REVIEW OF MODELS WHICH PREDICT THE FLASHOVER VOLTAGE OF POLLUTED INSULATORS

BY

Prem K. Patni

A Thesis

Submitted to the Faculty of Graduate Studies

in Partial Fulfillment of the Requirements

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Department of Electrical and Computer Engineering

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ABSTRACT

Pollution of insulator surface could lead to a flashover of insulators. The flashover of insulators caused by pollution generally dominates at voltages above 500 KV. Mechanism of pollution flashover is very complex as it depends on numerous factors.

Over the years the researchers have presented various models for better understanding of flashover phenomenon and prediction of flashover voltages. Due to complexity of problem researchers made various assumptions to simplify the problem.

The objective of this dissertation is to review and compare various models and to evaluate their capabilities in predicting the flashover voltages of insulators. Several models have been reviewed and out of these models, those which contain sufficient information for predicting the flashover voltages have been selected. The selected models have been applied to different types of insulators and the flashover voltages are calculated. In order to compare the models the conditions e.g. resistivity, under which the model are applied to insulators are kept the same. Five types of configurations of insulator models are considered, i)10 x 1 cm flat plate, ii)10 x 10 cm flat plate, iii) cylinder, 100 cm long and 15 cm diameter, iv) IEEE insulator and v) Anti-Fog insulator. The calculated flashover voltages and other results are compared with each other and with experimental results.

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Chapter 1

General

1.1 Introduction

Outdoor power transmission line insulation is subjected to mainly three types of over voltages i.e. 1) lightning, 2)switching surges, and 3) abnormal voltage gradients caused by contamination on insulator surface. These over voltages may lead to flashover and subsequent outage of transmission lines. With higher transmission voltages the flashover due to contaminated surfaces become more predominant. The factors which affect the flashover of polluted insulators are numerous and therefore the flashover phenomenon is complex.

The flashover process develops in the following stages:

a) Surface contamination: Insulators operating in polluted atmosphere collect pollutants which are deposited on insulator surfaces. Deposition of pollutants on insulator surface depends on many factors e.g. shape of insulator, nature of voltage i.e. ac or dc, location, angle of inclination of insulator, wind, rain etc. The performance of the insulator itself is not altered significantly by the presence of dry contaminant because the electrical strength of a dry polluted insulator is close to that of a clean insulator.

b) Wetting process: When the polluted surface becomes moist due to fog or rain then the polluted layer becomes conductive. The process of moistening depends on wetting conditions e.g. moisture absorption depending on the nature of contaminant, temperature of surroundings, condensation, mounting, etc.

c) Dry band formation: Due to the presence of the conducting layer the electric field is greatly distorted along the polluted surface. The electric stress may exceed that of air and the spark over occurs, causing discharges to occur along small portions of the insulator surface. The discharges are maintained by current which flows through the wet but discharge free surface. Due to higher resistance at some locations the heat dissipated in that location may be greater and therefore moisture dries more rapidly at these locations leading to the formation of dry bands.

d) Break down of dry bands: Almost the entire applied voltage appears across the dry band and when the dry band can not sustain the applied voltage an arc is initiated and bridges the dry band.

e) Propagation of arc: Depending on the conditions e.g. applied voltage, leakage current, etc. the arc may travel further and bridge the insulator surface resulting in flashover or it may extinguish prior to flashover.

DC flashover voltages are lower than the AC under the same operating conditions. Under DC voltage there is no current zero. Moreover more pollutants are attracted to an insulator under DC voltage than AC. Also, due to absence of current zero in DC the propagation of arc is easier than in AC. The flashover voltages of both AC and DC depend on many factors and even when experiments are conducted under the same controlled conditions, the flashover voltage may not be the same. Thus, the two flashover voltages for the same exact conditions are not the same. This applies to both AC and DC.

Flashover of transmission line insulation due to pollution insulators were reported as early as in 1902. Since then an appreciable number of experimental and theoretical studies have been conducted to understand the complex process of insulator flashover. The flashover process mainly involves the propagation of an arc on a polluted surface. For an arc to propagate two conditions must be satisfied. These conditions are: 1) electrical condition, initiation and maintaining the arc (i.e. applied voltage and current) and 2) mechanism involving force which is responsible for movement of the arc generated from condition "1". Despite considerable research work, the process involved in flashover are still not fully understood. Studies were aimed to find the necessary conditions for initiation of an arc and then elongation of the arc. The process of flashover depends on factors such as type and nature of pollutant, non uniform wetting process, conductivity of wet layer, orientation, shape and profile of insulator, wind, location, etc. Therefore the researchers faced a formidable task to find a suitable solution which will take into account the effects of all the factors.

Based on experimental and theoretical studies many models were presented to explain the process of flashover. Since it is impossible to account all the factors involved, therefore the researchers had to make some assumptions in developing these models. It is therefore not surprising to see different theories explaining the flashover mechanism. It is desirable to compare some important models to predict the flashover voltages.

Chapter 2

Review of models

2.1 Brief History

Since the early days of transmission, pollution caused flashover has plagued over head lines. Flashover due to early morning fog were reported in 1902. System research into the pollution problem started in 1907 after the flashover of 25 kV lines in the Italian coastal area. This study considered the effects of electrostatic forces and self cleaning properties of insulators. A number of numerical studies in the 1930's contributed towards an understanding of practical problems, leading to improved insulator design.

In 1958 Obenaus proposed the first quantitative theory of flashover, known as the extinction theory [44] . During these early years many original, even bizarre ideas were suggested such as, wind driven brushes to sweep away the deposits [6]. After World War II, the adoption of higher transmission line voltages led to renewed interest in this problem. Since then a number of models based on experiments and theoretical studies have been proposed.

In this chapter several models, since the early model of Obenaus (1958) have been reviewed. Some of the reviewed models are not considered for comparison due to the reasons such as; 1) no formula for calculation is available, 2) only experimental model without any empirical formula, 3) not enough data available for calculating the flashover voltage, although some formula is given.

In order to understand the mechanism of pollution flashover it is necessary to explain the formation of dry bands on polluted surface. Almost all the models consider the formation of dry band in the process of flashover.

2.2 Formation of Dry Bands

The voltage gradient needed to initiate spark over in air is about 30 KV/cm. The average surface voltage gradient of an out door h. v. insulator is about 500 V/cm. Therefore in order to initiate an arc on a polluted insulator surface, the voltage distribution must be highly non uniform. Formation of dry band on a polluted flat plate surface takes place in the following steps [13].

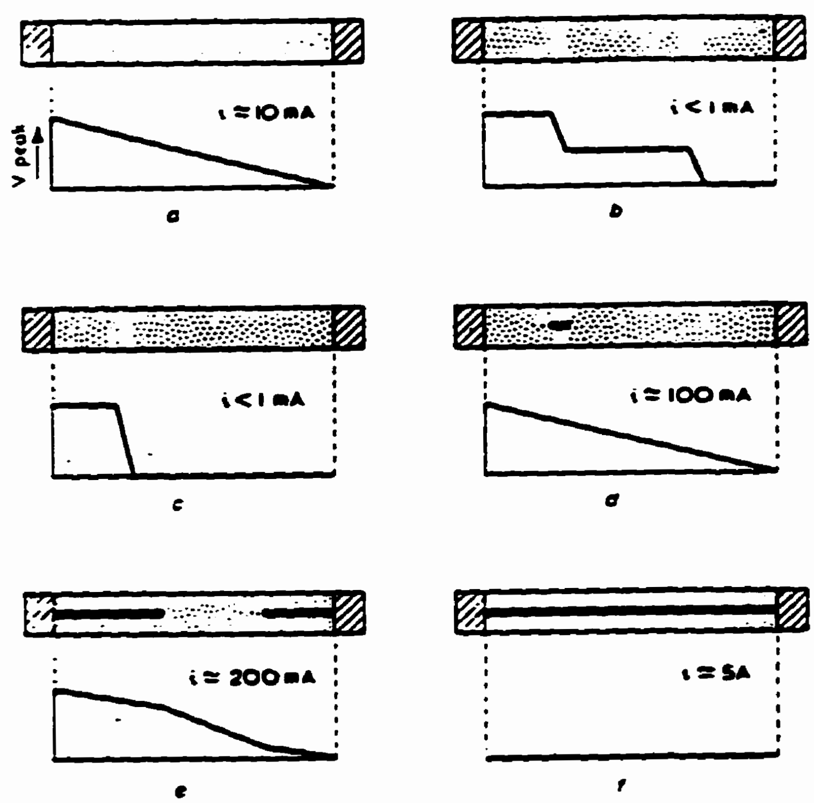

Fig. 2.1 Typical voltage distribution and formation of dry band

Initially the plate is dry and then subjected to wetting. In Fig. 2.1-a the voltage distribution is linear as the resistivity of layer is uniform. As the layer becomes wet its resistivity decreases and the surface leakage current increases. This condition does not last long due to slightly higher resistance values in some locations the voltage gradient in these locations may exceed that of air resulting in arc discharges along the small portions of insulator surface. Owing to heat generated at discharge root the area in the near vicinity of discharge dries out. The heat dissipation is more in these locations and therefore the area dries more rapidly than remaining surface, forming dry bands Fig. 2.1-b. If several dry bands are formed then after a short time only one dry band remains and due to its high resistance nearly all the source voltage is dropped across this dry band Fig. 2.1-c. The width of the dry band changes until the voltage across it is just less than that required to initiate a discharge in air across it. Any moisture falling on the dry band distorts the electrical field in the band and discharge occurs, a surge of current is generated which dissipates the heat energy in discharge thereby drying band. The frequency of these surges, each of which may last for several cycles, is such that the mean power dissipated in the dry band is just enough keep it dry. After the formation of dry band a sudden increase in the applied voltage may lead to flashover of surface, while a gradual increase may cause dry band to widen. When this happens the arc extinguishes at current zero and restrikes in the next half cycle. Fig. 2.1-d, e, f indicate the conditions several cycles after restrike. In Fig. 2.1-d the voltage distribution is linear. During subsequent cycles the leakage current increases and the arc lengthens and a greater portion of applied voltage appears across the rest of the polluted surface. A further dry band forms and flashes over immediately,

Fig.2.1-e and finally, the separate discharges combine to span the entire polluted surface, Fig. 2.1-f.

2.3 Pollution flashover models

From literature review the following models were considered. These models are divided into two main categories.

2.3.1 Category I

The models under this category have sufficient details which permit their applications to the insulators.

These models are further categorized on the basis of their applications.

2.3.1.1 Flat plate models

2.3.1.1.A. Model of F. Obenaus [44]

Obenaus was the first to propose a quantitative analysis of the arcs on a polluted surface. In this model an arc of length "x" is considered in series with the wet polluted layer having a resistance "Rp". Based on this simple model and the knowledge of arc voltage, the formulae for calculating the minimum voltage required to sustain an arc has been derived.

2.3.1.1.B. Model of G. Neumarker [19]

The model of Obenaus was applied by Neumarker with one difference. Instead of considering a fixed resistance of pollution layer in series with arc, Neumarker considered a uniform resistance per unit length of wet polluted layer. In this model the formula relating the minimum voltage required to maintain an arc and x/L are derived, where L is length of polluted surface. Also an equation for the critical arc length is derived.

2.3.1.1.C. Model of R. Wilkins [15]

Pollution can lead to formation of quasi stable gas discharges which burn in series with polluted resistive layer. A model for discharge burning in a rectangular strip is presented. Formula for calculating the resistance of the polluted layer and the factor which takes into account the change in resistance due to heat are derived. Criteria for flashover i.e. $di/dx > 0$ is presented and applied to compare the experimental results. The model can be applied to axi-symmetric insulators with complex shapes by replacing the practical insulator by its equivalent cylinder. The model is applicable to dc voltages and could be valid under ac energization by considering ac as series of applications of fixed voltages equal to that of peak alternating voltage.

2.3.1.1.D. Model of P. Claverie [16]

This model deals with the phenomenon of flashover mechanism. Discharge development is studied using a flat plate of glazed porcelain and the movement of arc is studied by using a high speed camera. The circuit resistance of pollution in series with the arc is considered with arc re-ignition conditions. Formulae for arc voltage is derived, together with voltage required for re-ignition. Conditions e.g. maximum arc length and resistance of pollution layer at maximum arc length is derived. Formulae for critical arc length and flashover voltage are derived and applied to practical insulators and results compared with experimental data. It is concluded that when geometric characteristics of pollution deposit do not vary and when the electrolyte conductivity is the only parameter then it is possible to evaluate safety margins of an insulator energized at a given voltage by measurement of leakage current.

2.3.1.1.E. Model of P. S. Ghosh & N. Chatterjee [18]

A mathematical model to predict the flashover voltage of polluted insulator under ac is presented. This model takes into consideration the appropriate arc constants for different chemical nature of pollutants. The critical values of flashover voltage and current are derived based on Renyu's model [11]. This model is compared with other model and experiments.

2.3.1.2 Cylindrical models

2.3.1.2.A. Model of L. L. Alston & S. Zoledziowski [9]

The mechanism of extinction has been considered in this model. The voltage required to maintain the discharge on polluted insulators may increase with an increase in discharge length, and if this voltage exceeds the supply voltage, the discharge extinguishes without causing a flashover. Based on this mechanism, criteria which define flashover conditions have been developed. A simple geometry of insulator with constant surface resistance per unit length is considered. Flashover criteria in terms of formulae relating to applied voltage, critical stress, discharge length and resistance have been developed. Flashover is considered impossible if the applied voltage and the initial arc length are less than the critical values defined in this model.

The authors have also included experimental results to validate their model.

2.3.1.2.B. Model of H. Boehme & F. Obenaus [10]

The authors have derived formulae to calculate the creepage-path flashover voltages or simply the flashover voltage of polluted insulators. Cylindrical insulators with and without the sheds with uniform pollution are considered. The phenomenon of flashover is described using a single arc in series with polluted layer of insulator. One individual arc is considered to represent a number of partial arcs and similarly a single layer of resistance represents many partial layers. Flashover is initiated by elongation of the partial arc. For elongation of the root the electric field is considered to be of main importance. If the electric field in the resistive layer is greater than the electric field in arc, then the arc will elongate. Formulae have been developed to calculate and predict the flashover voltages. The movement of arc is explained. Based on calculations the utilization factor for creepage path is shown. The calculated values using this model are compared with experimental values and data from other authors. The speed of arc travel which depends on the difference between field strength along the polluted layer and arc is measured.

2.3.1.2.C. Model of B. F. Hampton [13]

This paper deals with the flashover mechanism. In this model a flat insulating strip (polluted and wet) is considered for experiment and the voltage distribution along the plate as measured is shown. A good explanation of the formation of dry bands is given in this paper. Experiments done on water column of constant resistivity indicate that the if an arc propagates along the water surface, the arc will burn in an atmosphere of steam. The necessary condition for flashover along the water column is that the voltage gradient in the water column should exceed that of in the arc.

2.3.1.2.D. Model of H. H. Woodson & A. J. Mcelroy [17]

This paper deals with the mechanism of discharge. This model is not exactly based on cylindrical insulator but is based on a circular insulators. A mathematical model is considered using a simple geometry of a flat plate with concentric circular electrodes. When one or more discharges occur across a dry zone, the width increases by vaporization of water until either the dry zone becomes too wide for the discharge to continue or it attains a critical length beyond which the discharges rapidly cross the remaining portion of polluted surface and flashover occurs. A critical value of surface resistance is suggested below which flashover may occur and above which flashover may not occur. The model is applied to practical insulators (pin-cap).

2.3.1.3 Model of G. Zhicheng & Zhang Renyu [11]

In this model the surface area of pin-cap insulator is expressed as a two dimensional plane model having the same area as that of pin - cap insulator.

The phenomenon and arc propagation of ac and dc arcs have been recorded for wet polluted surface of cylindrical rods by means of a high speed camera. From the experimental results it is observed that for dc, the arc elongated along the surface and as soon as it reached a critical length of about 2/3 leakage length, flashover occurred. Ac arcs are more complex because two phenomenon were observed ; in one case the arc extinguishes and then reignites when current passes through zero and in the second case, the arc does not extinguish but is weakened and shortened when passing through zero. Based on these experimental results an empirical formula for ac and dc arcs are developed. Also the critical resistance is derived to calculate flashover voltage.

2.3.1.4 Model of R. Sundararajan & R. S. Gorur [29]

This model considers the actual geometry (shape) of an insulator. A dynamic model i.e. the one which takes into account the configuration of insulator profile at every instant (actual geometry) for dc is presented. As flashover is a very rapid process therefore dynamic models which take into consideration the instantaneous changes in arc parameters are more realistic. The model is based on Neumarker's model [19] which is an extension of Obenaus model [44]. The criteria for propagation of arc i.e. $Ep > Ea$ are checked at each instant and when arc length is almost equal to leakage length then the flashover is said to have occurred.

2.3.2 Category II

The models under this category do not have sufficient information to calculate the flashover voltage but contain some significant information.

2.3.2.A. Model of P. Claverie & Y. Porcheron [12]

Based on an experimental study the authors have suggested a theoretical approach to explain the flashover mechanism. According to this theory the resistance in series with arc depends on the position of arc root on the surface of the insulator. Thus R(x) is resistance at length x. It is shown that this function R(x) can be split into two factors ρ and F(x), where ρ is resistivity and F(x) is termed as distribution function. They develop a formula for calculating the critical flashover voltage and current based on this theory. An empirical formula for reignition condition of arc is presented.

However, based on information available in this paper it is not possible to do any significant calculations. Further, the value of functions F(x) and R(x) must be determined from experiments by measurement of leakage current. Therefore this model will not be considered for comparison analysis with other models.

2.3.2.B. Model of A. M. Rahal & C. Huraux [5]

The flashover phenomenon is studied in this model. It is indicated that two conditions are responsible for flashover: 1) during the entire propagation of arc the source voltage should be large enough to maintain the arc, 2) a physical mechanism is present which pulls the discharge and leads to flashover. A laboratory model consisting of h.v. electrodes and electrolyte is used. This model in terms of electrical circuit is the same as of that of Obenaus i.e. an arc in series with the pollution layer of constant resistance. Values of critical flashover voltage, critical arc length are derived. The existence of a force on the arc is investigated. The authors conclude that it is mainly electrostatic force that is responsible for movement of arc.

The electrical conditions i.e. critical voltage etc. are not new and have been derived by others. Although the authors showed through experiments that the electrostatic force was the main force responsible for flashover as the discharge can be fed by power source. Still there is not enough evidence (experimental) or application to the insulators to explain their theory of electrostatic forces on arc. There is no calculation of flashover voltage based on this theory. Therefore this model is not considered for comparison analysis with other models.

2.3.2.C. Model of D. A. Swift [1]

This model mainly deals with the circumstances leading to propagation of the arc. If the arc is arrested before it reaches the opposite electrode then the flashover can be avoided. Experiments are conducted to study the behavior of arc movement, in particular of arc arrest when a narrow metal strip is placed within or near the metal surface of an electrolyte contained in a flat insulating trough. Arc propagation and arrest are photographed and corresponding waveforms recorded. A theoretical model was developed to describe the arc arrest.

Although the paper describes some interesting phenomenon and includes a theoretical model to describe the arc arrest by deriving the formula for conditions which will stop the movement of the arc by placing a narrow strip across the flashover path. As no evidence on practical applications and no calculations for flashover are given, therefore this model will not be considered for comparison analysis with other models.

2.3.2.D. Model of T. C. Cheng, C. Y. Wu & N. Nour [3]

Experiments are conducted on a water channel model (simulated as insulator surface) to study the effects of chemical nature of contaminants and contamination levels on flashover voltages. A mathematical model which takes into account the presence of multiple arcs has been introduced to study the breakdown of the electrolyte surface. In contrast to a single arc, therefore the power source has to sustain multiple arcs with corresponding electrode drops, resulting in overall higher voltage than a single arc at critical condition. A model to develop electrode fall drop voltage is also introduced. The model is compared with one experimental result.

This model (paper) does not indicate any calculation to calculate the critical voltage. It seems impossible to calculate the critical voltage from the given data / information. Depending on the number of arcs the arc current will differ. The number of arcs is not shown in calculations and in the figures. It would have been helpful if the authors would have given the curves for critical voltages versus critical current. Therefore this model is not considered for comparison analysis with other models.

2.3.2.E. Model of T. C. Cheng & H. I. M. Nour [25]

The paper deals with discharge region consisting of multiple arcs and the wet pollution region in series with it. The wet region is characterized by conductance of pollution layer and form factor (depends on insulator profile). A mathematical formula has been developed to calculate the minimum voltage required to sustain the "m" number of arcs. Maximization of minimum voltage leads to flashover voltage. A parameter, effectiveness of leakage length is introduced and an empirical formula for it is developed. The critical voltage is proportional to effective portion and to total creepage path.

There is no comparison of this model with experiments and others. The paper is not very clear as to how to decide the value of "m" and how many arcs are to be considered. This model is therefore not considered for comparison analysis with other models.

2.3.2.F Model of F. A. Chagas [40]

This model is developed to study the effect of voltage source on critical flashover voltage of dc insulators under pollution. The experimental results of flashover voltages for insulators are presented and these are compared with model of Sundararajan [20].

The flashover voltage equations derived in the model are for calculating the effect of source on experimental procedures. Therefore this model is not considered in detail for comparison analysis with other models, although the experimental results from this model are used for comparison.

Chapter 3

Analysis of selected models

3.1 Procedures

The selected models are described in this chapter. Each model is applied to the four types of insulators i.e. a) 10 x 1 cm flat plate, Fig. 3.1, b) 10 x 10 cm flat plate, Fig. 3.2, c) cylinder, 100 cm long and 15 cm dia., Fig. 3.3, and d) IEEE insulator, Fig. 3.4.

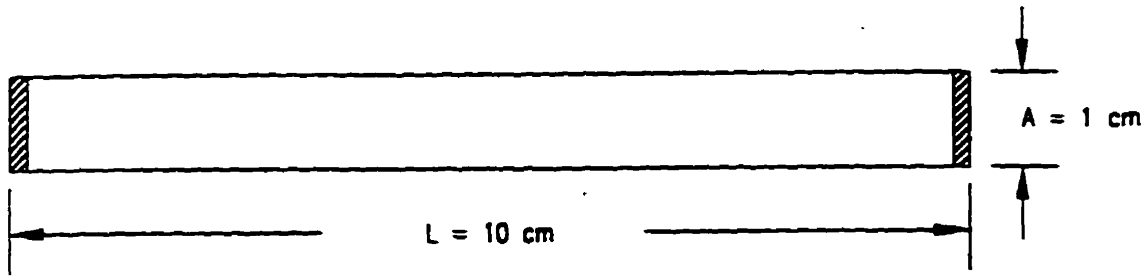

Fig. 3.1 Flat plate insulator, 10 x 1 cm.

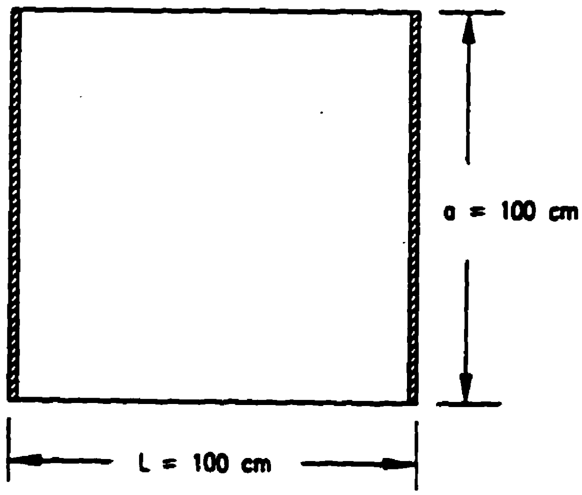

Fig. 3.2 Flat plate insulator, 10 x 10 cm.

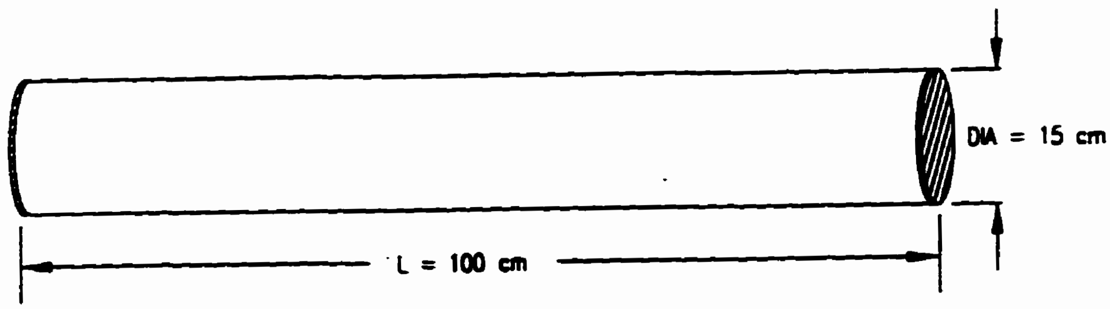

Fig. 3.3 Cylinder, 100 cm long and 15 cm dia.

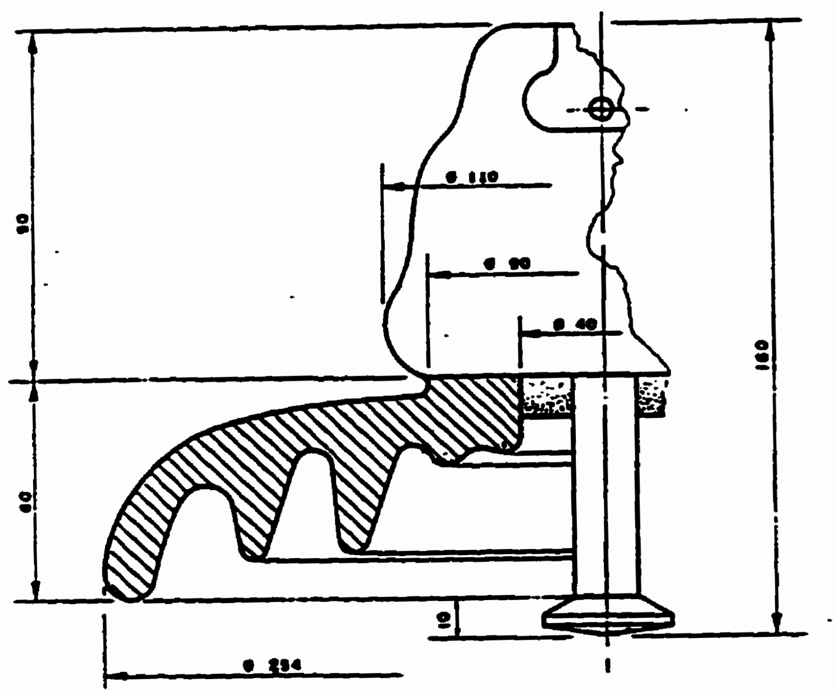

Fig. 3.4 IEEE insulator [40].

Models are derived from different types of insulator configurations and therefore when applying these models to the above four types of insulators following approach is considered.

When applying the models derived from flat plate to the cylindrical insulator, the equivalent surface of cylinder is considered. This means that the area of a flat plate is equal to the surface area of cylinder. Therefore, equivalent flat plate of cylinder will have L = 100 cm and a = 47.12 cm.

When applying the models derived from flat plate to the IEEE insulator, the equivalent surface area of insulator is considered. This means that the total surface area of insulator is equal to the area of a flat plate. For IEEE insulator L = 30.5 cm and total area is 1559 cm^2. Therefore equivalent flat plate will have L = 30.5 cm and a = 51.11 cm.

When models derived from cylinder are applied to the flat plate insulator, then the area of flat plate is considered equal to the surface area of cylinder. Thus for 10 x 1cm plate the equivalent cylinder will have L = 10 cm and D = 0.32 cm, and for 10 x 10 cm the equivalent cylinder will have L = 10 cm and D = 3.2 cm.

When models derived from cylinder are applied to IEEE insulator, then the surface area of the insulator is considered equal to that of cylinder. Thus equivalent cylinder for IEEE insulator will have L = 30.5 cm and D =16.28 cm.

When applying dc models to ac some researchers i.e. Ghosh, Machhiaroli [18] considered a factor of 1.3 between ac peak and dc. Wilkins [15] suggested a constant peak equal to dc as a first approximation, others gave a factor ranging from 1.3 to 1.6. For practical purposes and in this comparison study a factor of 1.4 is considered between ac peak and dc. Therefore, the dc values are considered equal to ac rms.

3.2 Flat plate models

3.2.1. Model of Obenaus[44]

This is the first model in which a quantitative treatment of pollution phenomenon has been considered. An arc burning in series with a polluted layer is considered as shown in Fig. 3.5a.

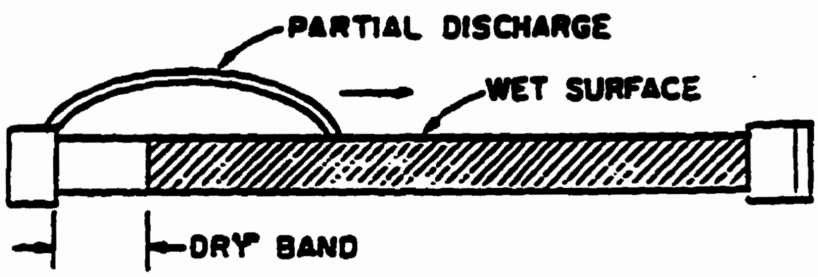

Fig.3.5a Obenaus's model for pollution flashover.

