03352	130750	0.35679
56000	0.05373	67060	0.05512	98000	0.05014	129860	0.31357
46500	0.0723	65430	0.0662	106000	0.05568	138730	0.28476
46500	0.0723	63380	0.06676	104000	0.04958	120110	0.34404
47500	0.06676	59200	0.05512	105000	0.06122	169030	0.04044
48500	0.06122	67590	0.0723	106000	0.06066	142110	0.52244
47500	0.0723	72910	0.06759	105000	0.08366	128090	0.35623
47000	0.06066	72470	0.08366	93000	0.04404	146090	0.41385
48500	0.0723	72550	0.10111	100000	0.04404	138730	0.48366
48500	0.07729	62710	0.06759	100000	0.05568	143160	0.50693
46500	0.06676	67150	0.09529	102000	0.05568	125430	0.13873
55500	0.02188	65820	0.13019	105000	0.0723	128980	0.45152
59500	0.02188	76840	0.02188	100500	0.18726	127200	0.61163
61000	0.01634	75620	0.02244	90000	0.12742	111250	1.14017
62000	0.01634	79530	0.02798			120110	0.13158
66000	0.0169	75070	0.02188			154070	0.14127
66500	0.0169	77040	0.02742			135120	0.2072
68000	0.0169	76180	0.03352			129140	0.14127
66500	0.0169	72300	0.03352			132520	0.19834
69000	0.02244	81160	0.03352			133410	0.17839
54500	0.145	76180	0.03906			129860	0.19834
54000	0.135	76730	0.03906			126810	0.21163
57500	0.133	76540	0.03352				
48500	0.119	72550	0.0385				
49500	0.164	66460	0.15692				
50000	0.136	67300	0.17603				
50500	0.172	62810	0.19035				
		63480	0.1286				
		63650	0.12823				
		60520	0.18203				
		58750	0.1952				
		56220	0.18632				
		55880	0.21023				
		57490	0.20236				

Insulator Length = 206 Cm							
Gap Length = 16 Cm		Gap Length = 26 Cm		Gap Length = 36 Cm		Gap Length = 46 Cm	
Maintenance Voltage(volt)	Current (Ampere)	Maintenance Voltage(volt)	Current (Ampere)	Maintenance Voltage(volt)	Current (Ampere)	Maintenance Voltage(volt)	Current (Ampere)
113000	0.06732	161500	0.29901	210000	0.04718	231500	0.69211
111500	0.07817	159500	0.25352	200500	0.03944	253000	0.08662
113000	0.07324	155000	0.39296	207000	0.05183	244500	0.12592
107000	0.08831	169000	0.36761	208500	0.07817	244500	0.15028
114000	0.11028	142500	0.34789	203000	0.07352	241000	0.27648
117000	0.12408	166500	0.37324	203000	0.07352	245000	0.28099
118500	0.12042	176500	0.1524	206500	0.09423	243500	0.23817
115500	0.12042	184500	0.1676	196000	0.09507	241000	0.80366
115500	0.14056	173500	0.1722	199500	0.13141	237000	0.86986
115500	0.13507	169000	0.1892	207000	0.12676	241000	0.69634
113000	0.03593	163500	0.1532	172000	0.58817	238000	0.51211
124000	0.03593	163500	0.1912	182000	0.53831	237000	0.46817
134000	0.03926	158000	0.1662	189000	0.40732	274500	0.04621
132500	0.04576	162000	0.1524	189000	0.40479	285500	0.04913
132500	0.04012			189000	0.24437	285500	0.03546
131000	0.03064					284000	0.06053
127000	0.02989					273000	0.0561
128000	0.02944					274500	0.04098
127000	0.02721					272000	0.0597
134000	0.02135					266500	0.0532