The equivalent electrical circuit of the above model is shown in Fig. 3.5b

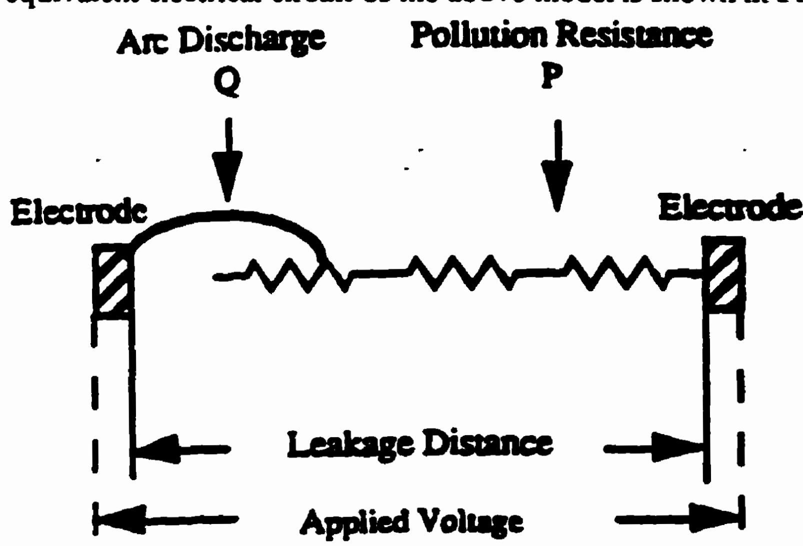

Fig.3.5b Equivalent circuit for Obenaus model

The following main assumptions are made in this model:

A fixed resistance is considered for wet layer.

Electric field is uniform.

Flashover will occur when the arc is able to bridge the insulator i.e. when arc length is equal to insulator length and it travels without extinguishing at critical voltage.

The applied voltage can be related to the arc voltage and resistance of the wet polluted layer by the following eq.:

$$V = V_{arc} + R_p i \quad (1)$$

The arc voltage is given as,

$$V_{arc} = x.N.i^{-n} \quad (2)$$

Therefore from eqs. 1 and 2 we get,

$$V = x.N.i^{-n} + R_p.i \quad (3)$$

Where,

V_{arc} = arc voltage

V = applied voltage

x = arc length

i = leakage current

R_p = pollution resistance

n = exponent of static arc charecterstic

N = static arc constant

From above the value of leakage length x is given as,

$$x = \frac{i^n}{N}.(V - i.R_p) \tag{4}$$

The maximum arc length can be found by differentiating x with respect to i and equating it to zero, thus,

$$\frac{n.i^{n-1}}{N}.V - \frac{(n+1).i^{-n}}{N}.R_p = 0$$

$$\therefore i = \frac{V.n}{(n+1).R_p} \tag{5}$$

This "i" is the critical value of current and is denoted as i_c.

Thus,

$$i_c = \frac{V.n}{(n+1).R_p} \tag{5a}$$

and the critical value of arc length x_c is obtained by substituting the value of i_c in equation (4), thus

$$x_c = \frac{1}{N}.\frac{n^n}{(n+1)^{n+1}}.\frac{V^{n+1}}{R_p{}^n} \tag{6}$$

Obenaus did not solve this eq. any further. By substituting the value of x_c in eq. (6) the critical value of voltage $V = V_{cx}$ for critical arc length of x is given as,

$$V_{cx} = [x\, N\, (n+1)\, R_p{}^n / n^n]^{1/(n+1)}$$

$$V_{cx} = \frac{n+1}{n^{n/(n+1)}} N^{1/(n+1)} x^{1/(n+1)} R_p{}^{n/(n+1)} \tag{7}$$

This model only identifies the necessary condition for flashover but not the sufficient condition. This means that it identifies the voltage, below which no flashover can occur due to discharge extinction, but not the higher value at which the flashover will occur.

This model assumes that flashover occurs if the discharge is able to bridge the insulator without extinguishing. This model was developed for dc voltage.

3.2.1.1 Application of model

3.2.1.1.a Flat plate10 x 1 cm

This model is applied to a flat polluted insulator plate, 10 cm long and 1 cm wide as shown in Fig. 3.1.

Pollution resistance of wet plate is 50,000 ohm.

A voltage of 10,000 volt is applied. Let us assume an arc length of 1 cm.

The values of $N = 63$ and $n = 0.5$ have been used in this model.

From eq. (5a) critical current is calculated as,

$$i_c = \frac{0.5 * 10000}{(1+0.5).5000} = 0.0666 \text{ amp.}$$

and critical arc length from equation (6) is,

$$x_c = \frac{1 * 0.5^{0.5} * 10000^{1.5}}{63 * 1.5^{1.5} * 50000^{0.5}} = 27.32$$

To maintain an arc length of 27.32 a voltage of 10000 V is required

From equation (7)

$$V_{cx} = \frac{.5+1}{.5^{.5/1.5}} 63^{1/1.5} 27.32^{1/1.5} 50000^{.5/1.5} = 10000 \text{ V}$$

According to this model the arc should be able to bridge the insulator for flashover to take place. This means x = 10 cm. Minimum voltage required to maintain this arc is calculated using eq. (7) and is,

$$V_{cx} = \frac{.5+1}{.5^{.5/1.5}} 63^{1/1.5} 10^{1/1.5} 50000^{.5/1.5} = 5117 \text{ V}$$

Therefore the critical current at this voltage using eq. (5a) is:

$i_c = .5 * 5117 / (1.5 * 50{,}000) = 34.11$ mA

From the above it means that the flashover can not take place below 5117 volts and that at this voltage the current is 34.11 mA. The flashover is assumed to occur when arc length is equal to insulator leakage length, and the flashover voltage is 5117 V.

The minimum voltage required to maintain an arc of x = 1 cm can be calculated using eq. (7) and is :

$$V_{cx} = \frac{.5+1}{.5^{.5/1.5}} 63^{1/1.5} 1^{1/1.5} 50000^{.5/1.5} = 1102 \text{ V}$$

The critical voltage is calculated for different values of resistance for the same geometry and is shown in Fig.3.6.

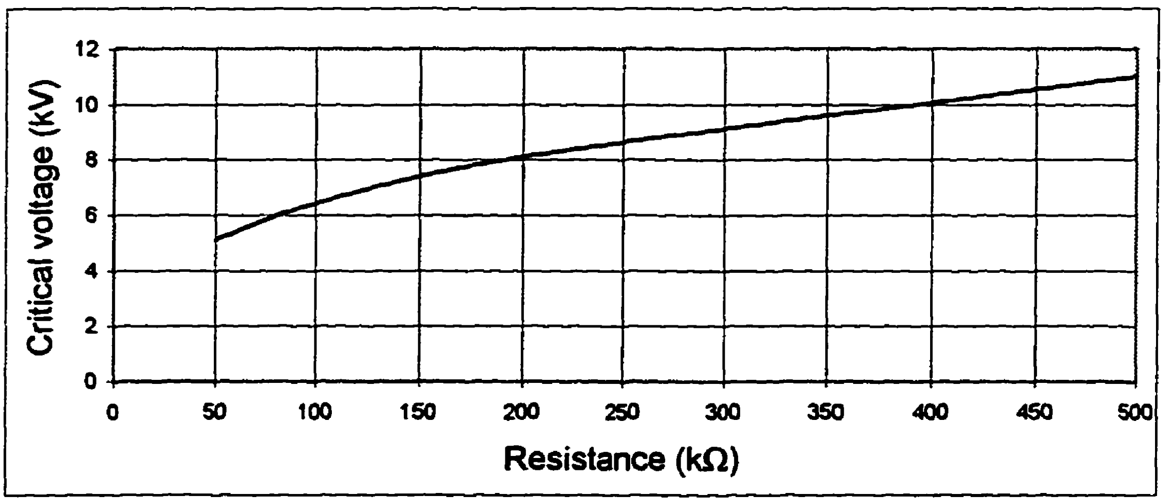

Fig. 3.6 Relationship between critical voltage and pollution resistance for 10 x 1 cm plate in Obenaus model.

3.2.1.1.b Flat Plate 10 x 10 cm

This model is applied to flat plate configuration of 10 x 10 cm shown in Fig. 3.2

According to this model flashover may take place when the arc bridges the insulator. From eq. (7) the minimum voltage required to maintain this arc length of x = 10 cm, is calculated for different values of pollution resistance, R_p. The critical current for each of these voltages is calculated using eq. (5a).

Fig.3.7 shows the comparison of critical voltage obtained using this model with the experimental results [15].

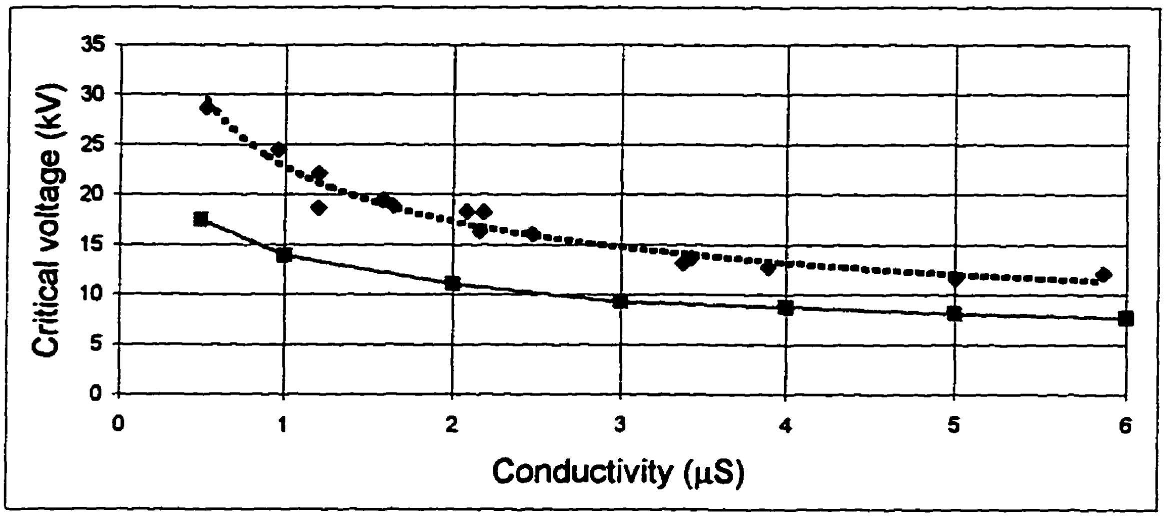

Fig. 3.7 Relationship between critical voltage and conductivity for 10 x 10 cm plate.
i) Obenaus model _______
ii) Experimental _ _ _ _ _

3.2.1.1.c Cylindrical insulator, 100 cm long and 15 cm diameter

This model is applied to a cylindrical insulator of L = 100 cm and diameter of 15 cm shown in Fig. 3.3.

From eqs. (7) and (5a) the critical voltage and current can be calculated for different values of pollution resistance.

Fig. 3.8 shows the comparison of the critical voltage obtained using this model with the experimental results[9].

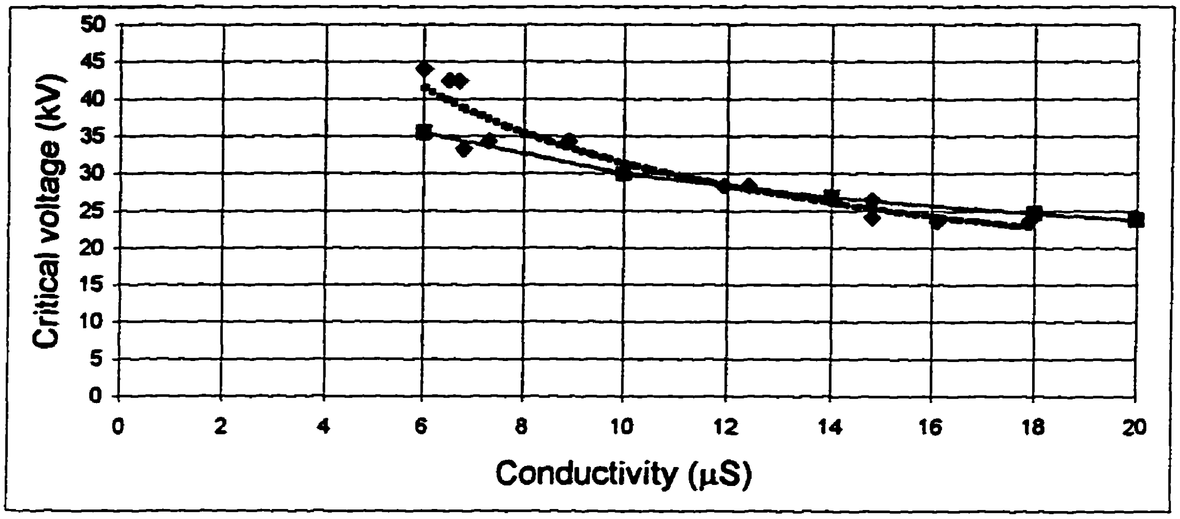

Fig. 3.8 Relationship between critical voltage and conductivity for cylinder 100 cm long, and 15 cm dia.
i) Obenaus model ______
ii) Experimental _ _ _ _ _

3.2.1.1.d IEEE insulator

This model is applied to the IEEE insulator shown in Fig.3.4

The critical voltage and current can be calculated from eqs. (7) and (5a) for different values of pollution resistance.

Fig. 3.9 shows the comparison of the critical voltage obtained using this model with the experimental results[40].

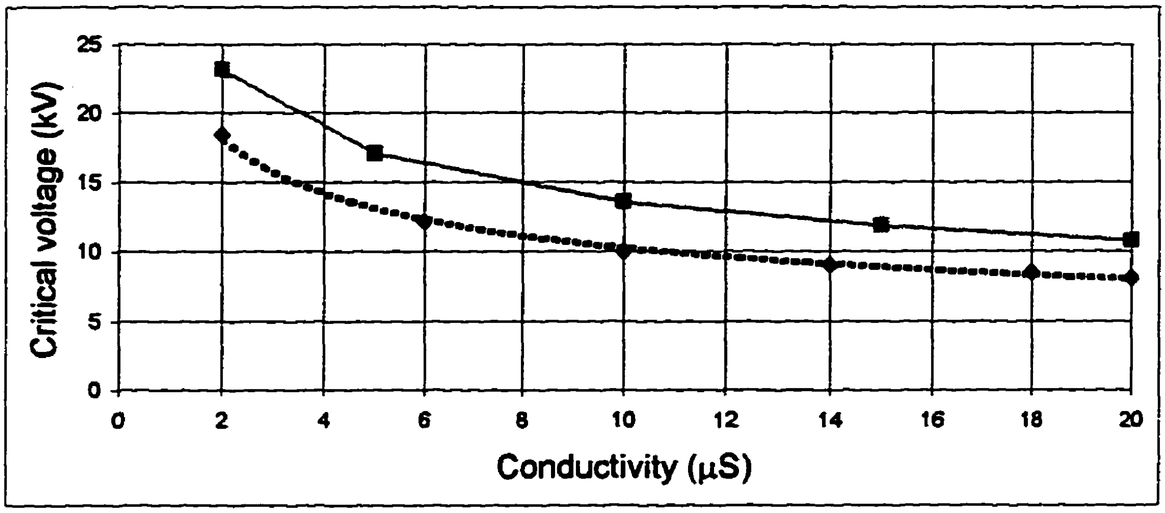

Fig. 3.9 Relationship between critical voltage and conductivity for IEEE insulator.
i) Obenaus model _______
ii) Experimental _ _ _ _ _

3.2.2 Model of Neumarker [19]

The model of Obenaus is applied with a slight modification. Instead of a resistance R_p representing the pollution layer connected in series with the arc (as in Obenaus model), a uniform pollution resistance per unit length is assumed for the wet portion.

Uniform pollution resistance per unit length is assumed.

Therefore, $R_p = r_p (L - x)$ (8)

Where r_p is the pollution resistance per unit length.

The applied voltage V is given as,

$$V = x N i^{-n} + i\, r_p (L - x) \quad (9)$$

The relationship between arc length x / L bridging a portion of leakage length L, and minimum voltage required to maintain the arc, i.e. V_{cx} is given by the following equation:

$$n\,N / r_p \{ V_{cx}/((1+n)\,NL)\}^{(n+1)/n} = (x / L)^{1/n} - (x / L)^{(n+1)/n} \quad (10)$$

The maximum value of V_{cx} can be obtained by differentiating it by with respect to x. This maximum value is the critical value of voltage denoted by V_c. The following eq. is obtained:

$$n\,N / r_p \{ V_c /((1+n)\,NL)\}^{(n+1)/n} = n / (n+1)^{(n+1)/n} \quad (11)$$

and the critical arc distance, $x_c / L = 1/(n+1)$ (12)

$$L / V_c = 1/\{N^{1/(n+1)}\, r_p^{\,n/(n+1)}\} \quad (13)$$

and the inverse of eq. (13) is E_c, the critical voltage gradient or electrical stress.

Therefore, $E_c = N^{1/(n+1)}\, r_p^{\,n/(n+1)}$ (14)

The critical current, i_c is defined as

$$E_c / r_p = (1 / r_p)\,(V_c / L) \quad (15)$$

$$i_c = (N / r_p)^{1/(n+1)} \quad (16)$$

3.2.2.1 Application of model

3.2.2.1.a Flat plate 10 x 1 cm

This model is applied to the same flat plate geometry of Fig.3.1

For x =1 cm and r_p = 5000 ohm/cm the minimum value of voltage required to support this arc length is calculated from eq. (10) and is, V_{cx} = 1064 V.

The minimum voltage required to maintain an arc length of 1 cm from Obenaus model can be calculated using Neumarker model.

From eq. (8) R_p = 45000 and from eq. (7) of Obenaus, V_c = 1064 V

Maximum value of V_{cx} i.e. critical voltage from eq.(13) is calculated as, V_c = 2707 and from eq. (12) critical length, x_c =6.67 cm.

Using this critical length of 6.67 in Obenaus model, R_p = 5000(10 -6.67) = 16650 ohm from eq. (7) V_c = 2706 volts, which compares very well with V_c of 2707 of this model.

From eq. (15) of this model $i_c = 5.414*10^{-2}$ amp. The same current is obtained from eq. (5a) of Obenaus model.

It can be seen that in this model the critical current is independent of leakage length. In this model critical length is about 2/3 of leakage length.

For different values of resistance, the value of critical voltage, critical length, and critical currents can be calculated from eqs. (10), (12) and (15) respectively.

The relationship between r_p and critical voltage V_c is shown in Fig. 3.10

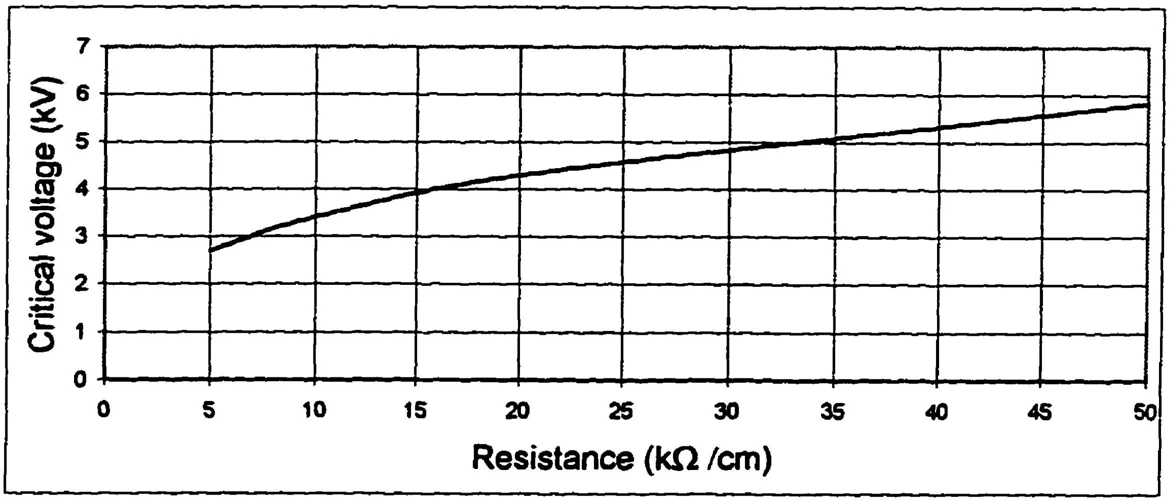

Fig. 3.10 Relationship between critical voltage and pollution resistance per unit length for 10 x 1 cm flat plate in Neumarker model.

3.2.2.1.b Flat plate 10 x 10 cm

This model is applied to 10 x 10 cm flat plate of Fig. 3.2. Critical current and arc length can be calculated from eqs. (15) and (12) respectively. For this calculated critical length the value of critical voltage (voltage required to maintain this arc) is calculated from eq. (13).

Fig.3.11 shows the comparison of critical voltage obtained using this model with the experimental results [15].

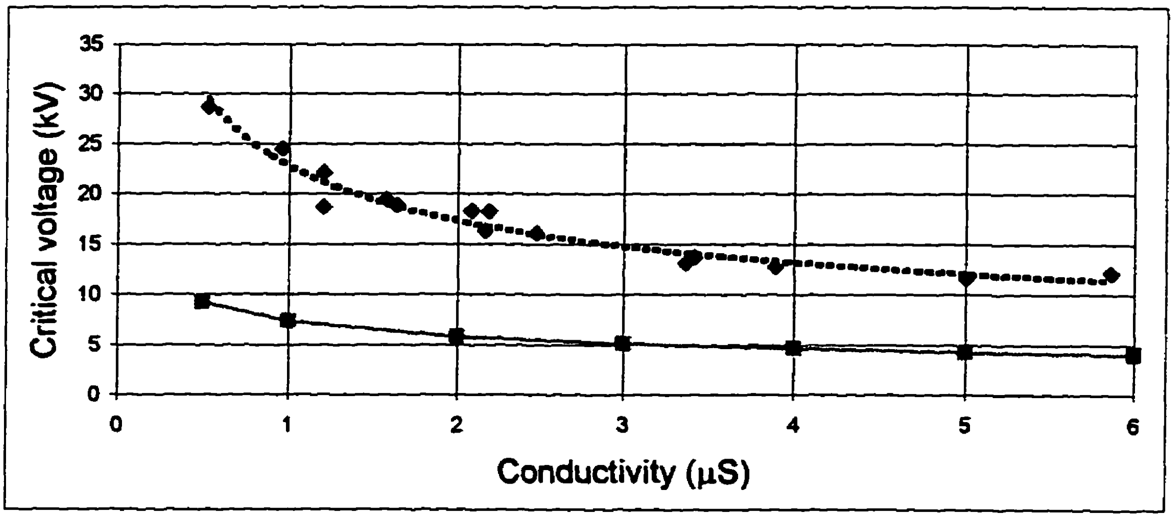

Fig. 3.11 Relationship between critical voltage and conductivity for 10 x 10 cm plate.
i) Neumarker model ______
ii) Experimental _ _ _ _ _

3.2.2.1.c Cylinder, 100 cm long and 15 cm diameter

This model is applied to configuration of Fig. 3.3 From eqs. (13) and (15) the critical voltage and current can be calculated for different values of pollution resistance. The critical leakage length is calculated from eq. (12) and is, $x_c = 66.7$ cm.

Fig.3.12shows the comparison of critical voltage obtained using this model with the experimental results [9].

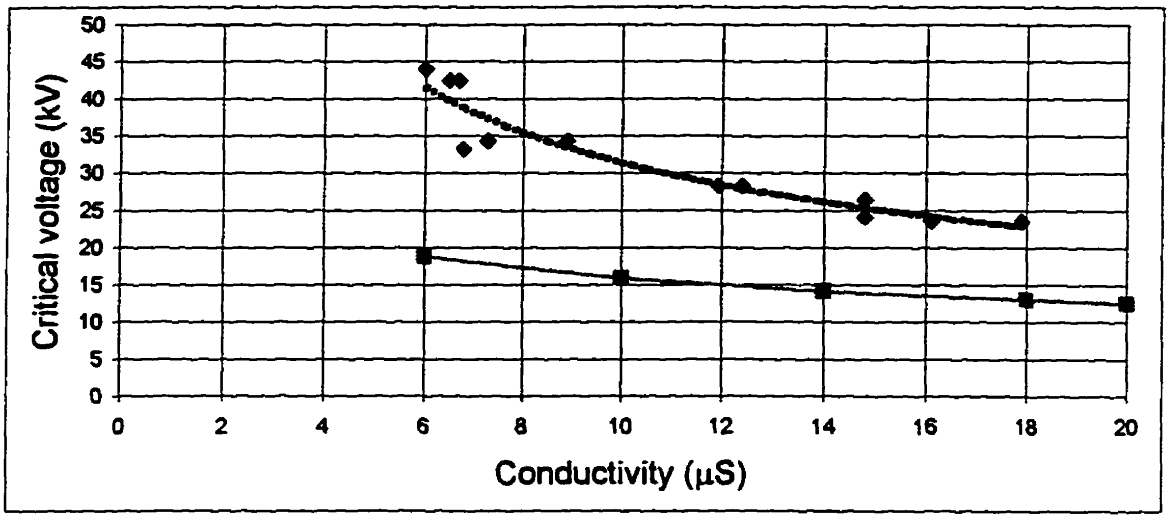

Fig. 3.12 Relationship between critical voltage and conductivity for cylinder, L = 100cm, dia = 15. cm.
i) Neumarker model ______
ii) Experimental _ _ _ _ _

3.2.2.1.d IEEE insulator

The model is applied to IEEE insulator of Fig. 3.4. The critical voltage and current can be calculated from eqs. (13) and (15) for different pollution resistance. The critical length is calculated from eq. (12) and is 20.33 cm. Fig.3.13 shows the comparison of critical voltage obtained using this model with the experimental results [40].

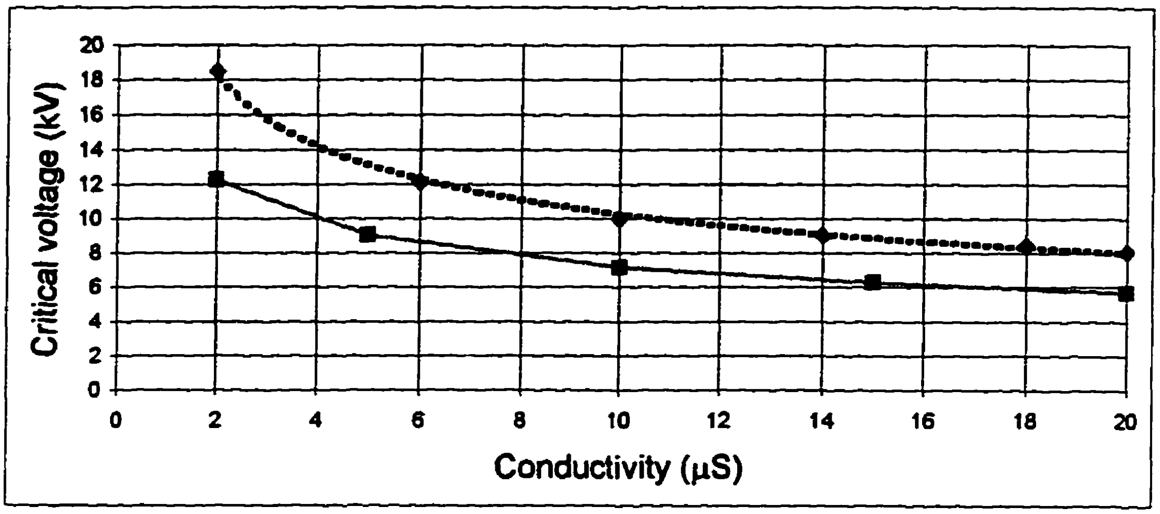

Fig. 3.13 Relationship between critical voltage and conductivity for IEEE insulator.
i) Neumarker model ______
ii) Experimental _ _ _ _ _

3.2.3 Model of R Wilkins [15]

This model uses the same initial idea as that used by Obenaus i.e. the arc burns in series with the resistance of pollution. Pollution can lead to formation of quasi stable gas discharges which burn in series with resistive polluted film. A model for discharge burning on rectangular plate is presented. The following assumptions are made:

Uniform pollution is considered.

Electrode fall voltage for both cathode and anode is 840 volts and electrode fall voltage is independent of discharge Current.

When voltage is applied to a flat plate with uniform pollution film, it will heat up uniformly until boiling point is reached and the surface conductivity will change by a factor given below:

$$F_{max} = 1 + \beta (T_b - T_{amb}) \qquad (17)$$

Where,

F_{max} is maximum form factor

β is temperature coefficient of conductivity

T_b is boiling point temperature

T_{amb} is ambient temperature

In case of practical insulators the film dries non uniformly. The conductivity factor " F" is given as,

$$F = I_{L1} / I_L \qquad (18)$$

Where, I_L is the leakage current upon initial application of test voltage and I_{L1} leakage current just before the dry band formation. Based on numerical analysis of thermo dynamic equations, a conductivity factor of 2.52 was calculated.

Flashover criteria

It is assumed that the discharge moves to a position where the rate of energy expenditure is maximum. A critical current value may be calculated above which power increases with the discharge length and below which power decreases with discharge length. For a discharge length of x, the movement will occur if $dP / dx > 0$. Where P is power taken from source.

If the applied voltage is constant i.e. dc, during discharge movement, then, $di/dx > 0$. This criteria was first proposed by Shkuropat and later on deduced by Hesketh. The flat plate model and discharge are shown in Fig. 3.14

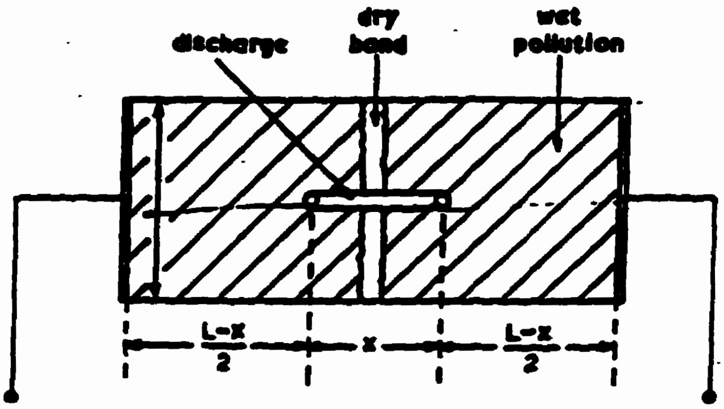

Fig. 3.14 Wilkin's model

Discharge burns centrally upon uniformly polluted plate of width "a" and length L. The applied voltage V is given as,

$$V = x\ N\, i^{-n} + V_e + 2\, i\, R \tag{19}$$

Where,

R = resistance of polluted surface between each discharge root and its corresponding electrode.

V_e = voltage drop of electrode.

<u>Calculation of resistance</u>

Initially it is assumed that the dry band is much smaller to the length L, so that this band is at right angle to strip and the discharge roots are circular. Resistance was calculated using Laplacian field problem for two cases, 1) Narrow strip, when $a \ll L$ and 2) Wide strip, where a is 3 times L.

For narrow strip resistance is given as,

$$R = 1/(2\pi\sigma_s)\{\pi(L - x)/a + \ln(a/(2\pi r_d))\} \qquad (20)$$

Where,

σ_s = surface conductivity, S

r_d = radius of discharge

For wide strip resistance is given as,

$$R = 1/(2\pi\sigma_s)\{\ln(2L/(2\pi r_d)) - \ln.\tan(\pi x/2L)\} \qquad (21)$$

Based on experiment it was found that the radius of discharge root is function of current and is given as,

$$i/(\pi r_d^2) = J = 1.45\ \text{Amp}/\text{cm}^2 \qquad (22)$$

Where,

J = current density in amp/cm^2

Substitution of r_d in above eq.s results in the following:

a) For narrow strip,

$$R = 1/(2\pi\sigma_s)\{(\pi(L - x)/a + (1/2)\ln(J a^2/4\pi i)\} \qquad (23)$$

and

$$R = (r_p/2)\{(L - x) + (a/2\pi)\ln(J a^2/(4\pi i))\} \qquad (24)$$

Where, r_p is resistance of pollution per unit length and is given as,

$$r_p = 1/(\sigma_s . a) \qquad (25)$$

b) For wide strip,

$$R = 1/(2.\,\pi\,\sigma_s)\{ (1/2)\ln(4\,L^2\,J/\pi\,i) - .\ln.\tan(\pi\,x/2\,L)\} \quad (26)$$

and

$$R = (r_p\,a/2\,\pi)\{ (1/2)\ln(4\,L^2\,J/\pi.i) - \ln.\tan(\pi\,x/2\,L)\} \quad (27)$$

Flashover Voltage:

a) Narrow strip

Substitution of the value of R from eq. (24) in eq. (19) results in the following eq.,

$$V = x\ N\,i^{-n} + V_e + ir_p\{(L - x) + (a/2.\,\pi)\ln(J\,a^2/4\,\pi\,i)\} \quad (28)$$

As applied voltage is constant, therefore,

$$di/dx = -\frac{\partial v/\partial x}{\partial v/\partial i} = \frac{Ni^{-n} - r_p}{\partial v/\partial i} \quad (29)$$

Since $\partial v/\partial i$ is always positive, flashover will result

when $\partial v/\partial x < 0$ (30)

or,

$$i > (N/r_p)^{1/(n+1)} \quad (31)$$

At critical condition $E_p = E_a$, $V_{arc} = V_c$, therefore,

$$N.i_c = i_c.r_p \quad (32)$$

$$i_c.r_p = N^{1/(n+1)}\,r_p^{n/(n+1)} \quad (33)$$

$$i_c = (N/r_p)^{1/(n+1)} \quad (34)$$

The critical current is the same as that obtained by Alston [9] and Neumarker [19].

Critical voltage at i_c is obtained from eq. (28) by substituting the value of i_c form eq. (34). Thus V_c is,

$$V_c = x\, i_c\, r_p + V_e + \{ i_c\, r_p \{ (L - x) + (a / 2\pi) \ln (J a^2/4\pi i_c)\} \qquad (35)$$

$$V_c = i_c\, r_p \{ L + (a/2\pi) \ln (J a^2/4\pi i_c)\} + V_e \qquad (35a)$$

or,

$$V_c = N^{1/(n+1)}\, r_p^{\,n/(n+1)} \{ L + (a/2\pi) \ln (J a^2/4\pi i_c)\} + V_e \qquad (36)$$

b) Wide Strip

Substituting the value of R from eq. (21) into (19) results in the following,

$$V = x\, N\, i^{-n} + V_e + 1/(\pi\, \sigma_s)\{ (1/2) \ln(4 L^2 J / \pi i) - \ln \tan (\pi x / 2L)\} \qquad (37)$$

Applying flashover criteria i.e. $di/dx > 0$, when $\partial v / \partial x < 0$, the following eq. is obtained,

$$N.i^{-n} - i /(\pi\, \sigma_s) \{ (\pi /2L)\, 2\mathrm{cosec}((\pi x /2L) \} < 0 \qquad (38)$$

Criteria of $di/dx > 0$ for all x is not satisfied until $x = L/2$. When $x = L/2$, then for flashover to occur the following condition should be satisfied,

$$i > (N\, \sigma_s\, L)^{1/(n+1)} \qquad (39)$$

At critical condition at flashover, critical current i_c is given as,

$$i_c = (N\, \sigma_s\, L)^{1/(n+1)} \qquad (40)$$

and critical voltage V_c as,

$$V_c = i_c/(\pi\, \sigma_s) \ln(4 L^2 J / \pi.i_c) + (L/2)\, N.\, i_c^{-n} + V_e \qquad (41)$$

or,

$$V_c = (i_c r_p.\, a / 2\pi) \ln(4 L^2 J / \pi.i_c) + (L/2)\, N.\, i_c^{-n} + V_e \qquad (42)$$

The above equations use the values of hot surface conductivity i.e. the conductivity at the time of flashover which is affected by high temperature. Therefore the flashover voltage values form these equations give higher values when compared with experimental values. These values may be divided by a suggested factor of about 1.8 (eq. 18), to take into account the variation in conductivity due to temperature.

3.2.3.1 Application

3.2.3.1.a Flat plate 10 x 1 cm

This model is applied to flat plate geometry of 10 x 1 cm of Fig.3.1. L =10 , a =1, r_p = 5000 ohm / cm

For narrow strip using the eq. (34) the critical current i_c is = 0.0833 amp and from (35a) critical voltage, V_c is = 5030 V.

The calculated values of critical voltage are for hot conductivity and are divided by a factor of 1.8 to convert them to normal conductivity values i.e. to V_c (normal).

The flashover voltage, V_c (normal) and the resistance, r_p and are shown in Fig. 3.15

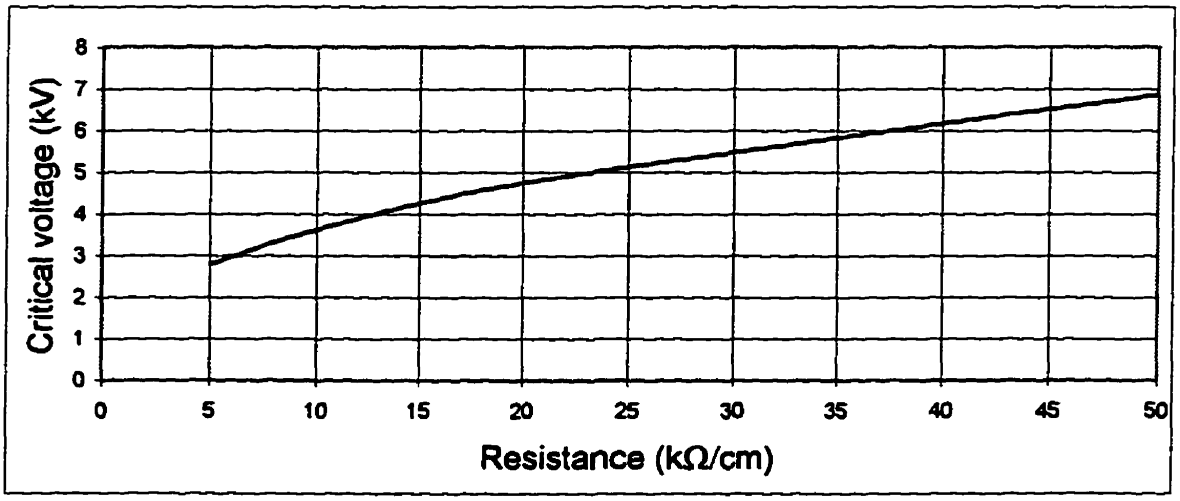

Fig 3.15 Relationship between critical voltage and resistance per unit length for 10 x 1 cm flat plate for Wilkins model

3.2.3.1.b Flat plate 10 x 10 cm

When length and width of flat plate are equal then either eq. (35) or (41) can be used for calculating the critical voltage and either (32) or (40) can be used to calculate the critical current. Eqs. (32) and (35) are used here to calculate the critical voltage and current for different resistance values.

The calculated values of Vc (normal) from this model are compared with experimental results [15] and shown in Fig.3.16.

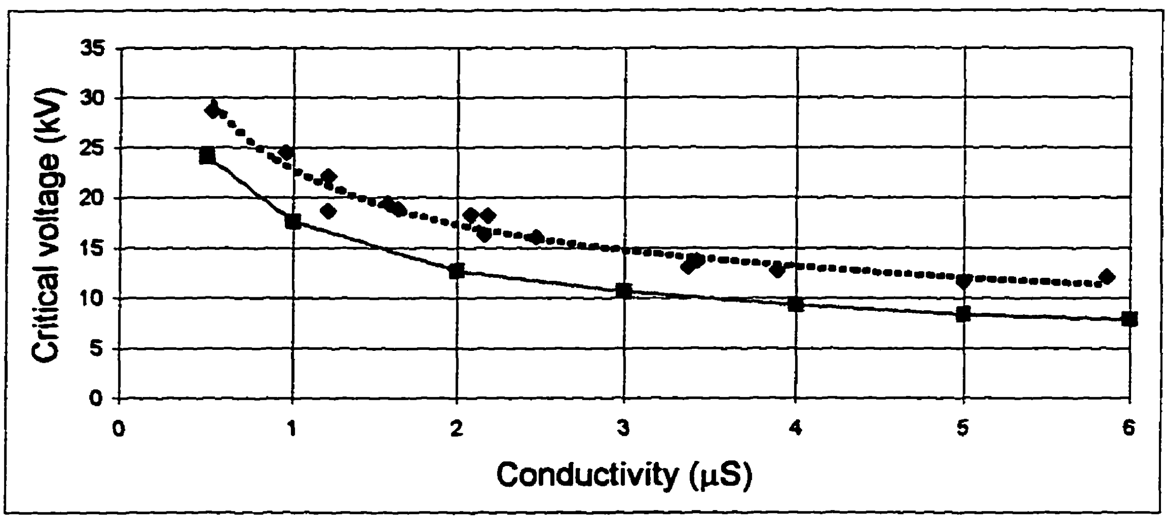

Fig. 3.16 Relationship between critical voltage and conductivity for 10x10 cm plate.

i) Wilkins model ______

ii) Experimental _ _ _ _ _

3.2.3.1.c Cylinder L = 100 cm, dia. = 15 cm

This model is applied to cylinder of Fig.3.3. The equivalent flat plate of this cylinder has L =100 cm and width, a = 47.12 cm. Since the length is greater than the width, therefore eqs. (32) and (35) are used for calculation of current and voltage.

The calculated values from this model are compared with experimental results [9] and shown in Fig. 3.17

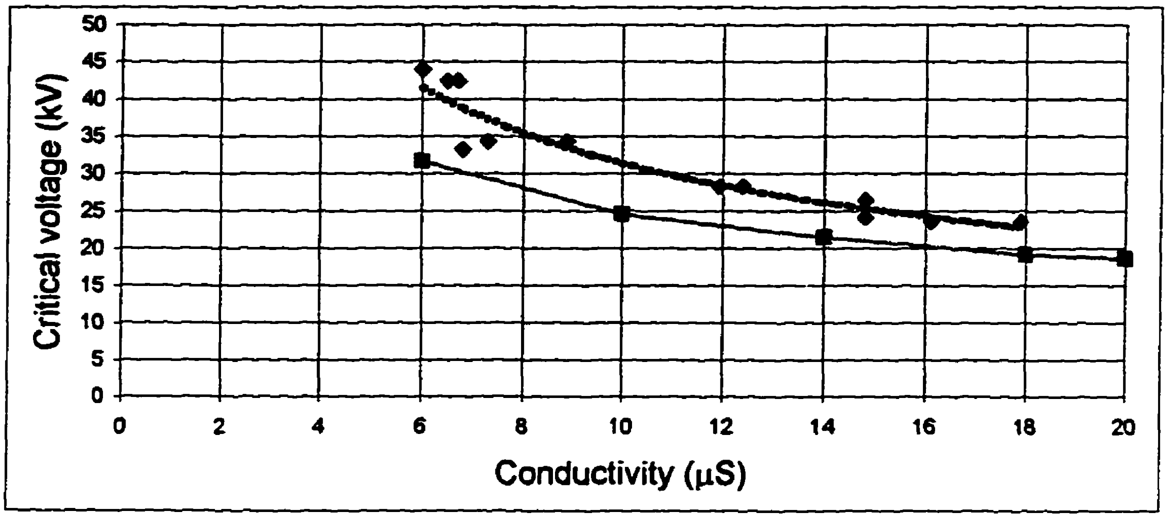

Fig. 3.17 Relationship between critical voltage and conductivity for cylinder
L = 100 cm, dia. = 15 cm.
i) Wilkins model _______
ii) Experimental _ _ _ _ _

3.2.3.1.d IEEE insulator

This model is applied to IEEE insulator of Fig. 3.4. The equivalent flat plate will have L = 30.5 cm and a = 51.11 cm (width). Since the width is greater than the the length, therefore eqs. (40) and (41) will be used to calculate current and voltage respectively.

The calculated values from this model are compared with the experimental results [40] and are shown in Fig. 3.18

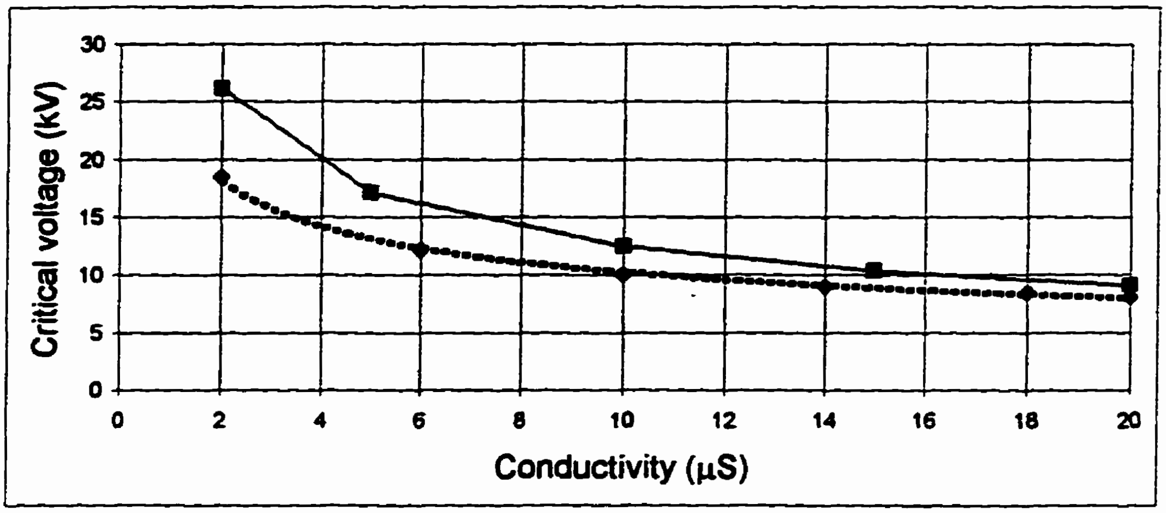

Fig. 3.18 Relationship between critical voltage and conductivity for IEEE insulator.
i) Wilkins model _______
ii) Experimental _ _ _ _ _

3.2.4 Model of P Claverie [16]

This model is based on Obenaus's work. An arc in series with a polluted layer (resistance) is considered. Based on experiments the criteria for reignition of arc is developed. The flat plate model and the electrode arrangement used for experiments is shown in Fig. 3.19.

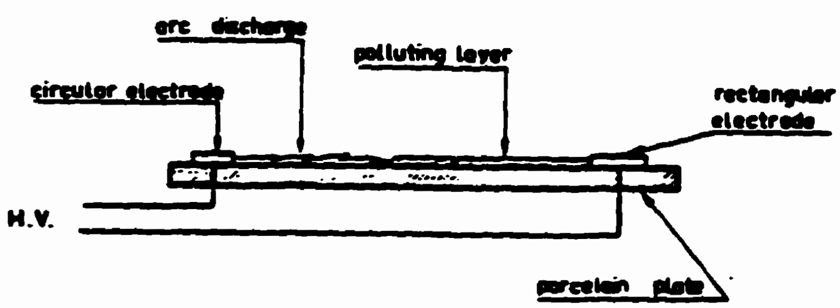

Fig. 3.19 Claverie's model

The following assumptions are made:

It is assumed that arc propagation speed prior to critical conditions is so low as to justify the quasi-stationary analysis. Otherwise, another voltage drop term required for expenditure of energy to move arc has to be added.

Single arc is assumed.

Uniform resistivity is assumed.

It is assumed that the arc propagation is due to thermal phenomenon, i.e. the arc grows due to heat energy, as it dries the layer in front of the root.

Based on experimental results an empirical formula for the arc voltage is given as,

$$V_{arc} \cong 100\, x /(I^{1/2}) \tag{43}$$

The resistance in series with the arc is function of the arc root position on the insulator surface. $R_p(m)$ is the resistance at point "m" and depends on the geometrical structure of liquid layer and conductivity and can not be calculated easily but can be measured.

$$V = 100\, x /(I^{1/2}) + R_p(m)\, I \tag{43a}$$

Where,

V = applied voltage

I = peak value of rms current

Assuming that the surface resistivity is uniform, then ,

$$R_p(x) = \rho F(x) \tag{44}$$

Where, F(x) is function of x

$$V = 100\, x /(I^{1/2}) + \rho F(x)\, I \tag{45}$$

Based on the several experiments the condition for arc reignition is given by the following eq.,

$$V > 940\, x / (I^{1/2}) \tag{46}$$

Thus if an arc occurs then for it to stabilize or glow the above condition must be satisfied. There exists a maximum arc length x_m, corresponding to current I_m in such that

$$V\ (I_m^{1/2}) = 940\ x_m \tag{47}$$

And from eq.s (45) and (46)

$$V = 100\ x_m^{2/3}\ F(x_m)^{1/3} \tag{48}$$

The resistance R(x) can be determined by measurements of the leakage current I_m under several voltages "V". An empirical formula to calculate the resistance of pollution layer, $R_p(x)$ is given as,

$$R_p(x_m) = 0.9\ V / I_m \tag{49}$$

And, $$x_m = V\ (I_m^{1/2}) / 940 \tag{50}$$

The critical voltage V_c is maximum of V as in eq. (48).

It is shown that the flashover voltage of plate varies proportionally to the cubic root of pollution liquid resistivity i.e. $V_c / \rho^{1/3}$ = constant.

Measurement of $R_p(x)$ for disc insulators were more complex than the plate. The critical flashover voltage is obtained in terms of critical length x_c,

$$V_c = 90\ \rho^{1/3}\ x_c^{2/3} F^{1/3}(x_c) \tag{51}$$

x_c is obtained from numerical solution of the following eq.,

$$d\ (x^2 F(x))/dx = 0 \tag{52}$$

In case of linear model (uniform resistance per unit length), the above equation can be simplified to yield,

$x_c = 2\,L/3$, which when substituted in (50) gives,

$$V_c = 47.6\, r_p^{1/3}\, L \qquad (53)$$

3.2.4.1 Application

3.2.4.1.a Flat plate 10 x 1 cm

Applying this model to flat plat model geometry 10 x 1 cm of Fig. 3.1.

L =10, a =1, r_p = 5000 ohm/cm

From eq. (53) the critical flashover voltage for above conditions is = 8139 V.

The critical voltage V_c (rms) and resistance r_p ,is plotted in fig 3.20

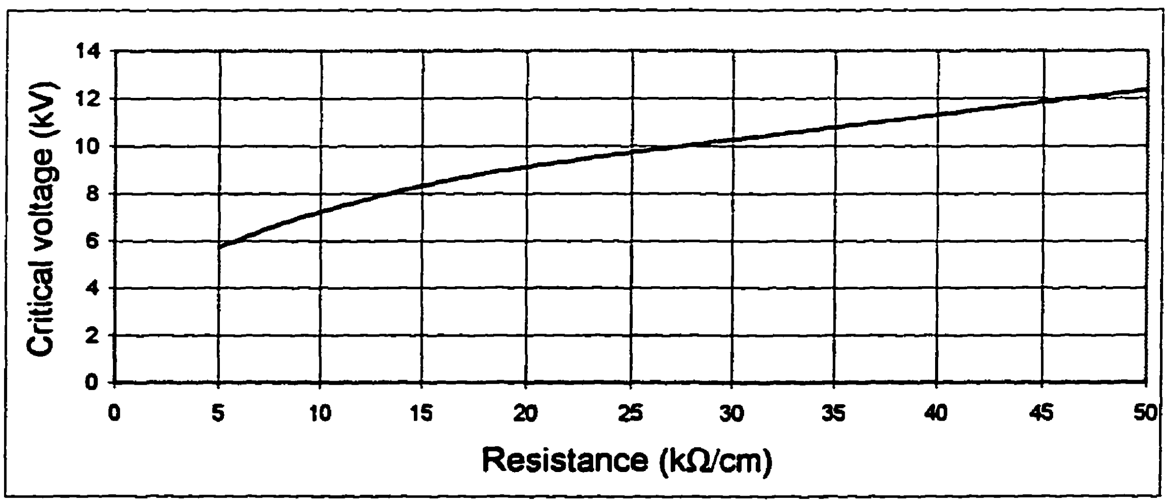

Fig.3.20 Relationship between critical voltage and resistance per unit length for 10 x 1 cm flat plate in Claverie model.

3.2.4.1.b Flat plate 10 x 10 cm

This model is applied to 10 x 10 cm flat plate of Fig. 3.2. Critical voltage is calculated from eq. (53) for different values of pollution resistance.

The calculated values of critical voltage, Vc rms from this model are compared with the experimental results [15] and shown in Fig.3.21

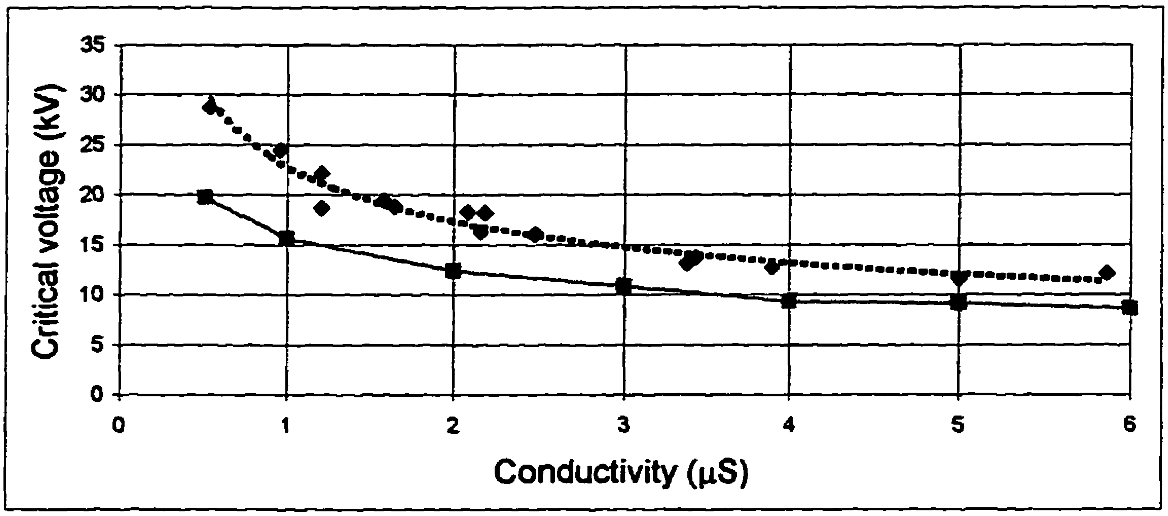

Fig. 3.21 Relationship between critical voltage and conductivity for 10 x 10 cm plate.
i) Claverie model ______
ii) Experimental _ _ _ _ _

3.2.4.1.c Cylinder L =100 cm, dia. = 15 cm

This model is applied to cylinder of Fig. 3.6. The critical voltage is calculated from eq.s (53) for different values of pollution resistance.

The calculated values from this model are compared with experimental results [9] and shown in Fig.3.22

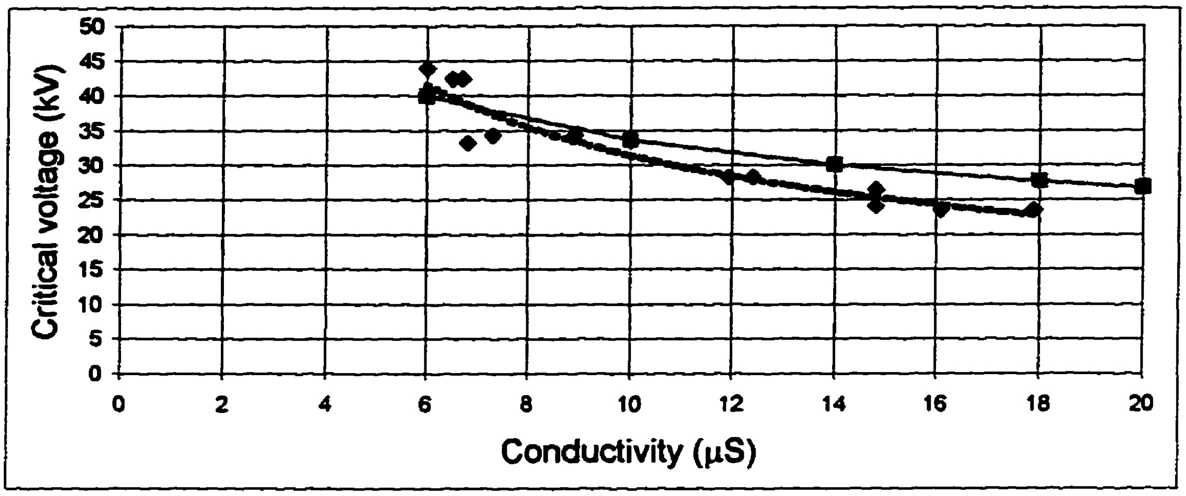

Fig. 3.22 Relationship between critical voltage and conductivity for cylinder L =100 cm, dia. = 15 cm.

i) Claverie model _______

ii) Experimental _ _ _ _ _

3.2.4.1.d IEEE insulator

This model is applied to IEEE insulator of Fig. 3.4. The critical voltage is calculated from eq. (53) for different values of pollution resistance.