Insulator Length = 259 Cm							
Gap Length = 16 Cm		Gap Length = 26 Cm		Gap Length = 36 Cm		Gap Length = 46 Cm	
Maintenance Voltage(volt)	Current (Ampere)	Maintenance Voltage(volt)	Current (Ampere)	Maintenance Voltage (volt)	Current (Ampere)	Maintenance Voltage (volt)	Current (Ampere)
98500	0.05183	163500	0.02718	206000	0.54085	293000	0.0241
104500	0.04451	169000	0.02465	203000	0.54085	290500	0.02798
103000	0.06254	176000	0.02718	203500	0.2138	284500	0.02798
104500	0.05224	170500	0.02718	231000	0.08662	280500	0.02798
98500	0.05718	173500	0.02859	226000	0.12324	283500	0.02798
105500	0.04986	180500	0.02972	231500	0.15324	282000	0.03186
98500	0.06254	180500	0.02972	227000	0.21718	276000	0.02798
98500	0.04986	182000	0.03072	224000	0.2718	283500	0.02798
101500	0.05451	180500	0.02859	231000	0.15352	286000	0.03186
97000	0.04986	180500	0.02859	218000	0.18662	287500	0.03186
107000	0.05541	177500	0.03225	216000	0.16324	286000	0.03407
107000	0.09648	144000	0.12254	212500	0.18324	290500	0.04737
110000	0.02225	146500	0.12254	208000	0.20718	254000	0.114594
111500	0.01831	145000	0.10056	204000	0.3218	246500	0.1230075
108500	0.01831	146500	0.13183	208000	0.29352	252500	0.1565976
111500	0.02113	151000	0.15352	223000	0.03961	248000	0.2220099
111500	0.01831	146500	0.10676	250000	0.03186	244000	0.3360075
108500	0.01831	144000	0.10394	227500	0.04183	236000	0.3881925
113000	0.01831	151000	0.15662	230000	0.04737	227000	0.2669955
114000	0.01831	159500	0.12845	238000	0.04571	244500	0.248997
110000	0.01831	170500	0.19014	230500	0.04571	244000	0.69211
111500	0.01831	190500	0.02225	245000	0.04349	304500	0.0538
111500	0.01831	183500	0.01437	235000	0.04571	296000	0.05775
110000	0.01831	194500	0.02225	230000	0.05125	303000	0.07352
85000	0.08169	199000	0.01831	231500	0.04737	297500	0.10423
96000	0.14085	199000	0.01831	225000	0.04737	293000	0.15775
94000	0.11972	197500	0.01613	229000	0.04958	283500	0.18225
94000	0.12535	200000	0.01718			272000	0.12535
91000	0.13239	200000	0.01831			293000	0.1169
87500	0.11972	196000	0.01831				
83500	0.11972	199000	0.01831				
89000	0.14507	197500	0.01437				
		203000	0.01831				
		154500	0.38845				
		142500	0.45437				
		150000	0.48225				
		150000	0.49718				
		153500	0.40761				
		156000	0.26085				
		153500	0.24648				

Insultaor Length = 309 Cm									
Gap Length = 16 Cm		Gap Length = 26 Cm		Gap Length = 36 Cm		Gap Length = 46 Cm		Gap Length = 56 Cm	
Maintenance Voltage(volt)	Current (Ampere)	Maintenance Voltage(volt)	Current (Ampere)	Maintenance Voltage(volt)	Current (Ampere)	Maintenance Voltage(volt)	Current (Ampere)	Maintenance Voltage(volt)	Current (Ampere)
124000	0.06579	153500	0.17673	235000	0.32742	276500	0.67867	358000	0.05
115500	0.04474	152000	0.25346	236500	0.36482	262000	0.81524	366500	0.06316
121000	0.08075	145000	0.27396	225500	0.44958	290500	0.02479	365000	0.07895
122500	0.08629	148000	0.28061	232000	0.38809	290500	0.02368	356500	0.10485
115500	0.08075	153500	0.24061	233000	0.38809	300500	0.02978	363500	0.09654
117000	0.0633	156500	0.25679	263000	0.09821	299000	0.02729	349500	0.10291
121000	0.08352	155000	0.24349	263000	0.09523	296000	0.02729	347000	0.09377
121000	0.0633	160500	0.25679	275000	0.08613	297500	0.0223	344000	0.10291
118500	0.0946	183500	0.07215	275500	0.08245	293000	0.02729	335500	0.10291
122500	0.11122	182000	0.07631	273500	0.08615	296000	0.0223	342500	0.13061
125500	0.09737	186000	0.06226	271500	0.08023	303000	0.02729	379000	0.01925
127000	0.10983	176500	0.07513	278000	0.08291	301500	0.02729	383500	0.01924
110000	0.08352	167500	0.08295	261500	0.1016	297500	0.01981	373500	0.02256
108500	0.091	166500	0.0725	262000	0.13523	293000	0.0223	366500	0.01524
120000	0.09183	162000	0.08316	263500	0.1642	211500	0.51357	371000	0.01432
121000	0.08546	163500	0.06953	256500	0.13323	201500	0.70055	378000	0.0181
121000	0.0946			258000	0.17398			365000	0.01722
121000	0.08906			246500	0.17356			371000	0.02148
122500	0.08629			248000	0.19045				
117000	0.08906			244000	0.15423				
121000	0.11316			249500	0.18656				
122500	0.11039								
149500	0.01976								
151000	0.02056								
145000	0.0265								
145000	0.02432								
139500	0.0351								
141000	0.029								
139500	0.02165								
138000	0.03212								
139500	0.02425								