The calculated values from this model are compared with experimental results [40] and shown in Fig.3.23

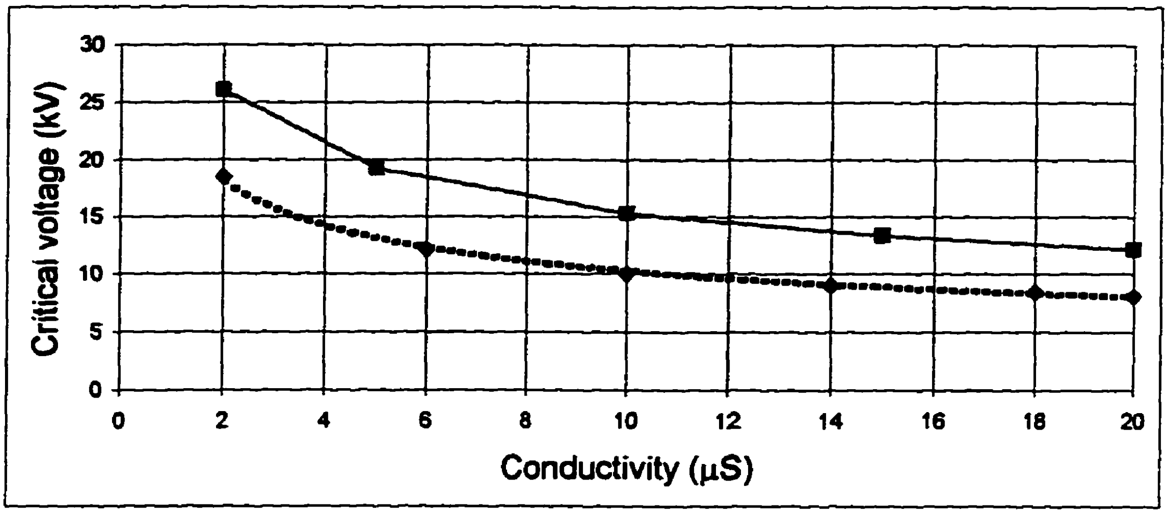

Fig. 3.23 Relationship between critical voltage and conductivity for IEEE insulator.
i) Claverie model ______
ii) Experimental _ _ _ _ _

3.2.5 Model of P S Ghosh [18]

This model is based on experiments conducted on different electrolytic surfaces with different electrolytes. The measured values of critical voltage, current and time to flashover etc. depend on electrolyte. The arc constants used in the model are derived from these measured values which were obtained for different electrolytes. Thus this model takes into effect the change in chemical nature of pollutants on flashover voltages under ac system. A flashover model earlier presented by Renyu [11] is used with a difference. Renyu used peak values of current and voltage, while this model uses rms values.

A flat plate insulator model is used for experiments as shown in Fig.3.24

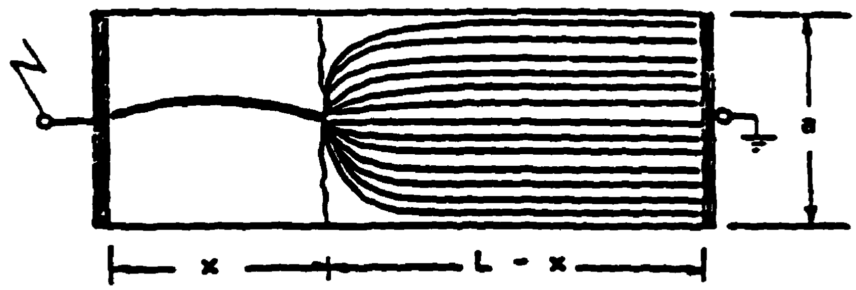

Fig.3.24 Two dimensional flat plate model

The main concept of Obenaus model i.e. an arc in series with polluted surface (resistance) is applied. From experimental results, it is shown that the critical current is independent of length of pollution layer. Also, it was shown that for every electrolyte, there is a particular value of applied voltage V, say V_m, corresponding to time to flashover of 1 ms, and any further increase in V beyond V_m does not change the value of time to flashover appreciably. The metal concentration in electrolyte were reduced after flashover.

Model

Under static voltage for a polluted layer,

$$V = x N i^{-n} + r_p (L - x) i + V_e \qquad (54)$$

Where, V = applied voltage in KV,

i = current in amp

r_p = resistance of pollution in KΩ

As per flashover mechanism proposed by Renyu for ac

$$V_{peak} = x N i_{peak}^{-n} + r_p (L - x) i_{peak} \qquad (55)$$

From eq.s (93) and (94) and considering a factor of 1.3 between ac peak and dc applied voltage, the following equation is obtained,

$$V = k\,x\,N\,i^{-n} + r_p\,(L - x)\,i + V_e \qquad (56)$$

where,

$$k = (\sqrt{2}/1.3)^{-(n+1)} \qquad (57)$$

The voltages and currents in eq. (56) are rms values.

Differentiating eq. (56) with respect to "i" and equating it to zero gives the critical values of "i" and voltage as in the following eq.,

$$V_c = L.k^{1/(n+1)}\; N^{1/(n+1)}\; r_p^{\,n/(n+1)} \qquad (58)$$

and, $$i_c = [\,k\,N/r_p\,]^{1/(n+1)} \qquad (59)$$

The value of applied voltage at which the time to flashover is 1 ms i.e. when $V = V_m$, at this time x is approximately equal to L, and $i = i_c$, therefore, eq. (56) can be written as,

$$V_m = k\,L\,N\,i_c^{-n} + V_e \qquad (60)$$

Based on experiments and using the eq. (60) the values of arc constants N and n are determined. Since V_m, i_c are different for different for different electrolytes therefor the calculated values of N and n take into account the chemical composition of electrolyte.

In this model the values of N = 450 and n = 0.49 for Nacl electrolyte are used.

3.2.5.1 Application

3.2.5.1.a Flat plate 10 x 1 cm

This model is applied to flat plate model of 10 x 1 cm of Fig. 3.1. For different values of resistance the critical current and voltage can be calculated from eqs. (59) and (58).

The critical voltage V_c and resistance r_p values are plotted in fig 3.25.

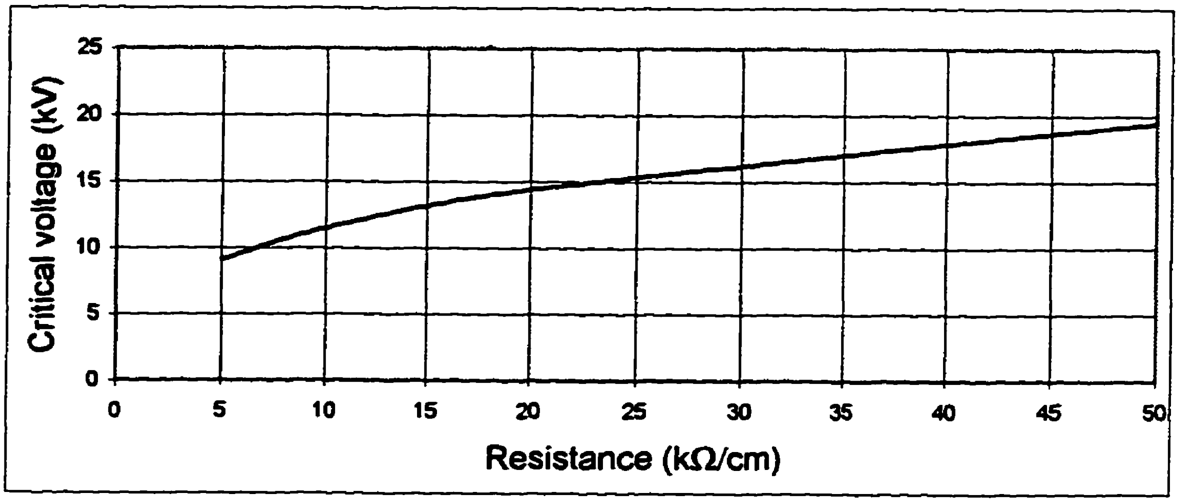

Fig.3.25 Relationship between critical voltage and resistance for 10 x 1 cm flat plate in Ghosh's model.

The critical current and voltage obtained in this model is similar to the model of Neumarker and others and differ by a factor 0.919, as can be seen from eq. (59). Therefore the critical current obtained by this model is slightly less than Neumarker.

The calculated results are much higher than Neumarker and others. It may be due to different value of N and n used in this model.

3.2.5.1.b Flat plate 10 x 10 cm

This model is applied to flat plate 10 x 10 cm of Fig.3.2. Critical voltage and current can be calculated from eqs. (58) and (59) respectively, for different values of pollution resistance.

The calculated values from this model are compared with the experimental results [15] and are shown in Fig.3.26

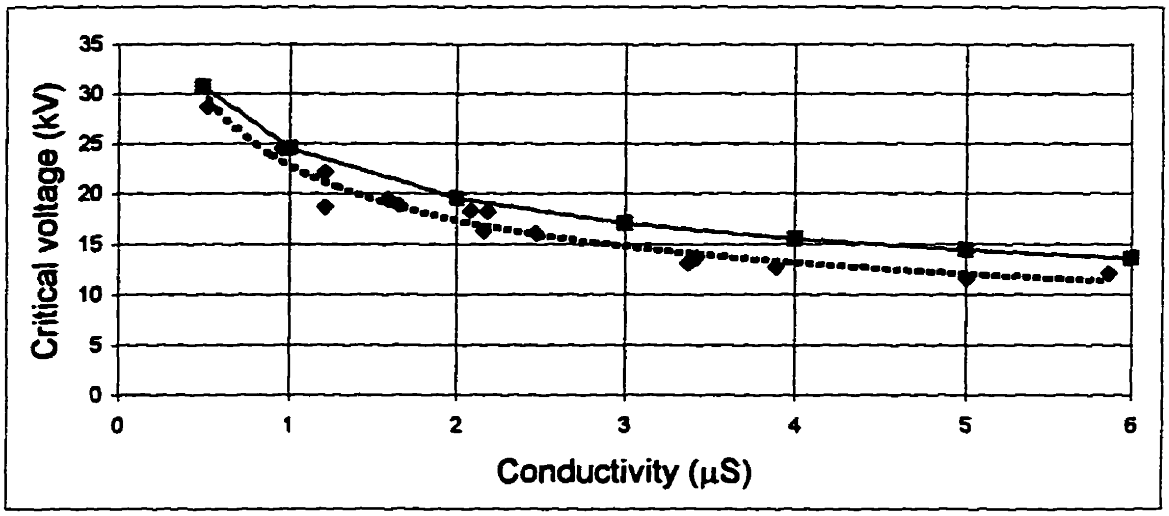

Fig. 3.26 Dependence of critical voltage on conductivity for 10 x 10 cm plate.

i) Ghosh model ______

ii) Experimental _ _ _ _ _

3.2.5.1.c Cylinder L = 100 cm, dia. = 15 cm

This model is applied to cylinder of Fig.3.3. From eqs. (59) and (58) the critical current and critical voltage can be calculated for different values of pollution resistance.

The calculated values from this model are compared with the experimental results [9] and are shown in Fig.3.27

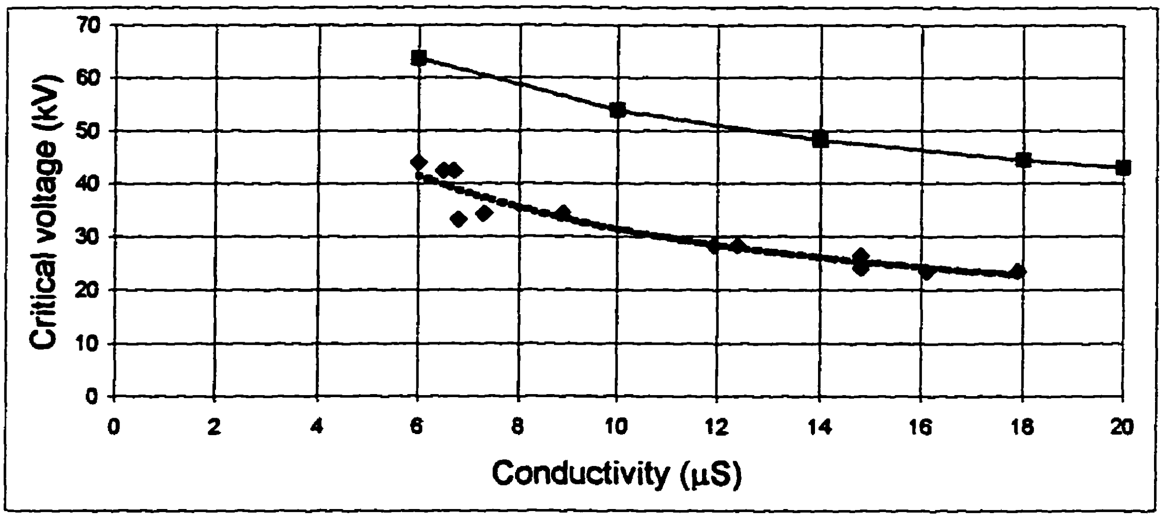

Fig. 3.27 Relationship between critical voltage and conductivity for cylinder
L =100 cm, dia. = 15 cm.
i) Ghosh model ______
ii) Experimental _ _ _ _ _

3.2.5.1.d IEEE insulator

This model is applied to insulator of Fig. 3.4. From eqs. (59) and (58) the critical current and critical voltage can be for different values of pollution resistance.

The calculated values from this model are compared with the experimental results [40] and are shown in Fig.3.28

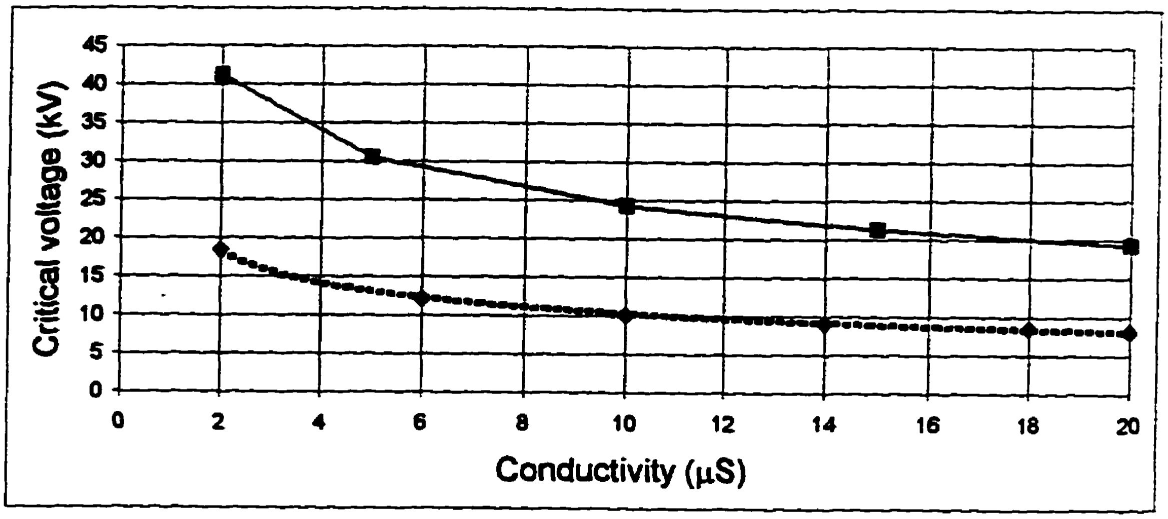

Fig. 3.28 Relationship between critical voltage and conductivity for IEEE insulator
i) Ghosh model _______
ii) Experimental _ _ _ _ _

3.3 Cylindrical Models

3.3.1 Model of L Alston [9]

This model consists of a cylindrical insulator of length L, with electrodes on flat ends, as shown in Fig. 3.29

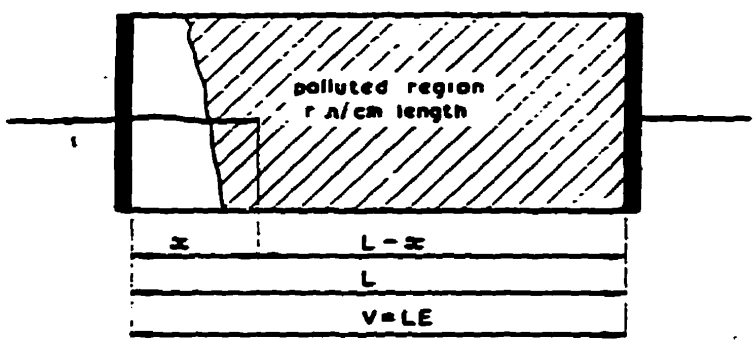

Fig. 3.29 cylindrical model

The assumptions made in this model are:

Discharge current is constant along the length of discharge, there is no contact between the discharge and pollution except that at discharge tip.

The dry band does not conduct the current. The current can only flow to polluted portion only through discharge and thus discharge current is same as current entering pollution layer.

The electrode voltage drop is neglected

Resistance per unit length is constant.

The electric field is uniform for most part of length.

Single arc is assumed.

Mechanism of extinction assumed is that as arc increases in length, the voltage required to support it also increases. If the arc voltage is more than the source voltage, the arc will extinguish.

The applied voltage is related to arc voltage and drop across polluted layer as in the following eq.:

$$V = V_{arc} + i\,R_p \qquad (61)$$

Based on experiments, measurements of currents and voltages were plotted to determine the arc characteristic constants of the discharges in air and the arc voltage is given as,

$$V_{arc} = x\,N\,i^{-n} + B \qquad (62)$$

$x\,N\,i^{-n}$ represents the voltage drop of discharge and B represents voltage drop near electrode. B is less than 400 volts and can be neglected if the applied voltage is in few kv.

R_p depends on resistivity of pollution and shape. The resistivity is assumed constant so that the resistance of pollution along the axis of cylinder is constant.

$$R_p = r_p(L - x) \tag{63}$$

r_p is resistance per unit length along the axis of cylinder. If the discharge free length is great compared to the diameter of cylinder, the electric field can be considered uniform over a greater length of cylinder.

$$V = x N i^{-n} + i r_p(L - x) \tag{64}$$

For any given arc length x, the voltage required to maintain this arc can be obtained by dv/di = 0, and this occurs at the current given in eq. (65)

$$i = \{n N x / r_p(L-x)\}^{1/(n+1)} \tag{65}$$

$$V_{cx} = (n+1)(N x)^{1/n+1} \{(L - x) r_p / n\}^{n/(n+1)} \tag{66}$$

Fig. 3.30 is a plot of V_{cx} and x.

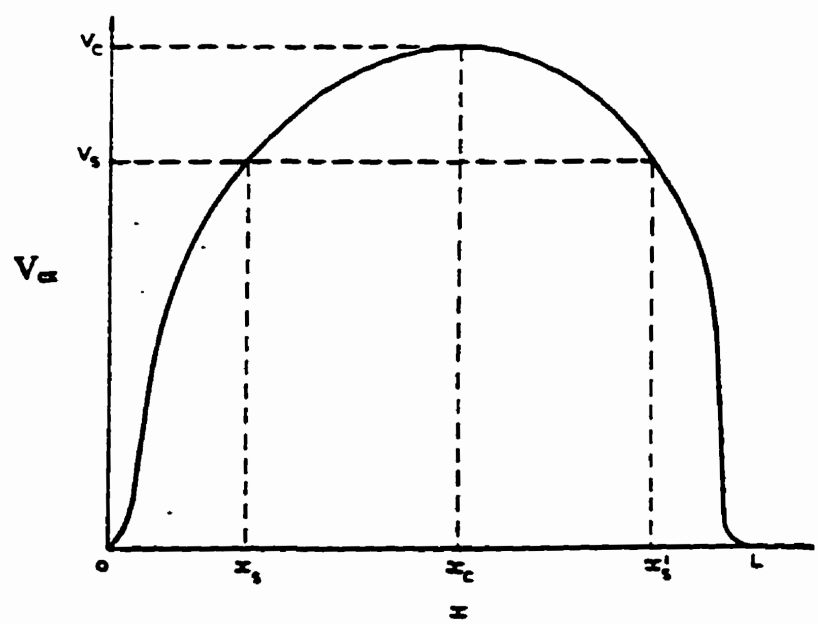

Fig. 3.30 Dependence of V_{cx} on arc length.

As can be seen that V_{cx} has a maximum value, called critical value V_c. For an applied voltage V_s, the arc can elongate up to an initial length of x_s, as for length greater than x_s the voltage required to maintain the arc is more than the supply voltage. On the other hand if the initial arc was x'_s then any increase in supply voltage will lead to flashover.

The value of V_c is given as,

$$V_c = N^{1/(n+1)}\ L\, r_c^{n/(n+1)} \tag{67}$$

and this occurs at $x = x_c$ and critical arc length is given as in eq. (68)

$$x_c = L/(1+n) \tag{68}$$

Flashover is impossible if applied voltage and initial length of arc are less than V_c and x_c given by (67) and (68).

It is interesting to note that the values of V_c and x_c are the same as that given by Neumarker [19].

$$E_c = V_c / L = N^{1/(n+1)}\ r_c^{n/(n+1)} \tag{69}$$

The above relationship defines the relation between the critical resistance and applied stress. It follows that for a given r_c, the flashover is impossible at any stress which is less than the E_c, similarly for any given stress E_c flashover is impossible for any value of resistance greater than r_c given in eq. (69).

In general flashover can not occur if

$$E < N^{1/(n+1)}\ r_p^{n/(n+1)} \tag{70}$$

Based on experiments the value of $N = 63$ and $n = 0.76$ is used in this model.

Therefore,

$$E < 10.5\ r_p^{0.43} \tag{71}$$

Peak values of E_c and E must be used for power frequency. Since E_c is the maximum value at which flashover is impossible.

The condition that the initial arc length should be less than x_c can be obtained using eq. (69) with the value of n = 0.76.

$$x_i = \text{initial length} < x_c < 0.57\ L \tag{72}$$

and critical current, $i_c = (N / r_p)^{1/(n+1)}$ (73)

N or r_c can be eliminated.

$$i_c = (N/E_c)^{1/n} \tag{74}$$

$$\text{and } i_c = E_c / r_c \tag{75}$$

Substituting the values of N and n , the maximum value of current that can flow under a stress of E_c without flashover is

$$i_{max} = 233.\ E_c^{-1.31} \tag{76}$$

Eq.s (71) and (72) define the conditions under which the flashover is impossible, not the conditions under which the flashover takes place. For example when the applied voltage is greater than the critical voltage, the flashover may not take place due to insufficient conditions e.g. forces for arc movement are not enough, the energy dissipated into discharge root is not sufficient to dry out the pollution.

Eq. (72) is assumed to hold for almost all practical applications. x_i, the initial arc length is the distance covered by an initial sparkover distance which triggers off the discharges and which is due to non uniformity of electric field by pollution. If the initial sparkover could span the distances compared to L i.e. more than critical length x_c then the flashover may suddenly occur without being preceded by discharges.

3.3.1.1 Application of Model

3.3.1.1.a Flat plate10 x 1 cm

This model is applied to flat plate of Fig.3.1.

If flashover is assumed to take place under controlled conditions based on this model it must occur at critical stress.

For $r_p = 5000$, From eq. (71) $E_c = 409$ v /cm and V_c is 10*409 =4090 volts, and from eq. (76) $i_c = 8.83*10^{-2}$ amp.

It is interesting to note here that although the formulae for critical voltage and critical arc length are same as in Neumarker, the calculated values are different. This is due to the different values of N and n used in two models. For N and n, Neumarker used the values 63 and 0.5 respectively, while Alston used the values of 63 and 0.76.

For an arc length of x = 1 cm, the calculated value of voltage required to maintain this arc length is 2131 V using this model, (eq. 66), while using the Obenaus model it is 1102 V (from eq. 7 in Obenaus's model). In Obenaus's model the value of N = 63 and n = 0.5 were used. If the values of N and n of Alston i.e. 63 and 0.76 respectively, are used in model of Obenaus then the value of supply voltage required to maintain the arc length of 1 cm is 2074 V, which is close to Alston's value of 2131 V.

For different values of r_p, the values of critical voltage, current and arc length can be calculated from eqs. (71), (76) and (72).

The values of resistance and critical voltage are plotted in Fig. 3.31.

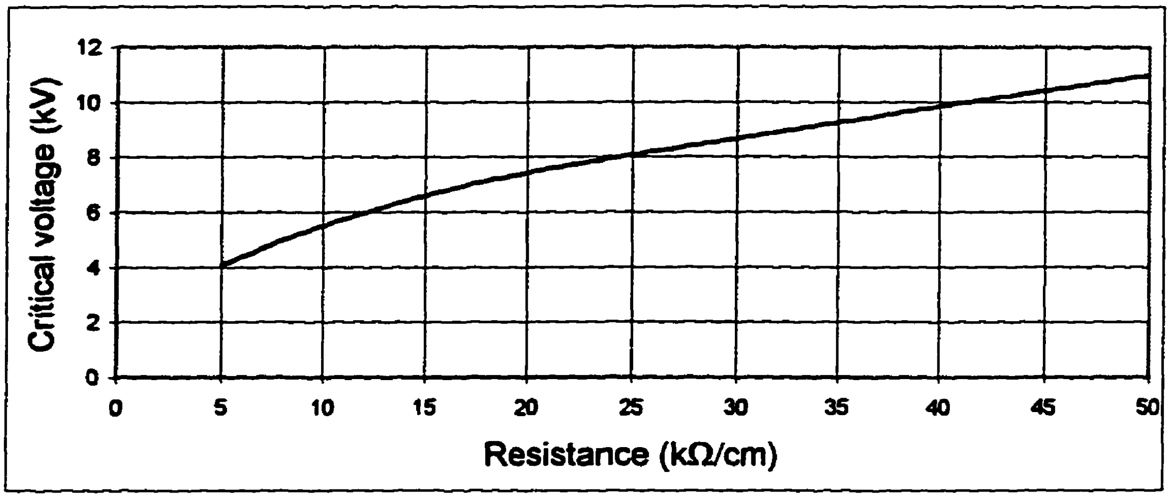

Fig. 3.31 Relationship between critical voltage and resistance for 10 x 1 cm flat plate in Alston's model.

The critical arc length is 5.7 cm when the model is considered under ideal conditions. From Neumarker's model the critical length is about 6.67 cm. It is quite likely that due to various assumptions the flashover voltage predicted by this model may be lower than the actual. The model may therefore give a safer but conservative values of flashover voltage.

3.3.1.1.b Flat plate 10 x 10 cm

This model is applied to flat plate of Fig. 3.1. From eqs. (71) and (76) the critical voltage and critical current for different pollution resistance can be calculated. Critical length is calculated from eq. (72) and is 5.7 cm.

The calculated critical voltage from this model is compared with the experimental results [15] and is shown in Fig. 3.32

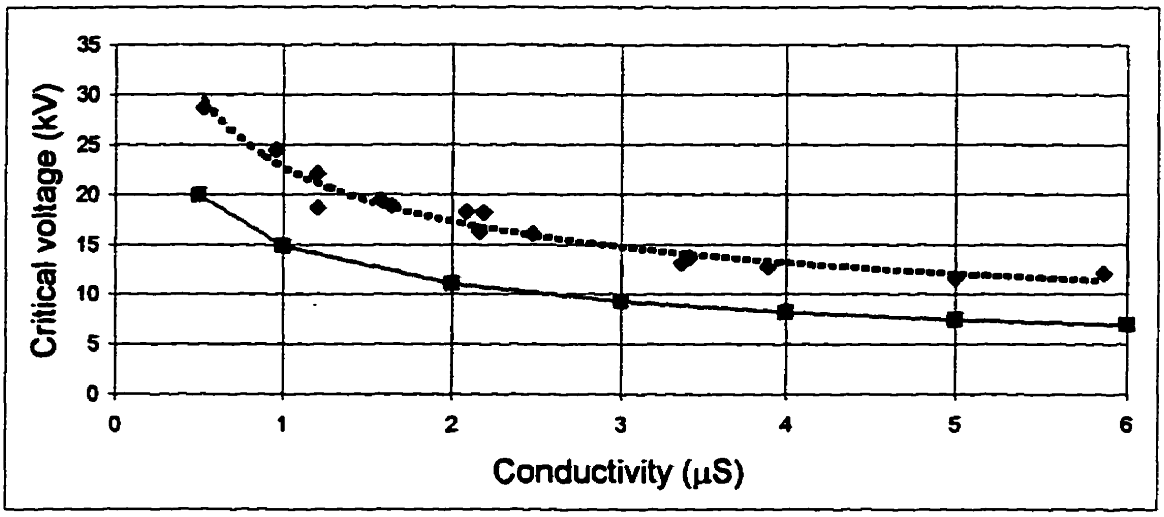

Fig. 3.32 Relationship between critical voltage and conductivity for 10 x 10 cm plate.
i) Alston model _______
ii) Experimental _ _ _ _ _

3.3.1.1.c Cylinder L = 100 cm, dia. = 15 cm

This model is applied to cylinder of Fig. 3.3. From eqs. (71) and (76) the critical voltage and critical current for different pollution resistance can be calculated. Critical length is calculated from eq. (72) and is 57 cm.

The calculated values from this model are compared with the experimental results [9] as shown in Fig. 3.33

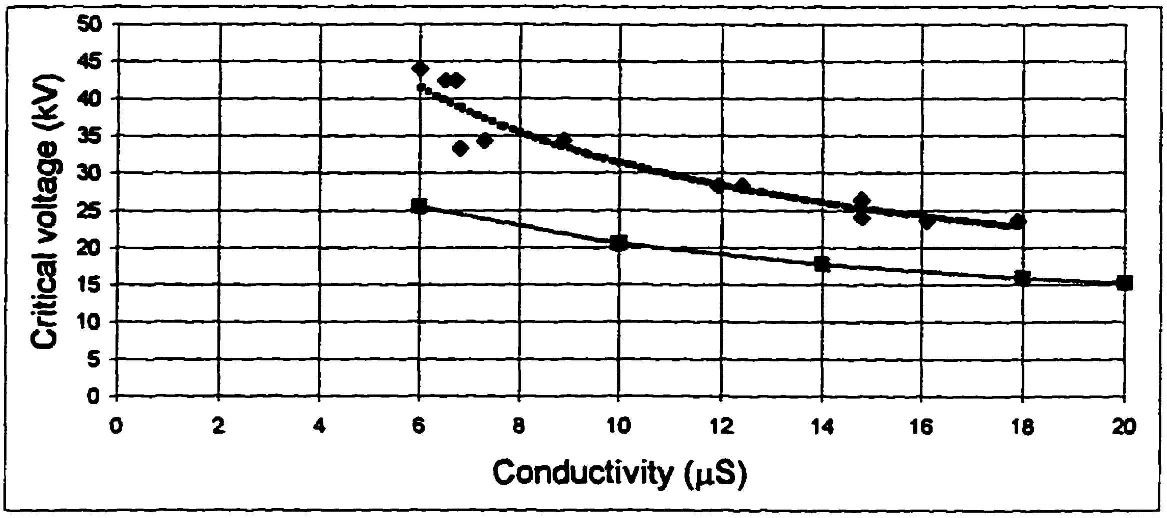

Fig. 3.33 Relationship between critical voltage and conductivity for cylinder,L=100 cm, dia. = 15 cm.

i) Alston model _______

ii) Experimental _ _ _ _ _

3.3.1.1.d IEEE insulator

This model is applied to IEEE insulator of Fig. 3.4 From eqs. (71) and (76) the critical voltage and critical current for different pollution resistance can be calculated. Critical length is calculated from eq. (72) and is 17.30 cm.

The calculated values of critical voltage from this model are compared with the experimental results [40] as shown in Fig. 3.34

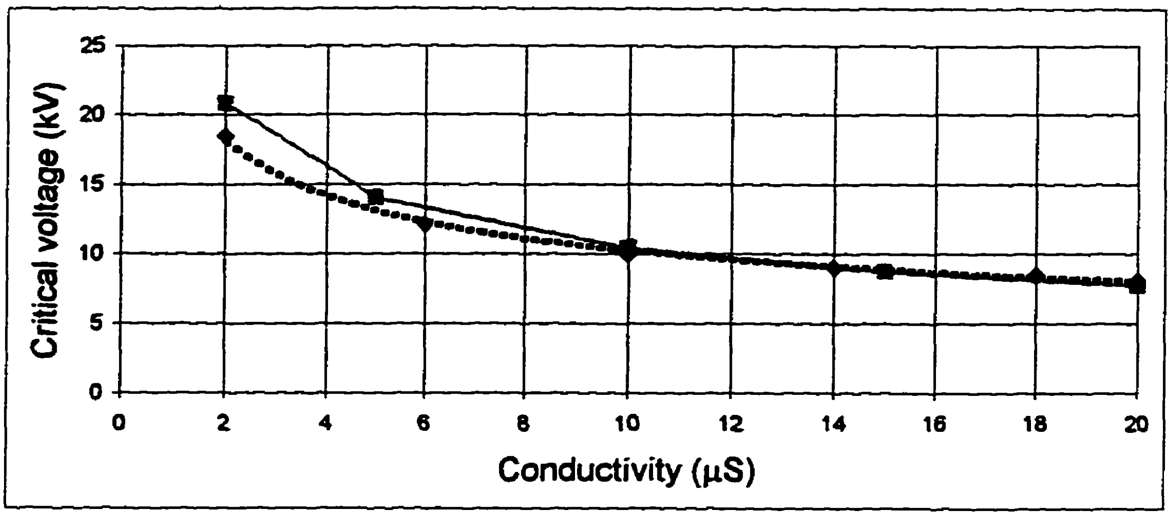

Fig. 3.34 Dependence of critical voltage on conductivity for IEEE insulator.
i) Alston model ______
ii) Experimental _ _ _ _ _

3.3.2 Model of Boehme & Obenaus [10]

This model uses cylindrical geometry for insulators. Cylindrical models with and without sheds have been considered. An arc burning in series with the resistance, representing the pollution layer is considered. The elongation of the arc which leads to flashover is based on the mechanism of Hampton [13]. The Fig. 3.35 describes the two cases of cylindrical models, I) without shed, and the other II) with sheds.

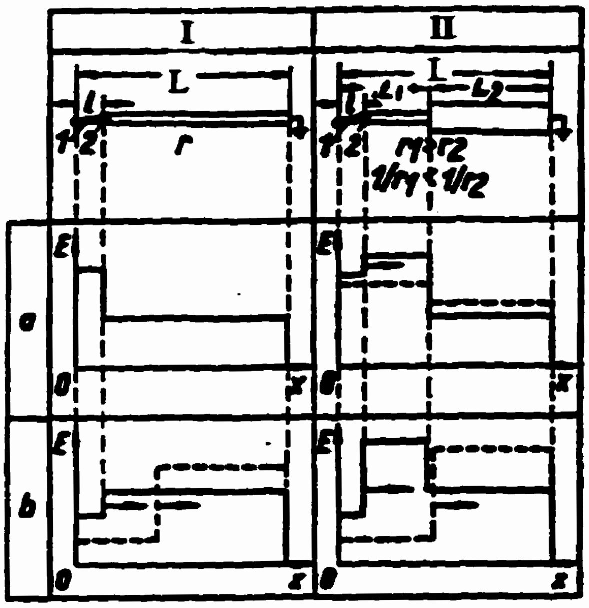

Fig. 3.35 Field strength distribution along the creepage path
a) without flashover b) during flashover

The following assumptions are made:

Single arc is considered.

Electric field along the creepage path is uniform and the resistance of the pollution layer is reduced by the elongation of partial arc.

As soon as the movement of root arc began it led to complete flashover for the case without sheds.

Arc travels along the leakage path.

In the case of a cylinder without sheds, the arc travels further if the field ahead of it i.e. of resistive layer is greater than the electric field of arc as in Fig. 3.35. In the case of a cylinder with sheds, which is assumed to have uniform resistivity, a single resistance in series with the arc is not adequate. Therefore two resistances corresponding to shed areas of leakage lengths L1 and L2 are considered. The geometry of this insulator is shown in Fig. 3.36

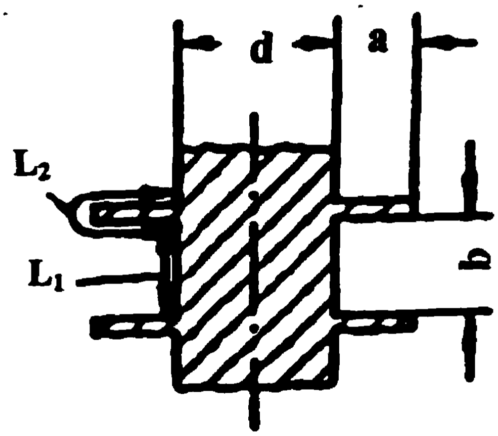

Fig. 3.36 Insulator with sheds.

When a partial arc burns at the edge of the polluted layer, forces act in two directions on the root. On the one hand they originate from the electric field parallel to the resistance and on the other from the field along the arc. In each case the arc root will move into a zone of higher field.

If the root travels on a stepped resistance (in case of model with sheds) r_{p1}, then it may travel as far as the transition point between r_{p1} and r_{p2} If the field magnitude in the arc is less than the field magnitude in resistance r_{p2} then the arc root travels over the transition and flashover occurs. In case the field magnitude in the arc is more than the resistive layer, then the movement of the arc is halted.

Flashover voltage depends on characteristics of arc and conductance of polluted layer, $1/r_{p1}$ and $1/r_{p2}$, $1/r_p = (L1+L2)/(L1\ r_{p1} + L2\ r_{p2})$. The path with lower conductance will be bridged first by partial arc. If L2 is small compared to L1 or the conductance $1/r_{p1}$ and $1/r_{p2}$ do not differ much, then flashover will take place, otherwise the stationary arc will be produced on L1 and flashover will only be possible if the applied voltage is increased.

In the arc voltage eq. " $N \times i^{-n}$", the value of n =1 is assumed in this model. Flashover voltage without stationary partial arc is given as,

$$V_c'/L = r_p(r_{p1} N)^{1/2} = (L1\ r_{p1} + L2\ r_{p2})/(L1+L2)\ (r_{p1} N)^{1/2} \tag{77}$$

If the flashover develops from stationary arcs, then,

$$V_c/L = (r_{p2}N)^{1/2} \tag{78}$$

Conductance r_{p1}, r_{p2}, leakage lengths L1, L2 can be represented by the geometry of insulator Fig. 3.36. If a partial arc travels along the leakage length L, and for all practical insulators a / b > 0.5, Then,

$$V_c/L = (r_{p1})^{0.5}\ \{0.5*d*b/(b*a)\ \ln(1 + 2ba/db)\}^{0.5}\ N^{0.5} \tag{79}$$

V_c/L therefore depends on conductance $1/r_{p1}$ and parameters of shed a and b. The value of term "$V_c/L\ \ (r_{p1} N)^{1/2}$ depends, very little for actual insulators, on parameters of sheds and on average amounts to 0.8. Therefore,

$$V_c/L = 0.8\ (r_{p1} N)^{1/2} \tag{80}$$

This model shows that the flashover voltage decisively depends on leakage length L .

3.3.2.1 Applications

3.3.2.1.a Flat plate 10 x 1 cm

This model is applied to 10 x 1 cm plate of fig 3.1. From eq. (80) the critical voltage is calculated for different values of resistance.

The relationship between critical voltage and resistance of pollution is shown in Fig. 3.37.

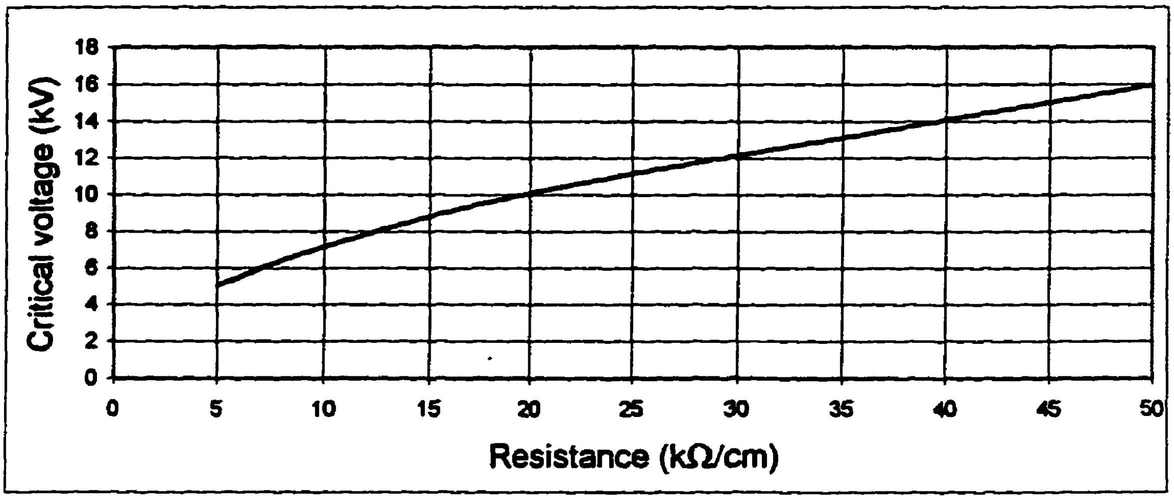

Fig. 3.37 Dependence of critical voltage on pollution resistance for 10 x 1 cm flat plate in Boeheme's model.

3.3.2.1.b Flat plate 10 x 10 cm

This model is applied to 10 x 10 cm plate of Fig. 3.2. From eq. (80) the critical voltage is calculated for different values of resistance.

The calculated values of critical voltage from this model are compared with the experimental results [15] and shown in Fig.3.38

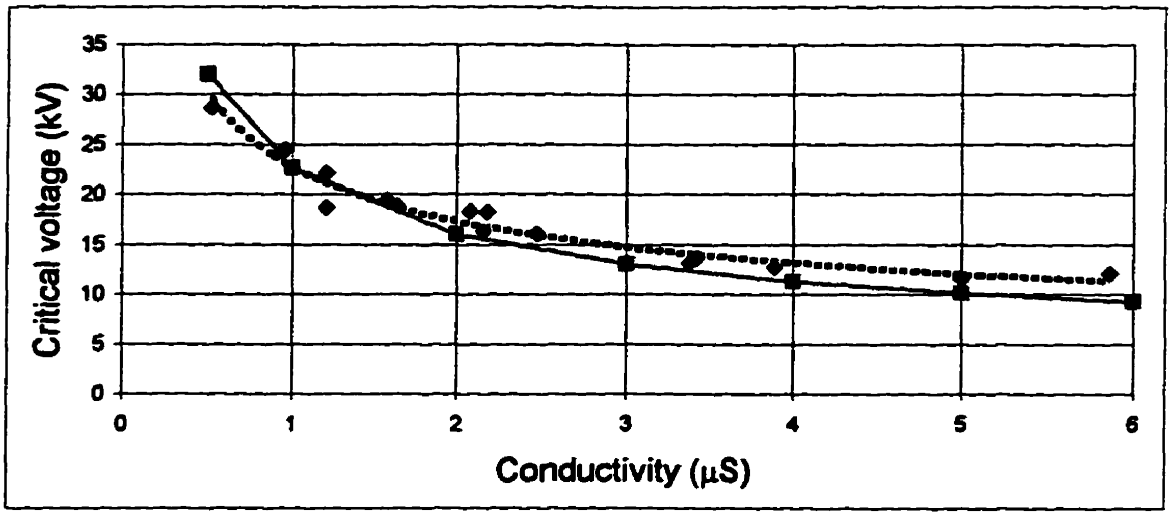

Fig. 3.38 Dependence of critical voltage on conductivity for 10 x 10 cm flat plate.

i) Boeheme & Obenaus model _______

ii) Experimental _ _ _ _ _

3.3.2.1.c Cylinder L = 100 cm, dia. = 15 cm

This model is applied to cylinder of Fig. 3.3. Critical voltage is calculated from eq. (80) for different values of pollution resistance.

The calculated values of critical voltage from this model are compared with the experimental results [9] as shown in Fig. 3.39

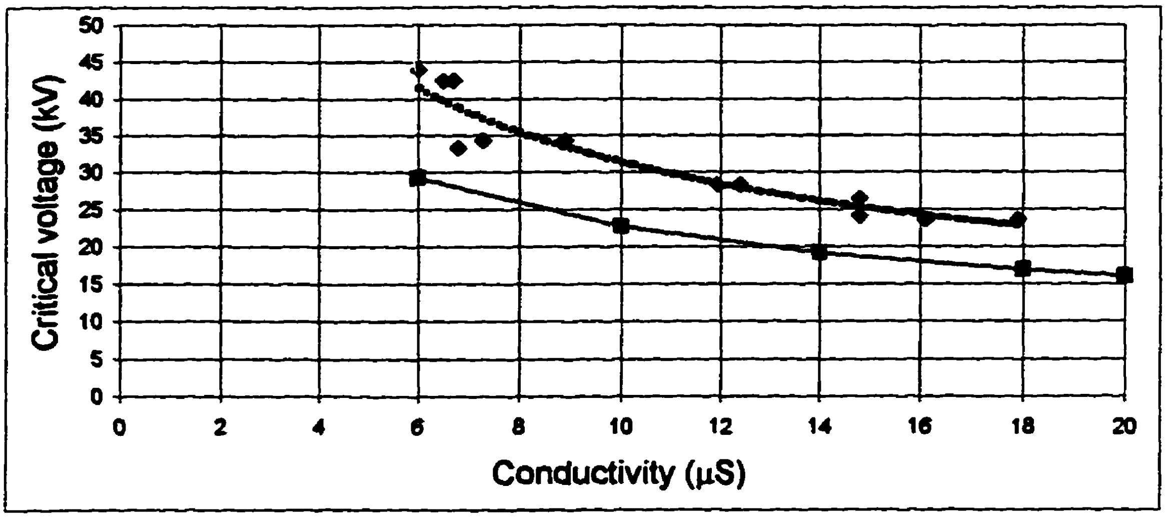

Fig. 3.39 Dependence of critical voltage on conductivity for cylinder L = 100 cm, dia. = 15 cm

i) Obenaus & Boeheme model _______

ii) Experimental _ _ _ _ _

3.3.2.1.d IEEE insulator

This model is applied to IEEE insulator of Fig. 3.4. The critical voltage is calculated from eq. (80) for different values of resistance.

The calculated values of critical voltage from this model are compared with the experimental results [40] and are shown in Fig. 3.40

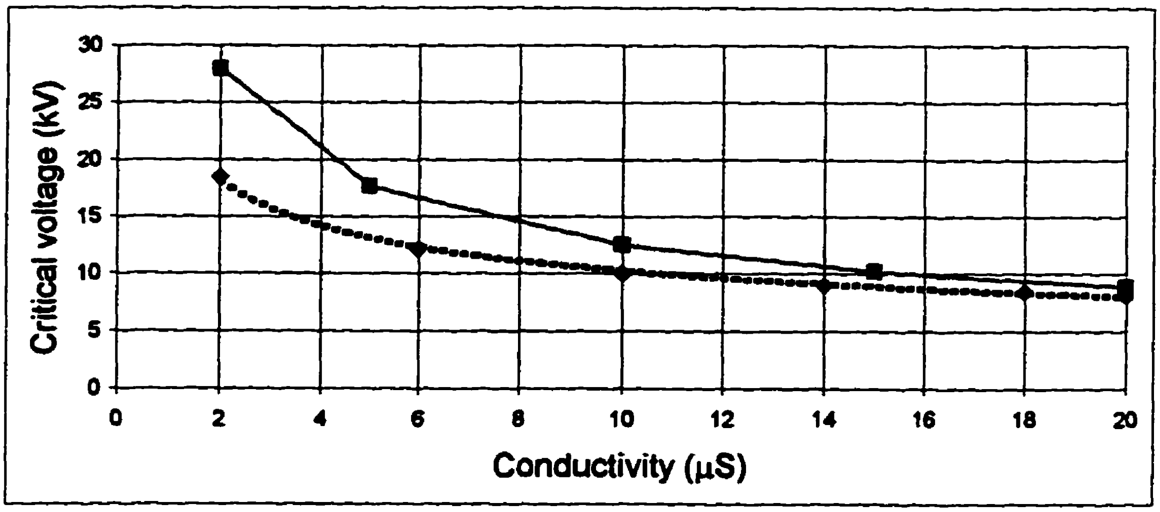

Fig. 3.40 Dependence of critical voltage on conductivity for IEEE insulator.
i) Obenaus & Boeheme model _______
ii) Experimental _ _ _ _ _

The model does not give any calculations for critical arc length and critical current. The critical voltage is only dependent on resistance of pollution and leakage length only. This means that the flashover voltage is not affected by shape, width etc. of insulator.

3.3.3 B F Hampton [13]

The formation of dry bands and subsequent growth of discharges on polluted surface of a flat strip insulator are the main subjects of this model. The following assumptions are made:

The resistivity of pollution layer is constant.

As arc moves it is not shunted any where along its length by wet polluted layer.

Experiments were conducted on a water column of constant resistivity. The flashover voltages as a function of water column lengths are shown in Fig. 3.41

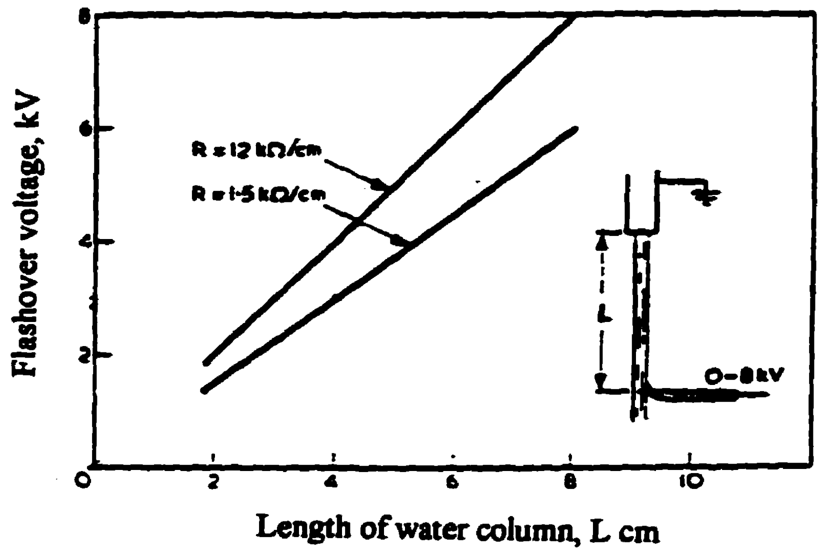

Fig. 3.41Flashover voltage of water column.

The straight lines almost pass through the origin. Since the total resistance of water column is proportional to its length, therefore these lines are also the lines of constant current. At flashover the following observations may be made: a) the arc current and therefore the voltage gradient along the water, is constant for columns of different lengths but the same resistivity, b) the arc current is lower and the voltage gradient along the column is higher for columns having greater resistivity.

The voltage across arc is known to decrease with increase in current, therefore it is possible that the gradient of arc voltage and the gradient of water column will be equal.

It has been shown that when the voltage gradient of resistance surface is greater than that of arc voltage gradient, then the arc propagates. This condition can be written as $E_{arc} < E_p$, Where, E_{arc} is arc gradient and E_p is gradient of resistive water column.

The arc burns in the atmosphere of steam. The voltage gradient in column of arc burning in atmosphere of steam is function of current and has been found to be considerably higher than that of similar arc burning in an atmosphere of air.

Under critical condition, it can be said that the $E_{arc} = E_p$. Since the $E_{arc} = N\,i^{-n}$ and $E_p = r_p\,i$, therefore,

$$N\,i_c^{-n} = r_p\,i_c \tag{81}$$

Where i_c is critical current at flashover, also

$$i_c = (N / r_p)^{1/(n+1)} \tag{82}$$

$$V_c = r_p n L\,i_c = r_p\,L\,(N / r_p)^{1/(n+1)} \tag{83}$$

$$E_c = N^{1/n+1}\,r_p^{n/n+1} \tag{84}$$

The eqs. (82) and (84) are same as in Neumarker's model.

3.3.3.1 Application of model

3.3.3.1.a Flat plate 10 x 1 cm

This model is applied to the flat plate of 10 x 1 cm of Fig. 3.1.

The value of arc constants are, N = 530, and n = 0.24

For $r_p = 5000$, from eq. (83) the value of critical voltage, $V_c = 8183$ volts and the critical current, $i_c = 0.163$ amp.

For different values of resistance, the critical values of voltage and current can be calculated from eqs. (82) and (83)

The value of resistance and critical voltage is plotted and shown in Fig. 3.42

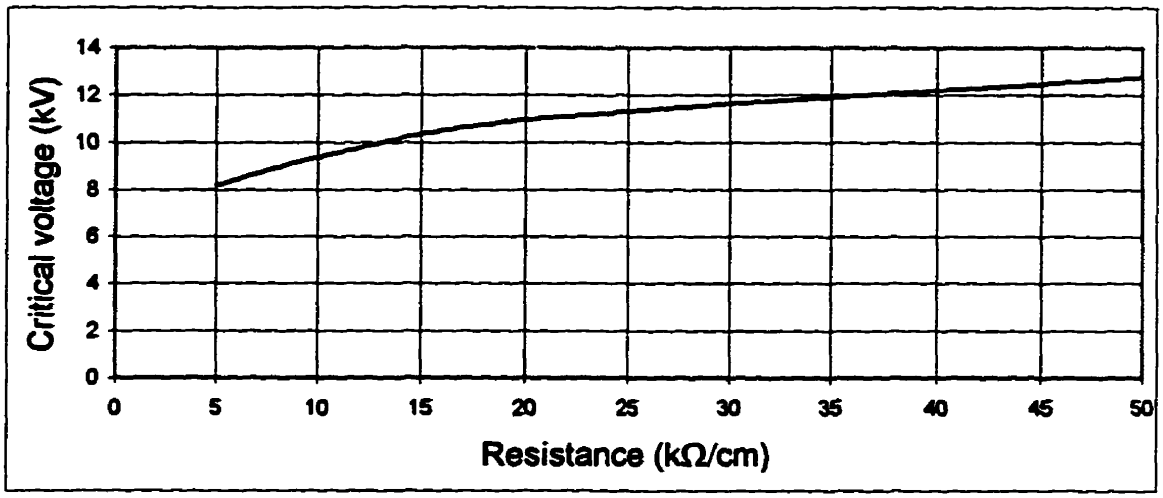

Fig. 3.42 Dependence of critical voltage on pollution resistance for 10 x 1 cm flat plate in Hampton's model.

3.3.3.1.b Flat plate 10 x 10 cm

This model is applied to 10 x 10 cm flat plate of Fig.3.2. The calculated values of critical voltage from this model are compared with the experimental values [15] and shown in Fig.3.43

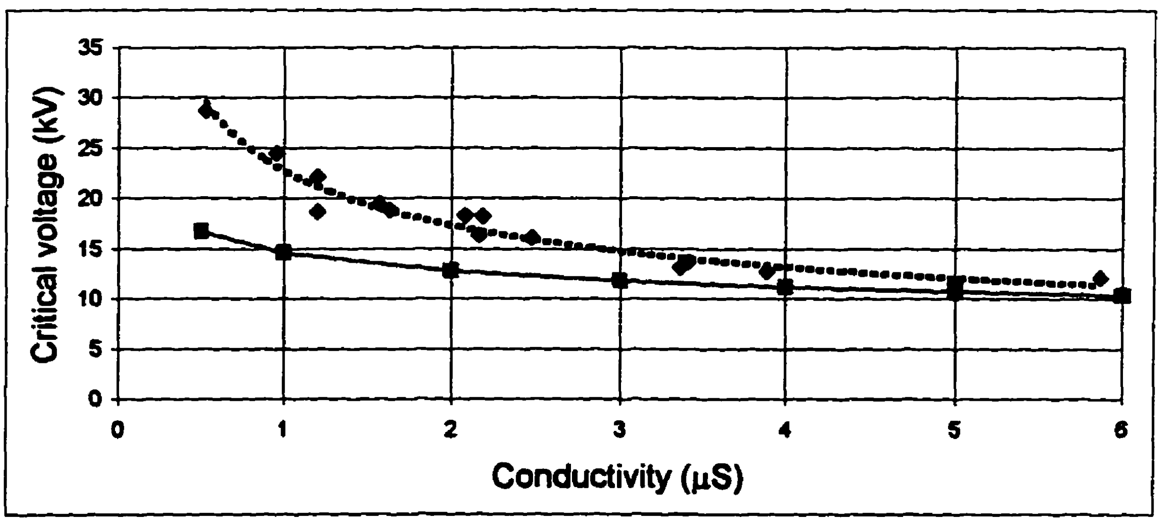

Fig. 3.43 Dependence of critical voltage on conductivity for 10 x 10 cm plate.

i) Hampton model _______

ii) Experimental _ _ _ _ _

3.3.3.1.c Cylinder L = 100cm, dia. = 15 cm

This model is applied to cylinder of Fig. 3.3. The calculated values from this model are compared with the experimental results [9] and shown in Fig. 3.44

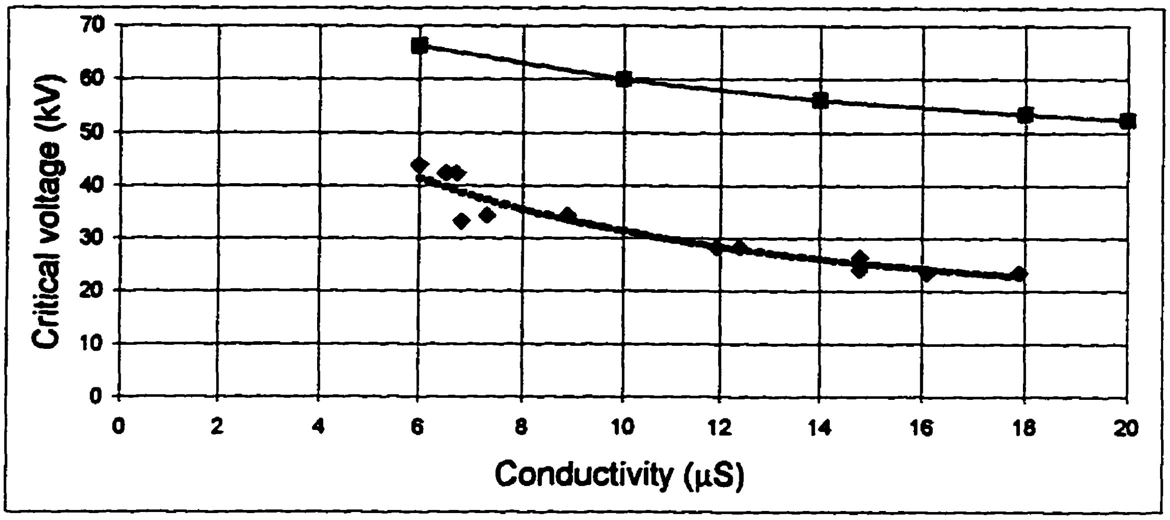

Fig. 3.44 Dependence of critical voltage on conductivity for cylinder
i) Hampton model ______
ii) Experimental _ _ _ _ _

3.3.3.1.d IEEE insulator

This model is applied to IEEE insulator of Fig. 3.4. The critical voltage and current are calculated from eq. (82) and (83).

The calculated values from this model are compared with the experimental results [40] and shown in Fig. 3.45.

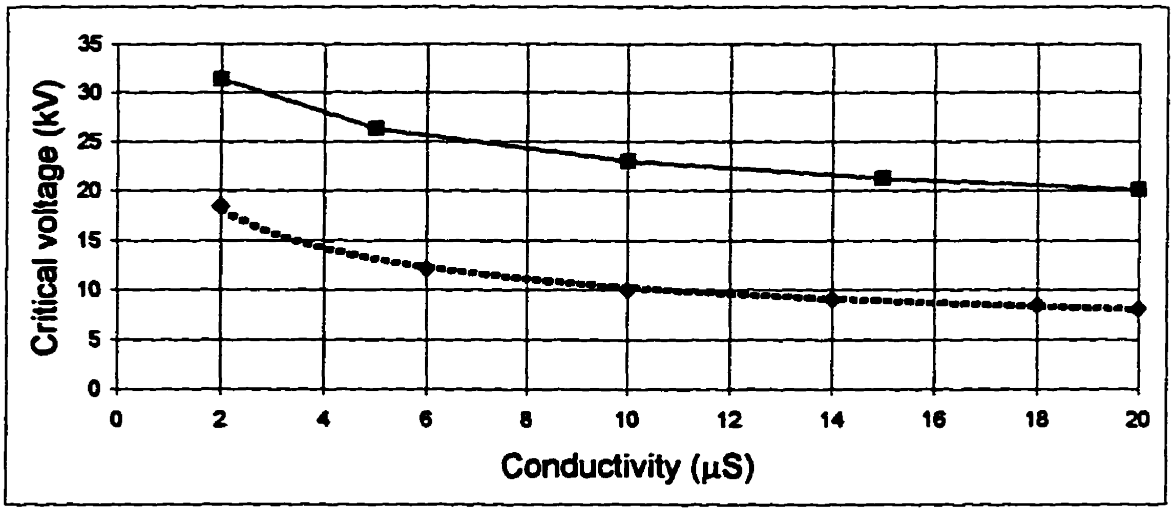

Fig. 3.45 Dependence of critical voltage on conductivity for IEEE insulator.
i) Hampton model ______
ii) Experimental _ _ _ _ _

This model basically gives a criteria for defining the voltage which is necessary to maintain an arc. The model does not describe the mechanism of movement of arc. It does not consider arc velocity.

This voltage is higher than in previous models because higher values of arc constants used in the model.

3.3.4 Herbert Woodson [17]

A mathematical model to consider the electrical discharge mechanism on dry bands across the wet contaminated insulation is presented. This model is based on constant surface resitivity. The constants used in the model were calculated from experiments. A flat plate model with circular concentric electrodes was used.

When one or more discharges occur across a dry zone, the marked increase in the current causes increased heating where the discharge enters the adjacent wet polluted zone, and the dry zone width increases by vaporizing the water until either it becomes too wide or it attains a critical length beyond which the discharge rapidly crosses the remaining portion of polluted surface and the flashover occurs. There appears to be a critical surface resistance below which flashover may occur and above which it will not. The geometry of insulator model considered is shown in Fig.3.46

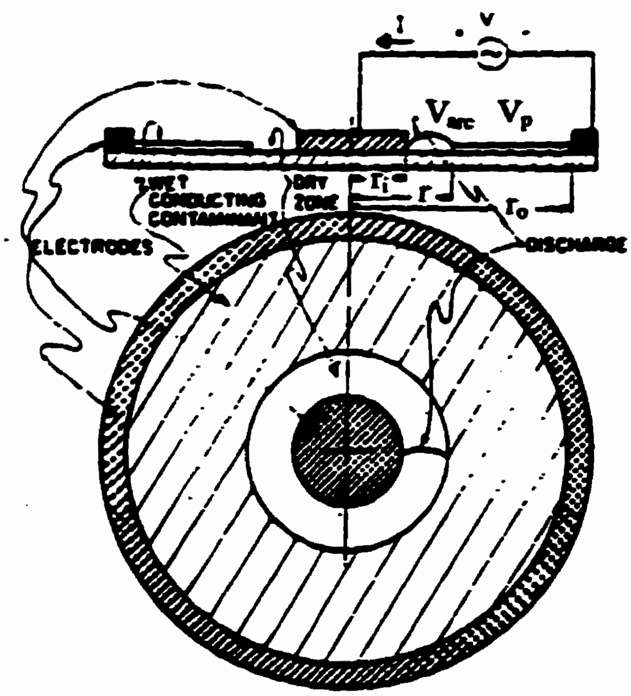

Fig 3.46 Two concentric electrodes arrangement in Woodson's model

The equivalent circuit diagram for above arrangement is shown in Fig.3.47

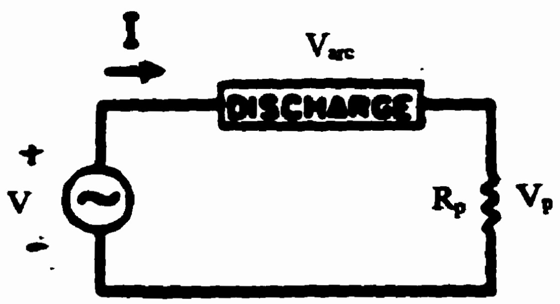

Fig. 3.47 Equivalent circuit of Woodson's model.

The arc current is in the range of 20 to 200 mA. Fig.3.48 shows the volt amp characteristic for three discharge lengths. For r_1, there are two intersections U and S of volt amp characteristic of discharge with volt amp characteristic of source and wet contaminant. According to the Kaufmann criteria for stability of an electric arc, the solution of U is unstable and for S it is stable. For r_2, the two curves are tangential leading to one stable solution. For r_3, there is no intersection and thus no discharge. Discharge across a dry zone with an initial length $r_1 - r_i$ can increase upto a length r_2 and if $r_2 > r_o$ then flashover may occur.

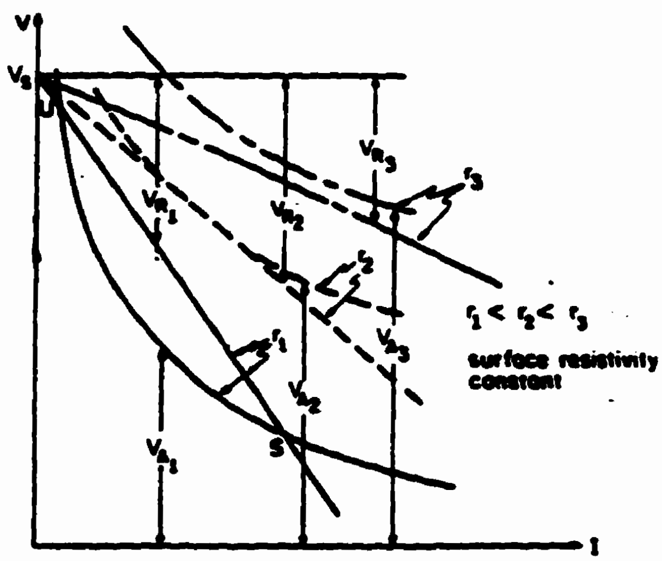

Fig.3.48 Volt - amp. characteristic for three discharge lengths.

From above circuit diagram the following eq. can be written.

$$V = V_{arc} + V_p \tag{85}$$

$$V_{arc} = N\, I^{-n} (r - r_i) \tag{86}$$

$$V_p = F(r, r_d, r_o) \tag{87}$$

Where,

V_p = voltage drop in pollution layer

r_i = radius of inner electrode

r_o = radius of outer electrode

r_d = radius of discharge

ρ_s = surface resistivity

It is assumed that the current density is constant and that the function F is independent of r_d, the radius of arc root and thus of current i. Therefore F depends only on dimensions only. It is further assumed that,

$$F = C\,(r_o - r)^m \tag{88}$$

Where C and m are constants and were determined experimentally.

The above four equations constitute the mathematical model, with parameters N, m, n, and C to be determined experimentally.

For a given constant resistivity, and arc length, reduction in applied voltage yields a minimum value of voltage below which arc will extinguish, as shown in Fig. 3.49

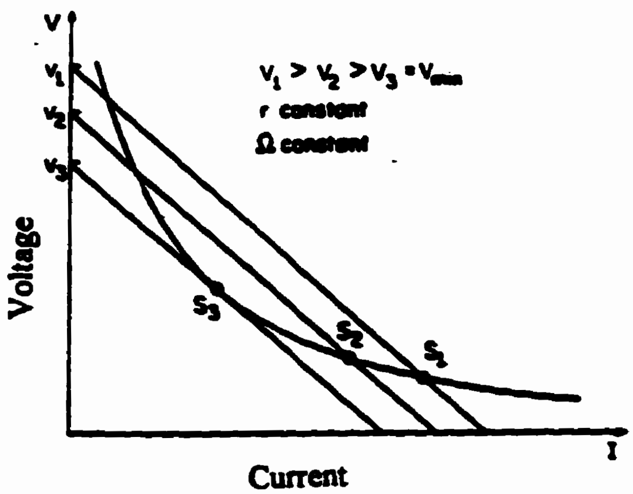

Fig. 3.49 Dependence of applied voltage on arc extinction

For each different arc length there will be a minimum value of applied voltage .

This when plotted with respect to r will be as shown in Fig. 3.50.

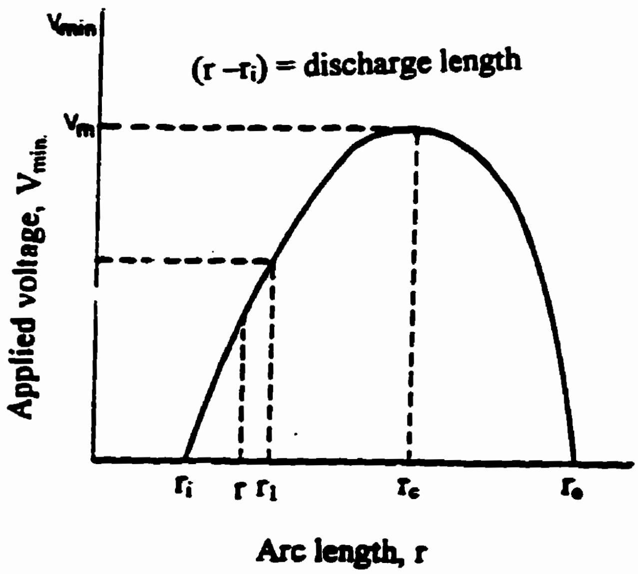

Fig. 3.50 Relationship between applied voltage and arc length.

Thus for a given surface resitivity and insulator geometry there is a voltage maximum voltage V_m called critical voltage, V_c occurring at discharge length $x_c = r_c - r_i$ below which discharges ultimately extinguish and above which discharges will develop to flashover.

Critical voltage can be calculated by solving following equations simultaneously

$$V_{min} = V_{arc} + V_p \tag{89}$$

$$0 = \frac{\partial Varc}{\partial I} + \frac{\partial Vp}{\partial I} \tag{90}$$

Using eq.s (85) and (86) in above results in the following:

$$V_{min} = (n+1)\, F(\rho_s/n)^{n/n+1} \{ N (r - r_i)^{1/n+1} \} \tag{91}$$

V_m can be found by differentiating (91) with respect to r and equating it to zero. This will give the value of critical length r_c. Since the dependence of F on r is not known therefore solution can be found symbolically only,

$$F(r_c, r_o) + n\,(r_c - r_i)\, \frac{\partial F}{\partial r}(r_c, r_o) = 0 \tag{92}$$

Assuming (86) has been solved for r_c, the V_c can be given as,

$$V_c = (n+1) \{ F (r_c, r_o)\, \rho_s /n \}^{n/(n+1)} \{N (r_c - r_i) \}^{1/(n+1)} \tag{93}$$

Associated with r_{max} is current i_{max}

$$i_{max} = \{ (n+1)\, N\, (r_{max} - r_i) / r \}^{1/n} \tag{94}$$

Solution of (85) at r_{max} gives,

$$F(r_{max}, r_o) = (n/n+1)\, [N (1 + N)]^{-1/n} [(r / \rho_s)^{-n} (r_{max} - r_i)^{-1/n}] \tag{95}$$

These equations together with experimental results are used to calculate the values of constants.

Based on experiments an empirical formula is derived for arc voltage as,

$$V_{arc} = 200\, i^{0.8} (r - r_i) \quad (96)$$

Thus arc constants are, N = 200 and n = 0.8

Also, following eqs. were derived :

$$F(r_{max}, r_o) = 1.6*10^{-2} (r_0 - r_{max})^{1.4} \quad (97)$$

and, $(r_c - r_i) = (r_o - r_i) / (1+ m\, n)$ (98)

3.3.4.1 Application

3.3.3.4.1.a Flat plate 10 x 1 cm

This model is applied to flat plate of Fig. 3.1. It is difficult to apply flat plate model geometry. However some simplifying assumptions are made to apply the equivalent flat plate model. To represent this flat plate closely to this model it would be desirable to have the distance between two electrodes to be same i.e. L be equal to $r_o - r_i$, and the area between two electrodes be equal to 10 cm^2 i.e. $\pi (r_o^2 - r_i^2) = 10$. Under this case it is not feasible to satisfy both conditions.

Let us assume $r_i = 2$, then from above, $r_o = 12$, $n = 0.8$, $m = 1.4$

From eq. (98), $(r_c - r_i)$ = critical arc length is calculated as 4.72. Function $F(r_c)$ is calculated from eq. (97) and is equal to 0.2577.

For different surface resistivity per square (in ohms per square) the critical voltage and currents can be calculated.

The critical voltage and resistance values are plotted in Fig.3.51

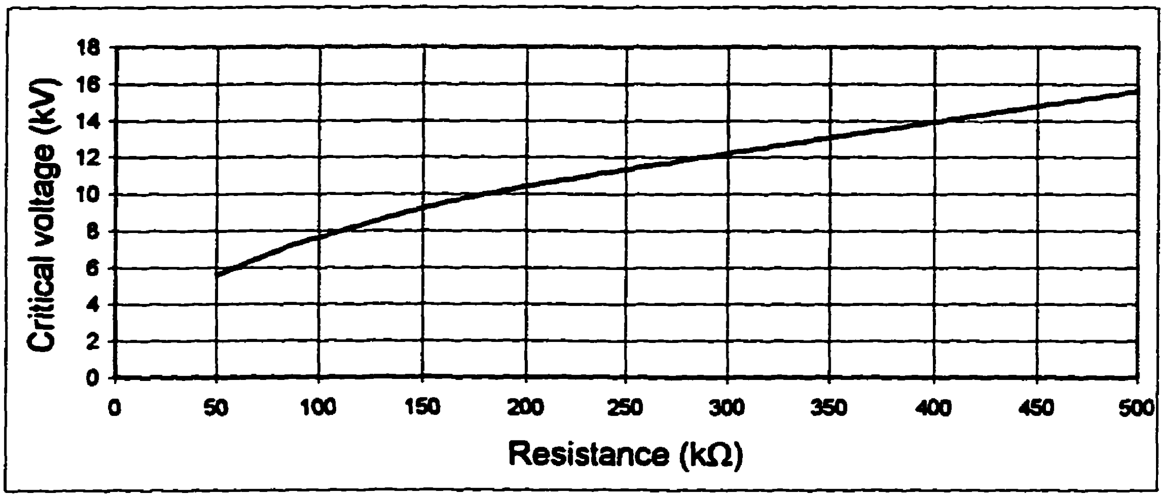

Fig. 3.51 Dependence of critical voltage on pollution resistance for 10 x 1 cm flat plate in Woodson's model.

3.3.4.1.b Flat plate 10 x 10 cm

This model is applied to flat plate of Fig. 3.2. It is difficult to apply flat plate model geometry. However some simplifying assumptions are made to apply the equivalent flat plate model. To represent this flat plate closely to this model it would be desirable to have the distance between two electrodes to be same i.e. L be equal to $r_o - r_i$, and the area between two electrodes be equal to 100 cm^2, This means that $\pi\ (r_o^2 - r_i^2) = 100$ and under this case it is not feasible to meet both conditions. Therefore, the value of r_i is assumed as 2 cm which results in r_o of 5.98 cm.

From eqs. (97) and (98) the critical voltage is calculated for different values of pollution resistance.

The calculated values of critical voltage from this model are compared with the experimental results [15] and shown in Fig. 3.52

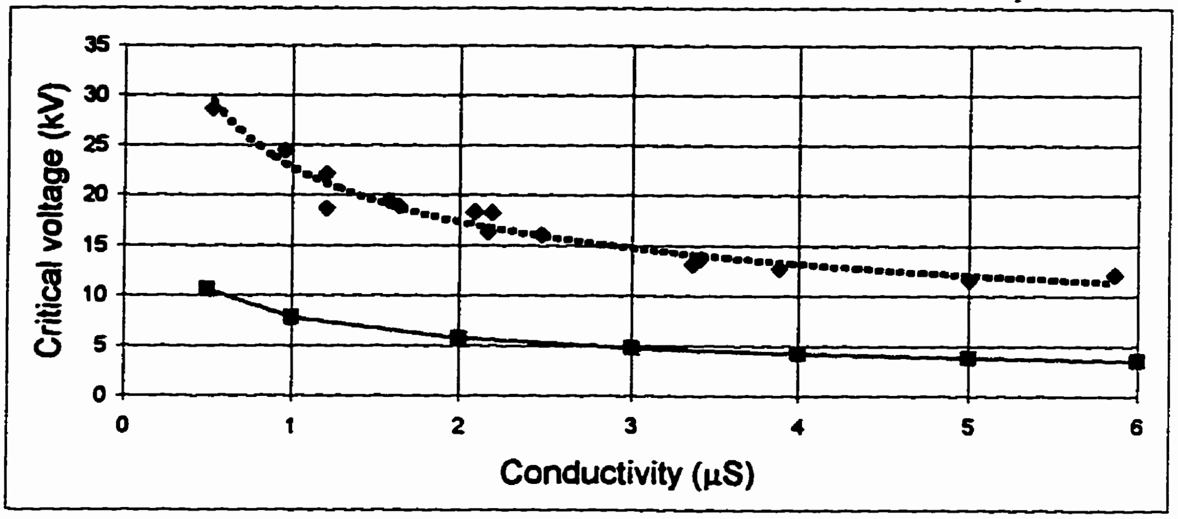

Fig. 3.52 Dependence of critical voltage on pollution resistance for 10 x 10 cm plate.
i) Woodson's model _______
ii)Experimental _ _ _ _ _

3.3.4.1.c Cylinder, L = 100 cm, dia. = 15 cm

This model is applied to cylinder of Fig. 3.3. Assuming r_i = 2 cm, r_o = 38.79 cm. From eqs. (97) and (98) the flashover voltage is calculated for different values of resistance.

The calculated values from this model are compared with experimental results [9] and shown in Fig. 3.53.

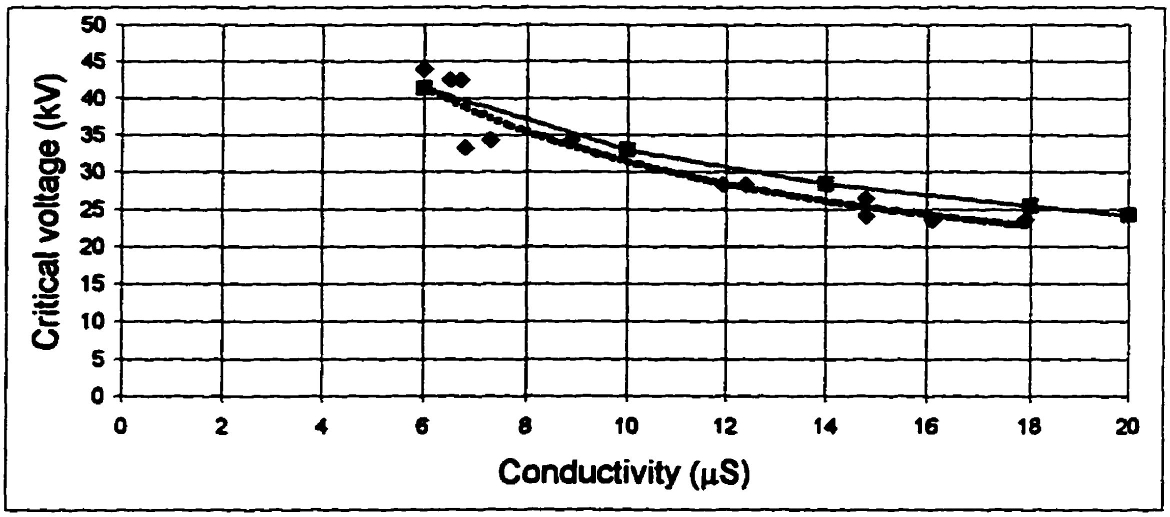

Fig. 3.53 Dependence of critical voltage on conductivity for cylinder L = 100 cm, dia. 15 cm.

i) Woodson's model _______

ii) Experimental _ _ _ _ _

3.3.4.1.d IEEE insulator

This model is applied to IEEE insulator of Fig.3.4. The top metal part of insulator is of about 110 mm dia. Therefore if $r_i = 5.5$ cm is assumed then r_o is 22.95 cm, which is close to dia. of 25.4 cm of insulator. From eqs. (97) and (98) the critical voltage is calculated for different values of resistance.

The calculated value of critical voltage from this model is compared with the experimental results [40] and shown in Fig. 3.54

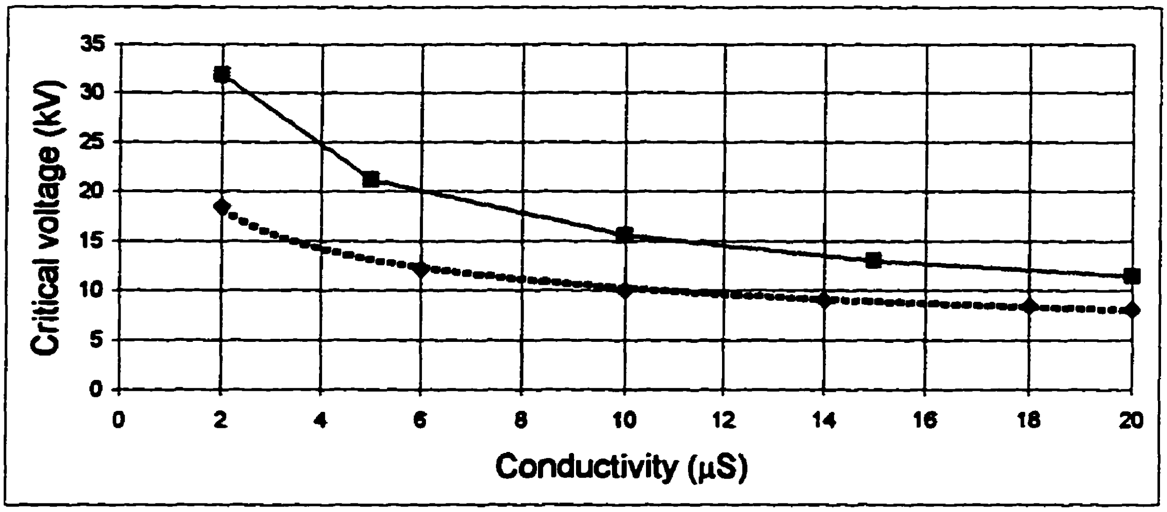

Fig. 3.54 Dependence of critical voltage on conductivity for IEEE insulator.
i) Woodson's model ______
ii) Experimental _ _ _ _ _

3.4 Z Renyu & G Zhicheng Model

Based on experimental observations and investigations empirical formulae for ac and dc arc characteristics are presented. The arc characteristic for ac and dc differ from each other. For ac the criteria for re ignition and recovery of arc are considered. It has been shown that most important factor is recovery condition. A formula for calculating the resistance of pollution layer is derived which can be used to calculate the flashover voltages. The following assumptions are made:

The voltage drop of anode and cathode are not considered.

Arc does not drift from surface when traveling along leakage path.

Usually the real insulators with complex shapes are converted to rectangular model Fig.3.55 . The area of rectangular is equal to the surface area of insulator.

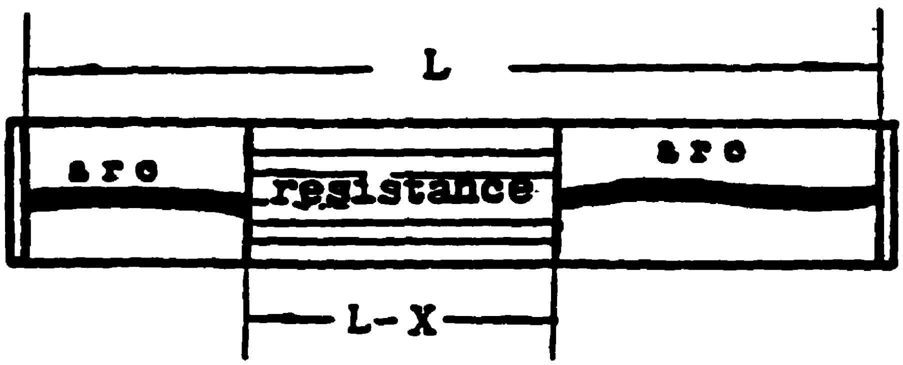

Fig. 3.55 Renyu's model

The flashover process can be described considering a part of polluted insulator (resistance) in series with the arc as shown in Fig.3.55. Based on experiments following empirical equations are given for arc,

For dc,

$$Varc = 138.x.i^{-0.69} \quad (100)$$

For ac,

$$Var_c = 140.x.i^{-0.67} \quad (101)$$

The arc characteristics depend on surroundings. The arc constants measured in this model are different than others (as others measured arc burning in air or steam between fixed electrodes). The conductivity of remaining pollution layer changes with the arc movement. The conductivity at flashover is different than the normal temperature conductivity. The relationship between these two conductivity can be represented by the following empirical formula.

$$\sigma_c = 1.25\ \sigma \quad (103)$$

Where, σ_c is conductivity at flashover and σ is conductivity measured ordinarily.

Cap - pin insulator fig 3.56 can be represented as shown in fig, 3.57.

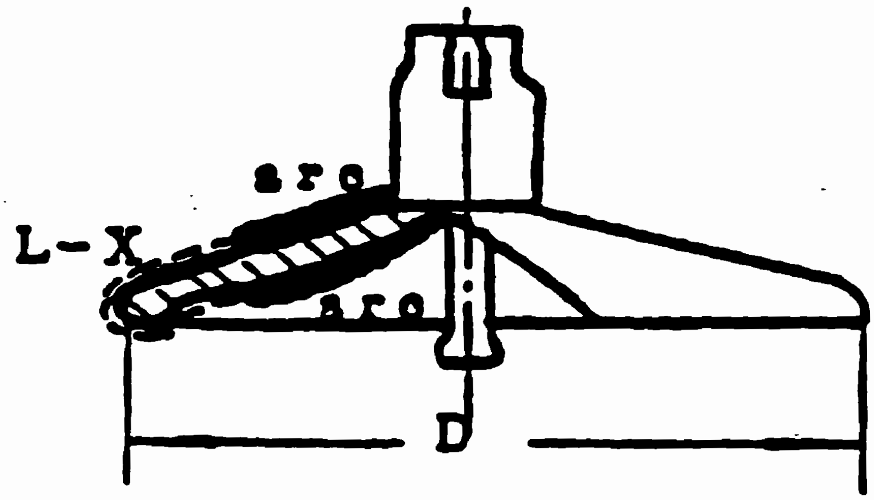

Fig.3.56 Cap and pin insulator.

The surface area under Fig. 3.57 is the total surface area (top + bottom) of

insulator.

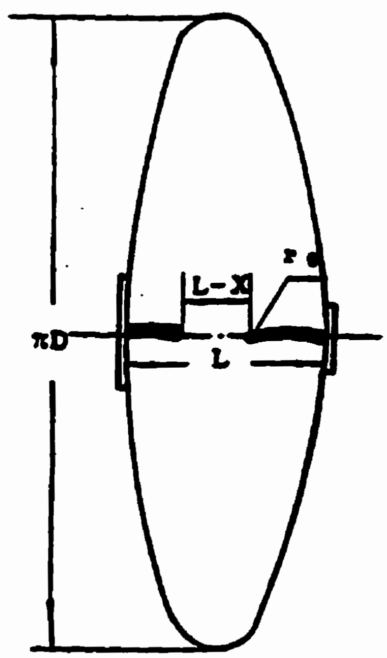

Fig.3.57 Plane model of insulator.

In Fig.3.57, L represents the leakage length along the insulator. πD is circumference, D is diameter of insulator and r_d is radius of arc root. Resistance of pollution layer can be calculated from following,

$$R_p(x) = (1/\pi\ \sigma_c)\ \ln.[(L - x)/ r_d] \tag{104}$$

Where,

$R_p(x)$ = resistance of pollution layer at arc length x.

From [15] r_d can be calculated as,

$$r_d = (i/1.45\pi)^{1/2} \tag{105}$$

Eq. (104) is suitable for models if insulator has enough width as in case of pin cap insulators.

Flashover Criteria

DC flashover:

For dc the eq. for applied voltage in terms of arc voltage and pollution layer voltage is given as,

$$V = N\ x\ i^{-n} + R_p(x)i \tag{106}$$

For a constant length of x, the minimum required voltage to maintain the arc can be calculated by differentiating V with respect to "i" and dv/di = 0.

$$i_{min} = \{(n\ N\ x)/ R_p(x)\}^{1/n+1} \tag{107}$$

and, $$V_{min} = [1+1/n][n\ N\ x]^{1/(n+1)}\ R_p(x)^{n/(n+1)} \tag{108}$$

Further when $d\ V_{min}/dx = 0$, then the critical arc length x_c can be calculated from the following condition,

$$R_p(x) = -\ n\ x\ \ dR_p(x)/dx \tag{109}$$

Substitution of x_c in eq.s (107) and (109) will result in eq. for critical current i_c as,

$$i_c = \{(n\,N\,x_c / R_p(x_c)\}^{1/(n+1)} \qquad (110)$$

and, $$V_c = (1+(1/n))\,(\,n\,N\,x_c)^{1/(n+1)}\ R_p(x_c)\}^{n/(n+1)} \qquad (111)$$

or, $$V_c = (1+(1/n))\,i_c\,R_p(x_c) \qquad (112)$$

AC Flashover

For ac the eq. (100) can be written as,

$$V_{peak} = N\,x\,i_{peak}^{-n} + R_p(x)i_{peak} \qquad (113)$$

In order to complete an ac flashover both the critical condition of arc stability and arc recovery conditions must be satisfied. The recovery condition can be expressed as function of current,

$$V_{arc} = f(i_{peak}) \qquad (114)$$

Recovery condition of arc, rather than the re ignition is used. The recovery of ac arc without extinguishing when passing through current zero is given as,

$$V_{peak} = 531\ L / i_{peak} \qquad (115)$$

The recovery condition of arc which extinguishes and re ignites when its current passes through zero is,

$$V_{peak} = 1050\ x_c / i_{peak} \qquad (116)$$

The value of $R_p(x)$ can be calculated as for the case of dc using eq. (104). The critical arc length x_c is derived from eq. (113) as in case of dc. The critical ac current and voltage are calculated when both the eq. for flashover (113) and the recovery condition (114) is satisfied. Eq. (117) is obtained from eq.s(113) and (114),

$$N\, x_c\, i_{peak}^{-n} + R_p(x_c) i_{peak} = f(i_{peak}) \tag{117}$$

i_{peak} is calculated from eq. (117) and once ic_{peak} is known then flashover voltage is calculated from either eq. (115) or (116)

If $x_c = 0.507$ L, then both eq.s (115) and (116) are same

3.4.1 Application

3.4.1.a Flat plate 10 x 1 cm

This model is applied to a 10 cm long and 1 cm wide flat plate of Fig. 3.1. Resistance can be calculated using eq. (104). If x = L, Then the arc spans the entire length, the $R_p(x)$ should be zero but the $R_p(x)$ would be infinite as ln(0) = infinity. When x = 0, i.e. no arc, then the maximum resistance of total layer should be $R_p(0)$ at initial stage using normal conductivity σ and not σ_c.

At x << L say x = L/1000, the resistance of pollution is maximum and almost equal to $R_p(L)$ .Eq. (104) is solved by using a computer program . Since the calculated flashover values are obtained using the conductivity values at the time of flashover (1.25 times the normal conductivity) therefore these values are divided by a factor of 1.25 when comparing with experimental results of others.

The plot of critical voltage and resistance is shown in fig 3.58 for dc.

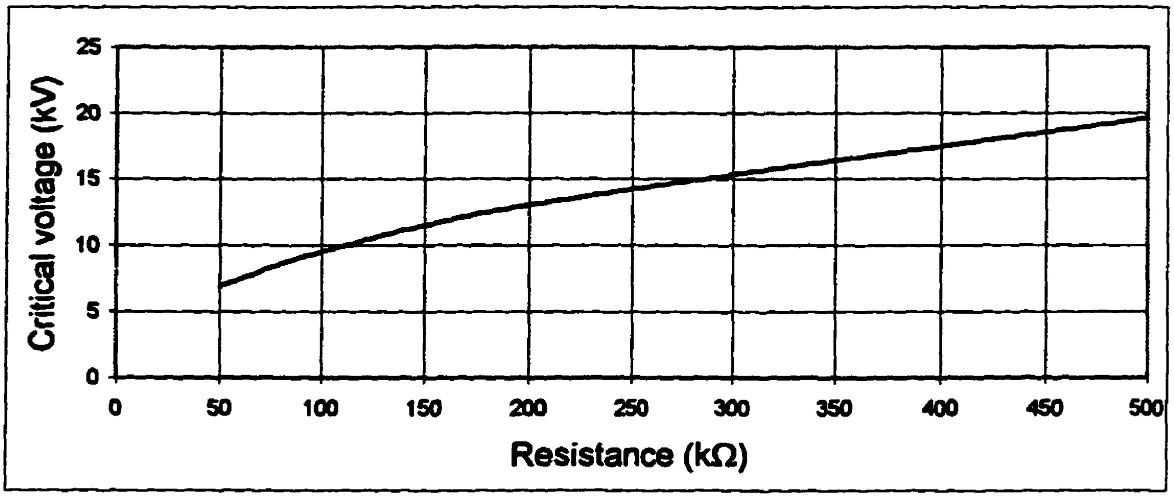

Fig.3.58 Dependence of critical voltage on resistance for dc case for 10 x 1 cm plate in Renyu's model.

The plot of critical voltage and resistance is shown in Fig.3.59 for ac.

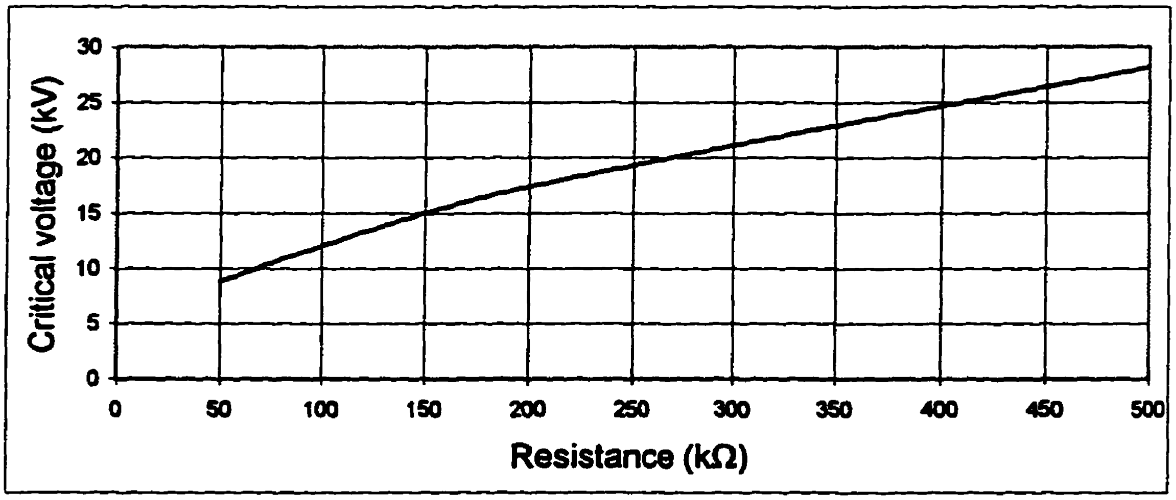

Fig.3.59 Dependence of critical voltage on resistance for ac case for 10 x 1 cm plate in Renyu's model.

3.4.1.b Flat plate 10 x 10 cm

This model is applied to 10 x 10 cm flat plate of Fig.3.2. The critical voltage and current are calculated using computer program.

The calculated values of critical voltage from this program are compared with the experimental results [15]as shown in Fig. 3.60 for dc.

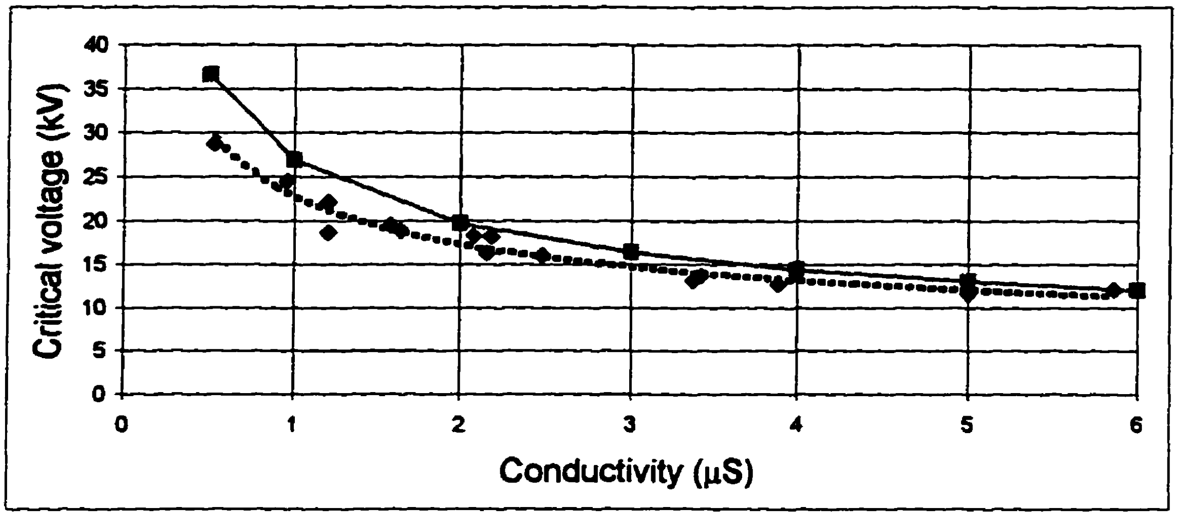

Fig. 3.60 Dependence of critical voltage on conductivity for 10 x 10 cm plate dc.
i) Renyu model ______
ii) Experimental _ _ _ _ _

The critical voltage and current for ac case are calculated from program.

The calculated critical voltage from this model are compared with the experimental results [15] as shown in Fig. 3.61 for ac.

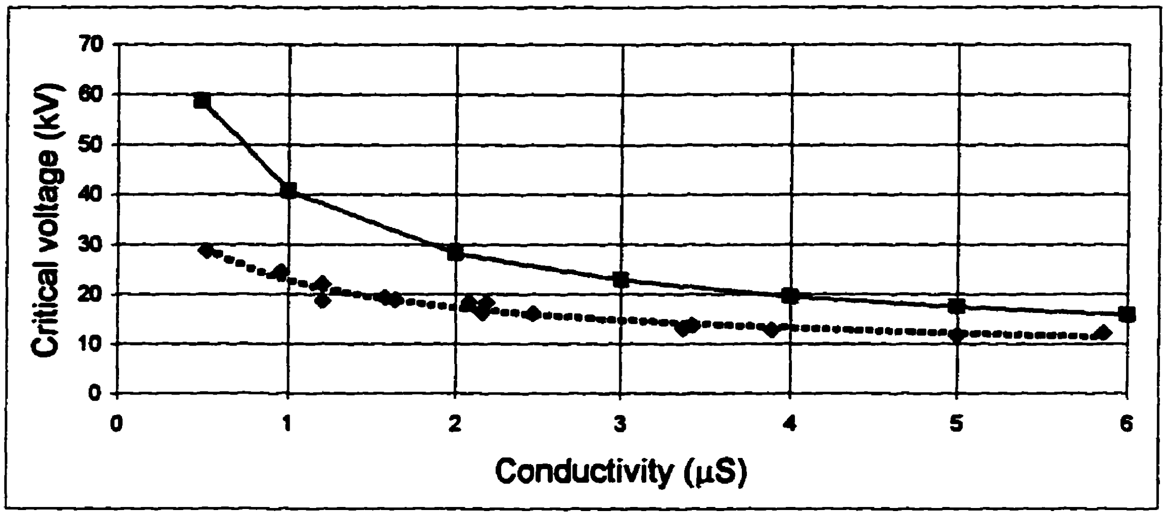

Fig. 3.61 Dependence of critical voltage on conductivity for 10 x 10 cm plate ac case.

i) Renyu model _______

ii) Experimental _ _ _ _ _

3.4.1.c Cylinder L= 100 cm, dia. = 15 cm

This model is applied to cylinder of Fig. 3.3. The calculated critical flashover for different values of resistance are compared with the experimental results.

The calculated values of critical voltage for dc are compared with experiment results [9] and shown in Fig. 3.62

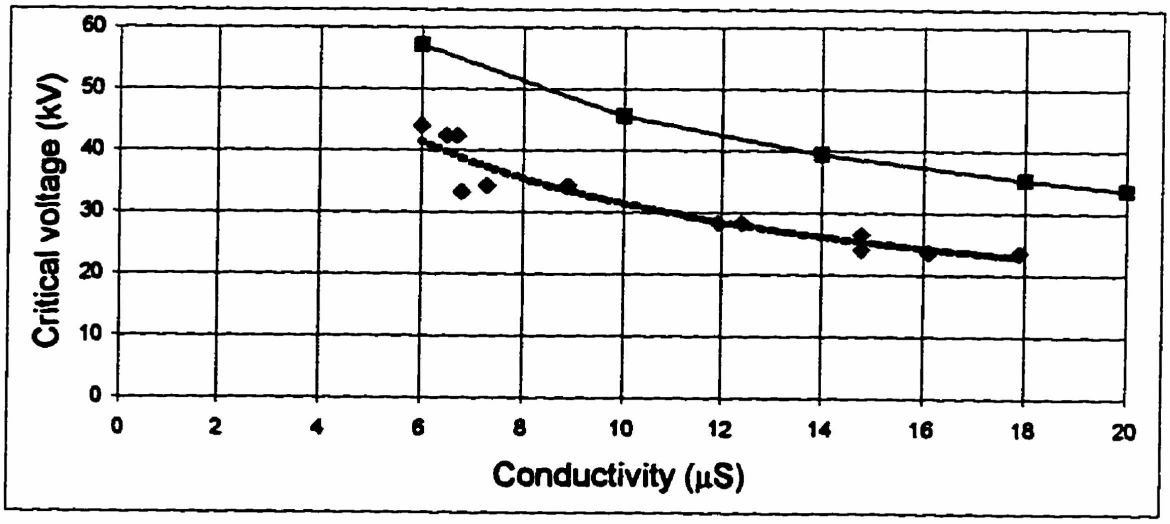

Fig. 3.62 Dependence of critical voltage on conductivity for cylinder, dc case.
i) Renyu model _______
ii) Experimental _ _ _ _ _

The calculated values of critical voltage for ac are compared with experiment results [9] and shown in Fig. 3.63.

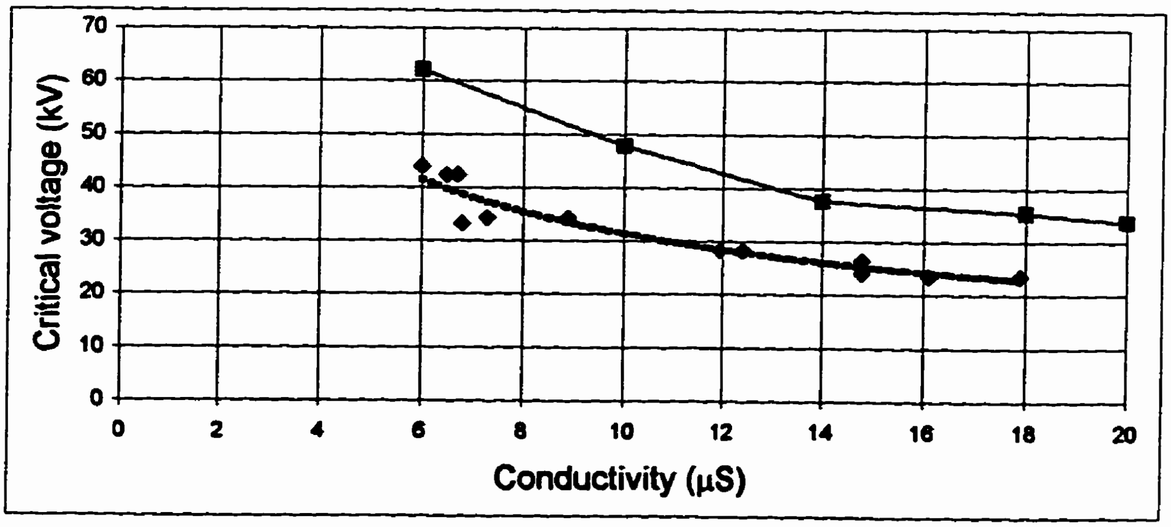

Fig. 3.63 Dependence of critical voltage on conductivity for cylinder, ac case.
i) Renyu model _______
ii) Experimental _ _ _ _ _

3.4.1.d IEEE insulator

This model is applied to insulator of Fig. 3.4. The calculated values of critical voltage and current from program are calculated for different values of pollution resistance.

The calculated values of critical voltage from this model are compared with the experimental results [40] as shown in Fig. 3.64 for dc.

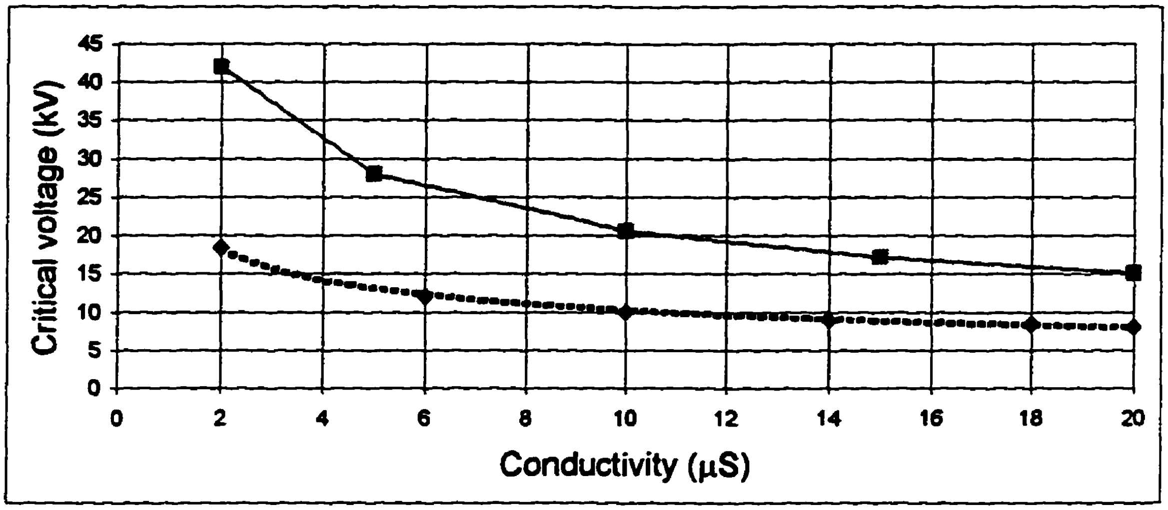

Fig. 3.64 Dependence of critical voltage on conductivity for IEEE insulator, dc case.
i) Renyu model ______
ii) Experimental _ _ _ _ _

<u>For ac case</u>

The calculated values of critical voltage are calculated from computer program for different values of resistance..

The calculated values of critical voltage are compared with the experiment results [40] for ac case and are shown in Fig. 3.65.

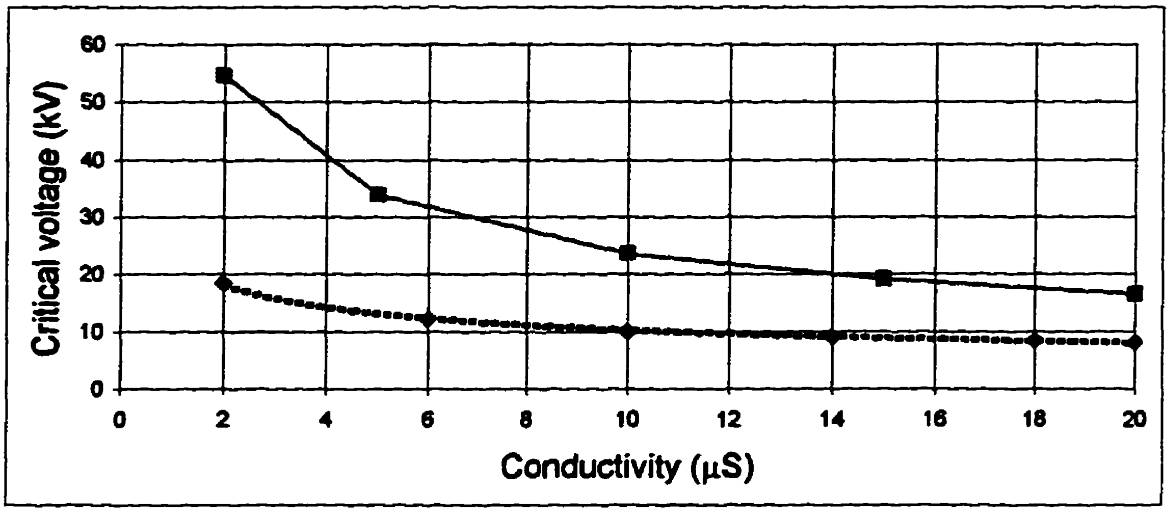

Fig. 3.65 Dependence of critical voltage on conductivity for IEEE insulator, ac case.
i) Renyu model _______
ii) Experimental _ _ _ _ _

3.5 R Sundararjan Model [20]

This model takes into account the configuration of insulator profile at each instant of arc. Since the arc propagation is very rapid time varying phenomenon, and the arc parameters change with the arc travel when sufficient conductive conditions for propagation exist. The variation of arc parameters e.g. arc resistance, pollution resistance, etc. with arc travel time is considered in this model together with the necessary conditions for arc movement. The concept of Obenaus i.e. a dry band arc in series with polluted insulator surface as shown in Fig. 3.66 is considered. The assumptions made in the model are:

Constant resistance per unit length is assumed.

Single arc dominant, effect of multiple arc and multi band assumed to result in single arc and single band.

Uniform pollution distribution assumed.

Resistance of source neglected as stiff source is assumed.

Varying thermal properties of arc and pollution layer not considered, e.g. conductivity changes with temperature.

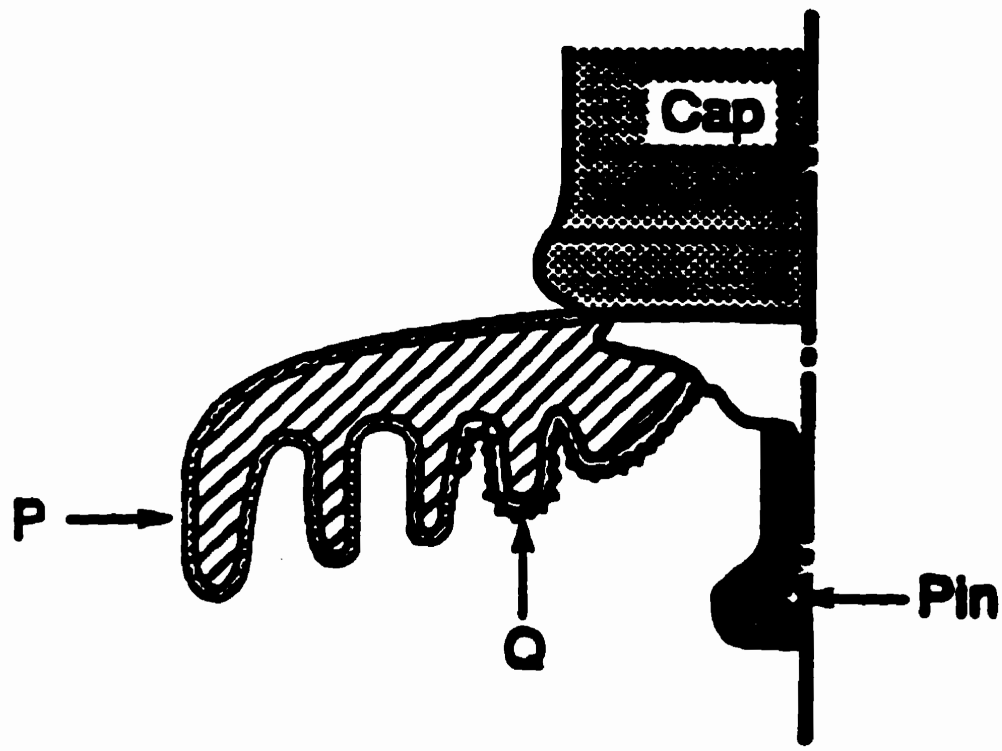

Fig. 3.66 Insulator showing an arc and dry band of an insulator

The equivalent circuit of above insulator is shown in Fig.3.67

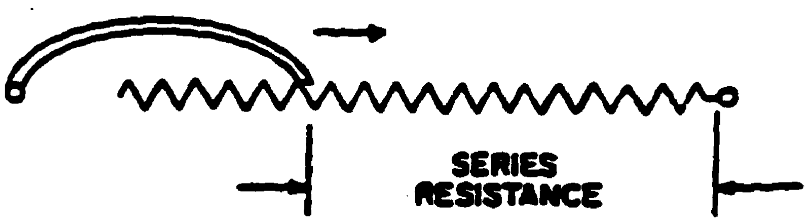

Fig. 3.67 Basic model of an arc in series with polluted surface (resistance)

For a given voltage and conductivity, the arc propagation criteria is checked. When arc propagates its length is checked and if the ac length is almost equal to 2/3 L then it represents the flashover. If the arc length is lower than the prescribed flashover length then, the arc resistance, arc current, etc. are calculated for that particular instant. With these new parameters, the above mentioned steps are repeated. In case the arc propagation criteria is not satisfied then the applied voltage is increased and the above steps are repeated.

A uniform resistance of pollution is considered.

Calculation of flashover voltage

The flashover voltage is calculated in the following steps,

Eq. for applied voltage is written as,

$$V = V_{ad} + V_{cd} + R_a \times i + i(R_p + R_s) \qquad (118)$$

Where,

V = applied voltage, V

V_{cd} = cathode drop, V

V_{ad} = anode drop, V

i = current entering pollution layer, A

R_a = arc resistance, ohm

R_p = pollution layer resistance. Ohm

R_c = internal source resistance

Assuming a stiff source, the internal resistance, R_c can be neglected, and thus the current at instant is given by,

$$i = (V - V_{cd} - V_{ad}) / (R_a x + R_p) \quad (119)$$

At time t = 0, for any given conductivity and applied voltage, the current is calculated using the following initial values,

x = L / 100

R_a = 100 ohm / cm

V_{cd} = 700 V

V_{ad} = 200 V

R_p is calculated as ,

$$R_p = (1 / \sigma) FF \quad (120)$$

Where,

$$FF = \int_x^L dl / 2\pi r$$

L = leakage length of insulator

dl = incremental leakage length

r = radius at distance dl

The form factor is calculated at every time step depending upon the arc length. The arc length varies with time and therefore the form factor also varies. Form factor at each step is calculated with the help of computer program.

For current calculated at each step. The arc voltage gradient E_a is calculated as,

$$E_a = N I^{-n} \qquad (121)$$

Where, N = 63 and n = 0.5 N and n are arc characteristic constants.

Pollution gradient E_p is calculated as, [19]

$$E_p = N^{1/n+1} r_p^{n/n+1} \qquad (123)$$

Where,

r_p = uniform pollution resistance per unit length

r_p is calculated from R_p as,

$$r_p = R_p / (L - x) \qquad (124)$$

If Ep > Ea i.e. if the gradient of pollution is greater than the arc gradient, then arc will propagate. This is due to ionization of path ahead of arc by increasing the current at every instant, enabling the arc to proceed.

If Ea ≈ Ep, then the arc extinguishes, the supply voltage is increased and above steps are repeated.

Ep > Ea, then the arc propagates and if the length of arc is almost equal to 2 /3 of leakage length, then it represents flashover. If the length of arc is less than this propagation length, then the dynamic change in arc resistance is calculated from,

$$d R_a /dt = R_a / T - R_a^2 i^{n+1} /(T N_x) \qquad (125)$$

Where,

T = arc time constant, = 100μs

N_x = static arc eq., given as = 60 V A $^{0.8}$

The new arc resistance is calculated as,

$$R_a \text{ (new)} = R_a \text{ (old)} + dR_a \qquad (126)$$

The new current is calculated using the new form factor, new arc resistance, new R_p. These values are calculated for each increment dt in time "t" i.e. $t_2 = t_1 + dt$,. Arc velocity = mobility * E_a. For a known mobility 5 - 50 cm ^{2} / v /s and arc length traveled, the increment in time dt can be calculated. For each step the arc propagation criteria is checked and flashover voltage calculated.

3.5.1 Application

3.5.1.a Flat plate 10 x 1 cm

The model is applied to 10 x 1 cm plate of Fig. 3.1 The following initial values are considered,

x = L / 100, Mobility = 50, R_a = 100, V_{cd} = 700, V_{ad} =200, N =63, n = 0.5

A program is written to solve the model equations and the calculated flashover voltages for different conductivity values.

The flashover voltage and resistance is plotted in Fig. 3.68

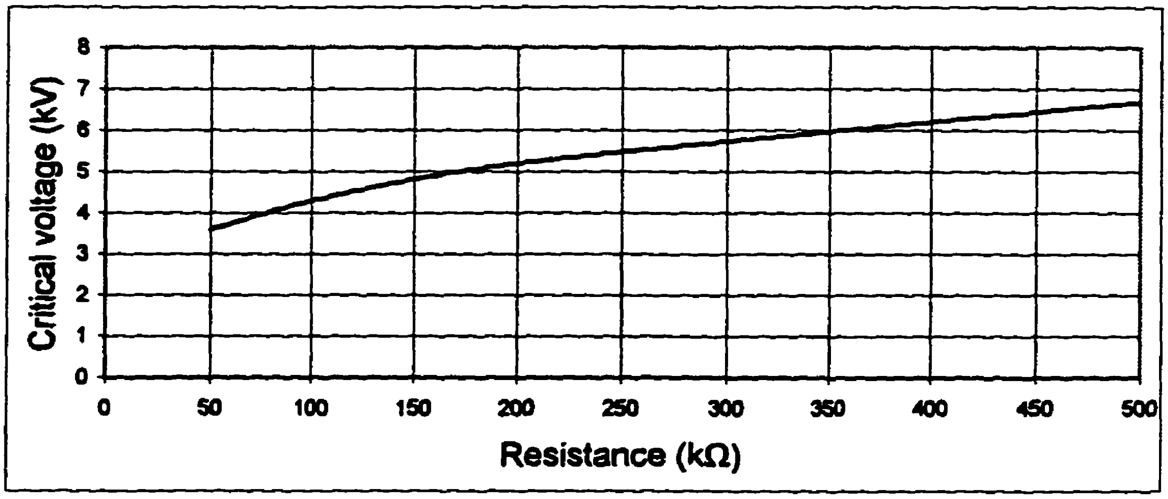

Fig. 3.68 Dependence of critical voltage on resistance for 10 x 1 cm flat plate in Sundararajan model.

3.5.1.b Flat plate 10 x 10 cm

This model is applied to flat plate of 10 x 10 cm of Fig. 3.2. For flat plate form factor is 1. Same initial values as for 10 x 1 cm are considered. The calculated values of critical voltages are compared with the experimental values [15] as shown in Fig. 3.69.

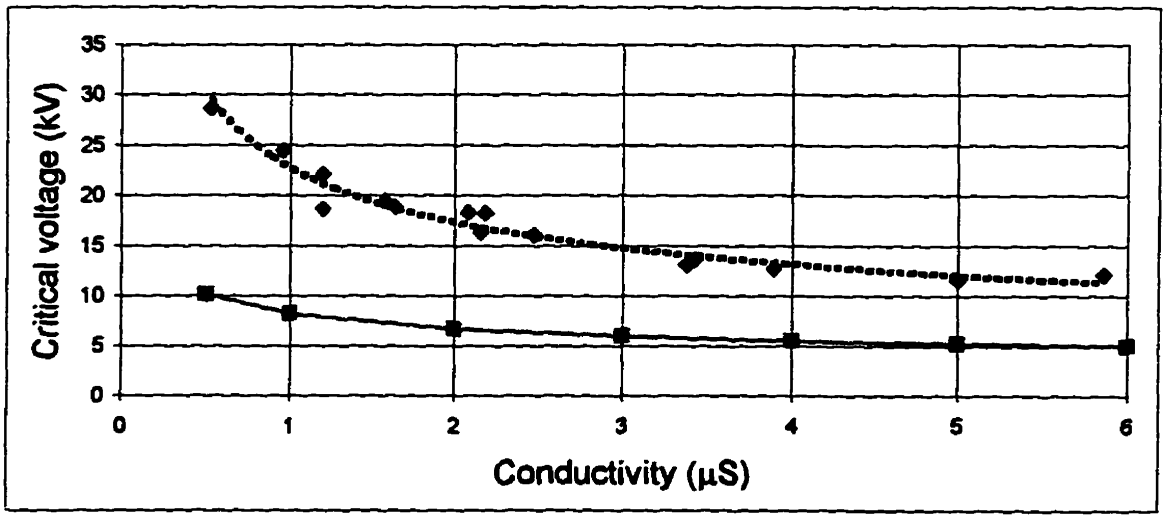

Fig. 3.69 Dependence of critical voltage on conductivity for 10 x10 cm plate.
i) Sundarajan model ______
ii) Experimental _ _ _ _ _

3.5.1.c Cylinder L = 100 cm, dia. = 15 cm

This model is applied to cylinder of Fig. 3.3. Same initial conditions as for 10x1 cm plate are considered.

The calculated are compared with experimental results [9] and shown in Fig. 3.70.

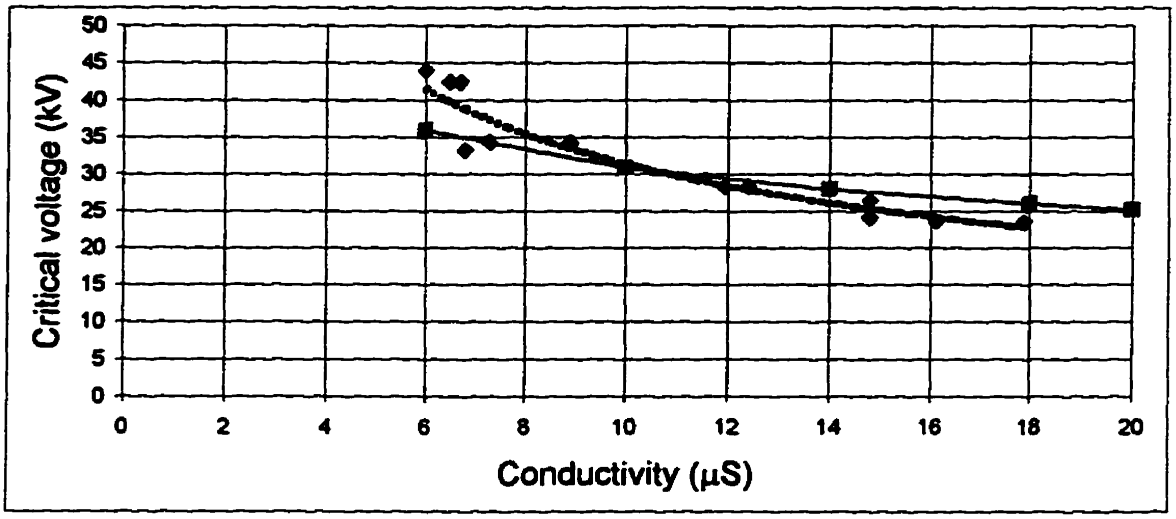

Fig. 3.70 Dependence of critical voltage on conductivity for cylinder.
i) Sundarajan model ______
ii) Experimental _ _ _ _ _

3.5.1.d IEEE insulator

This model is applied to the insulator of Fig. 3.4. Same initial conditions as for 10x1 cm plate are considered.

The calculated values of critical voltage are compared with experimental results [40] and shown in Fig. 3.71

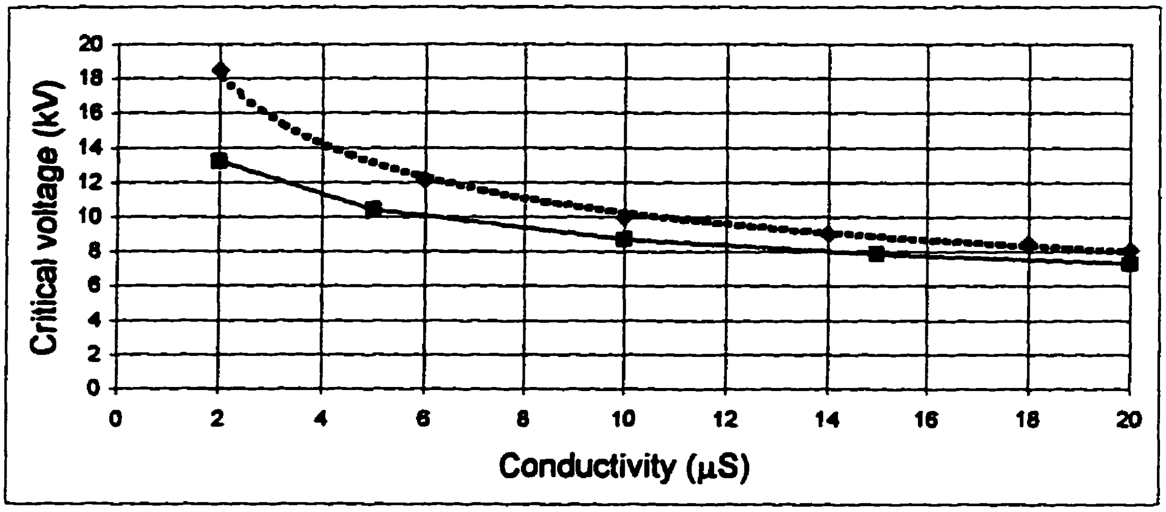

Fig. 3.71 Dependence of critical voltage on conductivity for IEEE insulator.

i) Sundarajan model ______

ii) Experimental _ _ _ _ _

Chapter 4

Discussion of Results

4.1 Analysis of results

In this chapter the results obtained in chapter 3 for various models are discussed. Models were developed for application of different types of voltage i.e. either ac or dc or both and are shown in the Table 4.1

Table 4.1 Category of models based on their application.

DC Models	AC models	AC and DC Models
1 Obenaus's model	1 Ghosh's model	1 Renyu's model
2 Neumarker's model	2 Claverie's model	
3 Alston's model	3 Renyu's model	
4 Wilkin's model		
5 Boeheme's model		
6 Woodson's model		
7 Sundararajan's model		

For a given pollution resistance of 5000 ohm / cm the calculated critical voltage, critical current, and critical arc length from different model are shown in Table 4.2. In the table "N/A" indicates not available from the model. As can be seen that there is a wide range in results.

Table 4.2 Critical voltage, current and arc length for different models for 10 x 1 cm plate.

Model	Critical voltage in kv	Critical current in amp.	Critical arc length in cm
Obenaus	5.117	0.024	10
Neumarker	2.707	0.054	6.67
Wilkins	2.794	0.046	6.67
Claverie	8.139	N/A	6.67
Ghosh	9.132	0.18	N/A
Alston	4.090	0.09	5.7
Boeheme	5.060	N/A	N/A
Hampton	8.183	0.16	N/A
Woodson	5.618	N/A	4.72
Renyu (dc) Renyu (ac)	6.947 8.834	0.10 0.36	7.66 7.71
Sundararajan	3.600	N/A	N/A

The prediction of critical voltages by different models differ from the experimental results. The variation in difference between predicted and experimental results for three insulators i.e. 1) 10 x 10cm plate, 2) Cylinder and 3) IEEE insulator is shown in Table 4.3.

Table 4.3 Difference between the predicted values and the experimental results for three types of insulators.

Model	Difference (%) for 10 x 10 cm plate	Difference (%) for cylinder	Difference (%) for IEEE insulator
Obenaus	30 to 60	0 to 10	24 to 32 (+)
Neumarker	160 to 200	117 to 134	40 to 50
Wilkins	19 to 38	20 to 38	12 to 40 (+)
Claverie	26 to 40	5 to 10	41 to 49 (+)
Ghosh	7 to 24	40 to 80 (+)	122 to 138 (+)
Alston	40 to 55	40 to 70	4 to 12
Boeheme	11 to 19	40 to 50	9 to 51 (+)
Hampton	8 to 70	50 to 120 (+)	60 to 140 (+)
Woodson	170 to 200	2 to 6	40 to 72 (+)
Renyu (dc) Renyu (ac)	12 to 27 (+) 48 to 58 (+)	29 to 58 (+) 41 to 58 (+)	86 to 120 (+) 100 to 200 (+)
Sundararajan	130 to 184	10 to 23	10 to 39

Note: (+) in the table indicates that the predicted values are higher than the experimental values.

Almost all the models assume uniform pollution. Generally this is not true for outdoor conditions.

For almost all the models the difference between the calculated and experimental results seems to decrease with increase in conductivity values.

All the models are based on Obenaus's work.

Model of Obenaus [44]

For cylinder the predictions made by the model are quite good. For IEEE insulator the model gives higher values than the experimental results and considering the assumptions made and conditions of experiment, the model can be said to predict well. For 10 x 10 cm plate it is comparable with the experimental results at higher conductivity levels.

This model assumes a fixed pollution resistance in series with the arc. The model does not predict any critical length. It assumes that the flashover occurs when arc length is equal to leakage length. The model also assumes that once the critical voltage is applied the arc will move and result in flashover. This means that at critical conditions there is enough force to move the arc without extinction. The model does not indicate the mechanism of movement of arc.

The critical voltage is independent of width of insulator.

The critical current does not depend on leakage length as can be seen from eq.(5a).

Model of Neumarker [19]

Predictions made by this model for flat plate and cylinder are not good. For IEEE the predictions are better than for cylinder and flat plate but still not good.

Neumarker's model gives lower critical voltage than Obenaus's model. This can be explained by the fact that in Obenaus's model the critical length x is assumed to be equal to L, while in Neumarker's model x = 0.67 L. Critical arc length is arc length at which flashover occurs.

This model assumes uniform pollution resistance per unit leakage length in series with the arc.

Model of Wilkins [15]

Predictions made by this model for flat plate and cylinder are quite good. For IEEE insulator it predicts 12 - 40 % higher values than the experimental results.

This model takes into account the effect of width of the flat plate while others e.g. Obenaus [44], Neumarker [19] do not consider the effect of width in their models.

The effect of temperature on pollution layer is considered in this model. At the time of flashover the temperature of pollution layer is much higher than that under normal conditions, and thus the conductivity is higher than at normal temperature. Conductivity at flashover is termed as hot conductivity in this model to differentiate from the conductivity at the normal temperature.

This model defines a condition for the movement of arc i.e. criteria for flashover. For a discharge of length x, the movement of arc will occur if $di/dx > 0$, where i is arc current.

This model considers the effect of electrode fall voltage in calculation of critical voltage. The critical voltage is increased due to it.

The model assumes the discharge root to be circular and the effect of this on critical voltage is considered. For the two types of flat plates considered i.e. narrow (when length is greater than the width) and wide (when the width is greater than the length), the pollution resistance is increased due to extra term "$(a / 2.\pi).\ln. (J.a^2/4\ \pi.i)$" in resistance in eq. (28) as compared to drop in resistance of $r_p(L -x)$ in other models. Thus the critical voltage is increased. The critical arc length for narrow plate is not affected by this term. For a wide plate no arc length can be calculated and it is assumed to be L/2.

Eq.(34) of this model for critical current is same as that of Neumarker. The critical voltage obtained from this model are higher than the others i.e. Neumarker etc. due to temperature affects and higher pollution resistance. Therefore, when comparing this model with others, the values may be reduced by a factor given in eq. (18).

Model of Claverie [12]

Generally this model predicts well for flat plate, cylinder and IEEE insulator. Although for IEEE insulator the predicted values are higher than experimental.

The model does not give any calculations for critical current and the critical arc length is assumed 0.67 L.

Since this an ac model therefore the equations derived for arc voltage are different than those for dc. This model is based on the conditions of reignition of arc.

Model of Ghosh [18]

This model predicts well for flat plate insulator. For cylinder and IEEE insulators the prediction is poor as the calculated values are higher than the experimental. This may be due to the higher value of arc constant "N" used in this model. Arc constants are derived from experimental measurement of arc voltage and therefore depend on surrounding conditions e.g. experimental conditions, pollution etc.

It is shown in this model that for every electrolyte there is a particular value of applied voltage V, say V_m, corresponding to time of flashover of 1 ms, and any further increase beyond V_m does not change the value of time, t, to flashover appreciably. The values of V_m, t, and critical current depend on electrolyte. The arc constants used in this model are derived from the measured values of V_m, t, and critical current and therefore depend on electrolyte.

It is interesting to note that the formulae for current and voltage in this model are same as those in Neumarker [19] except that these values are reduced by a factor of 0.919. Thus the current in this model will be 0.919 of Neumarker provided the same arc constants are used. The comparison between these two models reveal that the calculated values from this model are not lower but higher than those in Neumarker. This is due to higher value of arc constant "N" used in this model.

Eq. (54) refers to Renyu's model [11]. In Renyu's model the calculated values of resistance is given as, $R_p = 1/(\pi\rho) \ln (L - x) / r_d$ and the resistance of pollution depends on the conductivity which in turn depends on temperature and radius of discharge. In this model the resistance of pollution, r_p is used which is considered independent of temperature and is thus different from Renyu's model, but in this model they are considered the same.

Model of Alston [9]

For IEEE insulator the prediction made by this model are quite good.

For 10 x 10 cm flat plate, the calculated values of flashover are 40 to 55 % lower than the experimental results. It is indicated in eq.(27), $E_c = 10.5\ r_p^{\ 0.43}$ of this model that this equation for calculating the critical voltage is for ideal conditions and that for practical case $E_c = 15.6\ \ r_p^{\ 0.43}$ is more realistic. This means that the calculated values can be multiplied by a factor of about 1.48. Thus, the calculated values, after taking this factor in account, are close to experimental results.

For cylinder, the calculated values of flashover voltage are 40 to 70 % lower than the experimental results. It is indicated that the eq. (27), $E_c = 10.5\ r_p^{\ 0.43}$ is for ideal conditions and for practical case $E_c = 21.5\ \ r_p^{\ 0.43}$ is more realistic. This means that the calculated values can be multiplied by a factor of about 2.0. Thus, the calculated values, after taking this factor in account, are close to experimental results.

It is interesting to note that the equations for critical current and voltage are same as those of Neumarker [19]. However, the calculated values are different. This is due to arc characteristic constant, namely "N" and "n" having different values in both models. The equation for arc voltage is $V_{arc} = x\,N\,i^{-n}$. The constants N and n are derived from measurement of arc voltage and depend on characteristic of arc, conditions of experiments, etc.

The equations for critical arc length are same as those in Neumarker but the calculated values for arc lengths are different due to different values of arc constant, " n". For the same leakage length, L = 10 cm, the calculated critical arc length from this model and Neumarker's model are 5.7 cm and 6.77 cm respectively.

Flashover voltage is proportional to $r_p^{0.43}$.

Model Boeheme and Obenaus [10]

For flat plate the predictions made by the model are quite good. For cylinder and IEEE insulator the predictions made by the model are good at higher conductivity values.

This model does not yield either the critical current or the critical leakage length.

In this model the parameters of cylindrical insulator e.g. dia, width of sheds, etc. have been reduced to some constant factor and this factor is used in calculating the critical voltage. The arc moves on the resistive layer of pollution if the gradient of resistive layer is higher than that of the arc. This is the same condition as proposed by Hampton [13].

Model of Hampton [13]

The predictions made by this model for flat, cylinder and IEEE insulator are not good. This may be due to the fact that in this model arc is assumed to burn in the atmosphere of steam and therefore the higher values of arc constant N = 530 is used.

The critical arc current is lower and the critical voltage is higher for greater values of r_p.

It is interesting to note that the formulae for critical voltage and current are same as those of Neumarker, but the calculated values are different. Once again this is due to different values of arc constants used.

The necessary condition for flashover is that the voltage gradient in resistive column (column of water used in the model) should exceed that in the arc column.

Model of Woodson [17]

Predictions made by this model for cylinder are quite good. For flat plate and IEEE insulator it does not predict well and this may be due to arbitrarily assumed values of inner radius r_i of the inner electrode in the model.

This model describes the conditions for existence of discharge. According to the model, the discharge only exists in an electrically stable condition i.e. for a given resistivity and insulator geometry there is a voltage occurring at a critical arc length, below which the discharge will extinguish and above which discharge will evolve to flashover. Beyond a calculable limiting length, the discharge can not exist at all, and when the length is not limited i.e. when there is enough electrical force, then the electrically stable discharge will proceed to reach the other electrode. An additional driving force of evaporation due to the surface heating of insulator also helps the movement of the discharge.

Model of Renyu [11]

This model predicts the flashover voltages for both ac and dc applications. For dc and ac, the predictions made by this model for flat plate and cylindrical insulator are reasonable. (although the calculated values are higher than the experimental results). For IEEE insulator the predictions are not good for either ac or dc applications.

This model presents formulae for arc voltage for ac and dc. The arc constants in these formulae are different from other investigators. In this model the volt-amp characteristic of arc on an insulator are measured in comparison to others who measured these constants from burning arc either in the air or steam between a pair of fixed electrode. This model takes into the account the effect of temperature on pollution layer by introducing a factor which describes the relationship between the conductivity values at normal temperature and at flashover (higher temperature).

The ac models are based on recovery conditions of arc.

Model of Sundararajan [20]

The predictions made by this model are quite good for cylinder and IEEE insulators and not so good for flat plate.

This is the only model which takes into consideration the entire shape of insulator by calculating the form factor at different positions of the arc during its travel. As the arc travels the arc resistance and the pollution layer resistance change and thus the parameters affected due to this change i.e. current, voltage, form factor, etc. are calculated for different positions of arc. The criteria for arc travel are same as that of Hampton's [13].

In comparison to the other models the prediction of flashover by this model for complex shape insulators are more accurate. The other models convert the insulator to either equivalent flat plate or cylinder or elliptical shape and do not consider the change in parameters as arc moves.

It is worth while to mention here that when this model is applied to the equivalent cylinder of IEEE insulator, the difference between the calculated critical voltage and experimental result is about 10 to 39 %, and when this model is applied to actual IEEE insulator then this difference is about 23 to 39 % [40]. The difference between the predicted results when applying this model to actual IEEE insulator and equivalent cylinder is 0.4 to 10 % (Fig. 4.1).

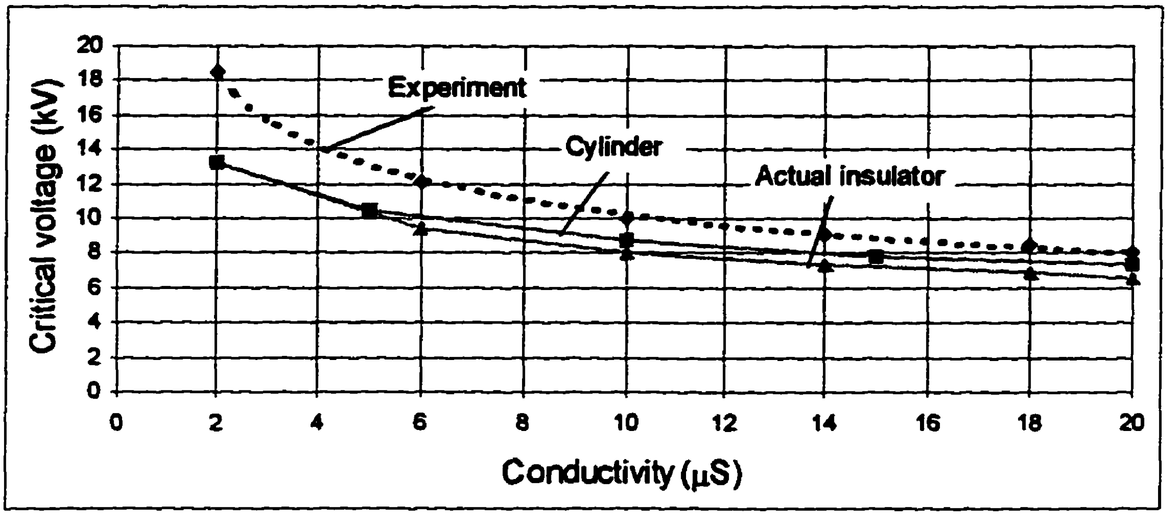

Fig. 4.1 Comparison of predicted results between equivalent cylinder, actual IEEE insulator and experiment, critical voltage and conductivity.

Since this model takes into account the shape of insulator therefore this model was applied to another real life insulator i.e. Anti - Fog insulator, shown in Fig. 4.2.

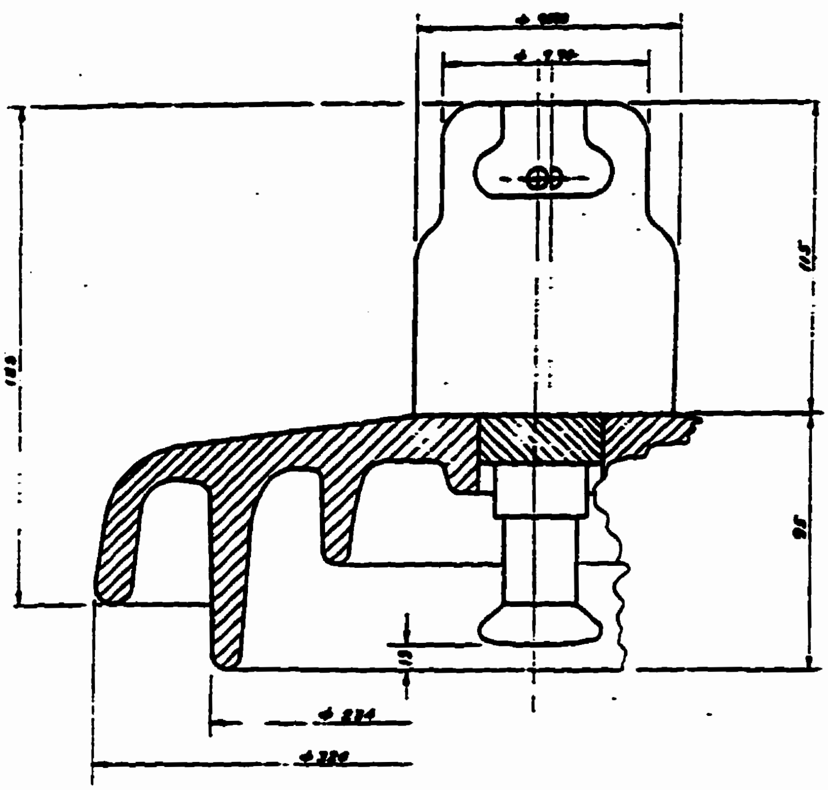

Fig. 4.2 Anti - Fog insulator.

This model is applied to the equivalent cylinder. The calculated values of critical voltages for different values of conductivity are shown in Fig.4.3

The difference between the calculated critical voltage and experimental result is about 7 to 20 % when this model is applied to equivalent cylinder and when, applied to actual geometry of Anti - Fog insulator, then this difference is about 37 to 42 % [40]. The difference between the predicted results when applying this model to Anti - Fog insulator and equivalent cylinder is 16 to 27 % Fig. 4.3.

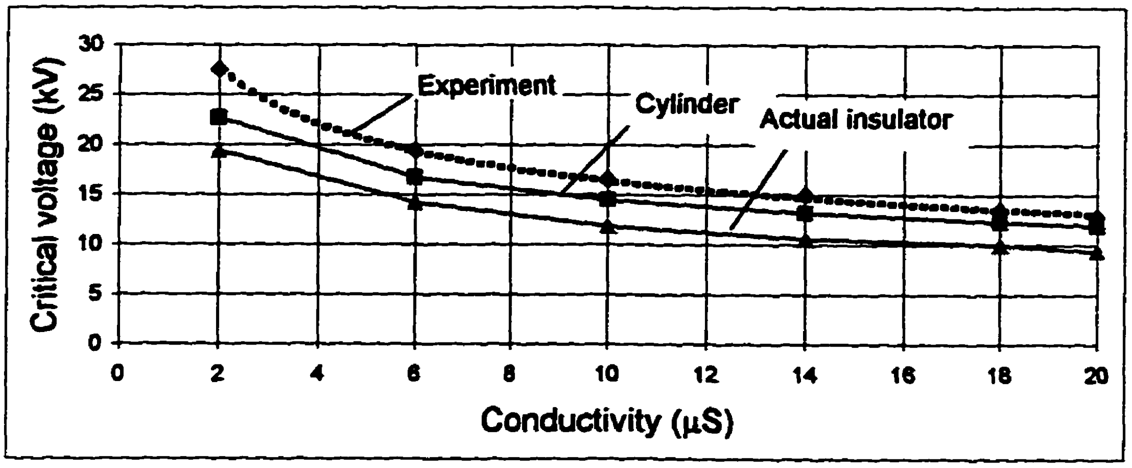

Fig. 4.3 Comparison of predicted results between equivalent cylinder, actual Anti fog insulator and experiment, critical voltage and conductivity.

Based on above this may lead one to question the efforts required to use the simulation of actual insulators.

Chapter 5

Conclusion

From the comparative study of various models it can be seen that no two models yield exactly the same result. One model may be good for a particular type of insulator but may not be suitable for another type of insulator.

Despite intensive research no model takes into account the physical processes involved in the movement of discharges along a wet polluted surface. Proponents of models, based on different theories have shown that their models agree with the data from tests. This is quite remarkable as these theories were based on assumptions which are different from each other.

Almost all the models use the voltage - current equation, $V_{arc} = x N I^{-n}$, for calculating the arc voltage. Based on the assumptions made in models, a wide range of arc constants e.g. N = 63 to 530 and n = 0.24 to 1.0 have been used. This equation is strictly valid for high current static arcs but is used in the analysis of low current non static arcs in all the models. None of the models consider the velocity of arc motion.

The calculated results vary widely. For example, for a given pollution resistance, the calculated flashover voltages ranges: 1) from 2707 V to 8183 V for 10 x 1 cm plate, 2) from 2866 V to 15013 V for 10 x 10 cm plate, 3) from 4190 V to 52390 V for cylinder and 4) from 3826 V to 22083 V for the IEEE insulator. The only model which considers the actual shape of the insulator is that of Sundararajan's which predicts more accurate results than the other models.

All the models compared are in one way or the other are the improvement of the earlier model of Obenaus. There is no single model which will be good for all the insulators and which could be applied easily. For practicing engineers it would be desirable to have such a tool.

It would appear that considerable work needs to be done in order to understand this complex phenomenon and come up with a clear and a simple practical model.

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