CHAPTER 2

DEVELOPMENT OF VERISIMILAR JUXTAPOSITION
PHYSICAL MODEL

2.1 INTRODUCTION

The simplified geometrical models equivalent to the actual insulator presently in existence for the purpose of analysis are the flat plates, troughs, cylinder or circular models. These models have been discussed elaborately in the introductory chapter. Among these models, the basic flat plate model has merited extensive attention in the context of pollution flashover. While the flat plate model boasts of simplicity, it has many serious limitations.

In an insulator, the current density is non-uniform, being highest at the pin and the least at the outermost rib. These conditions are not produced in the flat plate models. It is the non-uniformity of current density in the insulator that causes differential drying, which in turn effects a change in the conductivity profiles. A change in the conductivity pattern over the insulator alters the current distribution. Thus, an error in the representation of current distribution in a model could cumulatively lead to gross errors in the determination of temperature profiles.

The length of the strip is made proportional to the creepage length of the insulator and the model represents a strip extending from the pin to the cap. Wind effects cannot be duplicated with the flat plate models, as on the actual insulator, the leeward and windward sides are affected differently as shown in Figure 2.1 in the deposition of contaminants.
FIGURE 2.1 AIR-FLOW OVER SUSPENSION TYPE INSULATOR

1. Eddying turbulence
These observations necessitated for the development of a new model overcoming the drawbacks of the existing models.

2.2 DESIGN AND DEVELOPMENT OF THE VERISIMILAR JUXTAPOSITION PHYSICAL MODEL

2.2.1 Dimensionality consideration

The proposed model, equivalent to a standard disc insulator is circular in shape, made of an insulating material, namely epoxy resin with two metallic terminals, one on top and other at the bottom. A sectional view of the standard disc insulator is shown in Figure 2.2 and its simplified plan in Figure 2.3, where \( d_1 \) represents the diameter of the cap, \( d_2 \) denotes the diameter of the outermost rib and \( d_3 \) represents the diameter of the pin. The upper surface of the insulator from the cap upto the point \( X \) of the outermost rib is the unprotected creepage length \( l_1 \). The lower surface of the insulator consists of a number of ribs, which do not have a very regular geometry and hence it is approximated as shown in Fig. 2.3(b). Based on this approximation, the protected creepage length \( l_2 = x_1 + y_1 + x_2 + 2y_2 + x_3 + x_4 + 2y_3 + x_5 + x_6 + 2y_4 + x_7 + x_8 \) measured from the point \( X \) to the pin.

The cap was a turned aluminium member, having a diameter \( M_1 \) to represent the diameter of the cap \( d_1 \) of the insulator and the pin was made of steel with diameter \( M_2 \), proportional to the diameter of the pin \( d_3 \). Hence the diameters of the upper and lower surfaces of the model are \( (M_1 + 2l_1) \) and \( (M_2 + 2l_2) \) respectively as shown in Fig. 2.4.

The creepage length plays a vital role in the pollution flashover phenomena. In the developed model, the upper surface is represented by a circular area proportional to \( (M_1 + 2l_1) \). The lower surface of the model is represented by another circular area proportional to \( (M_2 + 2l_2) \).
FIGURE 2.2 SECTIONAL VIEW OF STANDARD DISC INSULATOR

DIMENSIONS OF INSULATOR

- Unprotected creepage length \( (l_1) = 86 \text{ mm} \)
- Protected creepage length \( (l_2) = 254 \text{ mm} \)
- Diameter of cap \( (d_1) = 111 \text{ mm} \)
- Diameter of outermost rib \( (d_2) = 375 \text{ mm} \)
- Diameter of pin \( (d_3) = 21 \text{ mm} \)

1. Cap
2. Outermost rib
3. Pin
FIGURE 2.3 (a) SIMPLIFIED PLAN OF STANDARD DISC INSULATOR
(b) SIMPLIFIED HALF SECTIONAL VIEW OF STANDARD DISC INSULATOR
FIGURE 2.4 DEVELOPMENT OF SCHEMATIC DIAGRAM OF V-J MODEL

1. Cap
2. Pin
3. Metallic ring

- Epoxy resin
A continuous path is available in the insulator for the leakage current to flow on the surface. Similarly, a continuity between the upper and lower surfaces of the model was found to be necessary for the radial flow of the leakage current and to account for the heat transfer phenomena. It was achieved by providing a metallic ring between the two surfaces. Due importance was given in the choice of the dimension of this metallic ring considering the two important factors, namely the electrical continuity and thermal conduction. The ring provided was made of stainless steel of 1mm thickness. It was proved in the later section of this thesis that the incorporation of the metal ring does not alter the magnitude and shape of the leakage current of the physical phenomena. Care was taken to minimise the radiation and convection losses by preventing this metallic ring from being exposed. This was achieved by embedding it with epoxy insulating material. The schematic diagram of the V-J model is shown in Figure 2.4 and the physical V-J model is shown in Fig. 2.5. With this developed model, it is possible to implement unequal volume deposition of contaminants on the upper and lower surfaces similar to that obtainable on an insulator. Wind directed towards this model could create effects similar to those on the windward and leeward regions of the surfaces of the insulator.

The non-uniform current density existing in the unprotected and protected creepage lengths of the actual insulator under wet contaminated condition is well brought out in this model with the upper and lower surfaces truly depicting the unprotected and protected creepage lengths and the proportionate metallic terminations for the cap and pin. Further, the radial flow of leakage current in both the surfaces of the model also resembles the actual situation occurring in an actual insulator.
FIGURE 2.5 VERISIMILAR JUXTAPOSITION PHYSICAL MODEL

(a) Upper surface
(b) Lower surface
2.3 EXPERIMENTAL ANALYSIS ON V-J MODEL

2.3.1 Experimental setup

Experiments have been conducted on this newly developed model to assess its characteristics, namely the leakage current pattern, the location of dryband and the variations in surface resistance while forming the dry band. The experimental setup to measure the leakage current is shown in Fig.2.6. The slurry was prepared as per the specifications of IEC-507 Solid layer method (1975) and IS 8704 (1978) and was coated uniformly on this model and kept in the test set up. A test voltage of 250V, 50Hz was applied across the terminals $M_1$ and $M_2$ and the leakage current was recorded in a storage oscilloscope through an AC/DC converter the voltage drop fed across resistor $R$. Conventional protective measures were provided in the experimental set up by using a pair of spheres. The leakage current wave form recorded from the instant of application of voltage till the formation of dry band is shown in Fig.2.7. Another important result obtained from the experiment was the location of the dry band. The dry band was precisely located on the model. Its shape, contour of growth and the locations were physically measured.

2.3.2 Leakage current measurement and analysis

Comparing the construction of this V-J model with the standard disc insulator, the presence of the stainless steel metal ring between the upper and lower surfaces projects a difference of thought, since such a metallic ring is not present in the actual insulator. The current in an insulator is reasonably assumed to be radial under the conditions of uniform pollution. As a result, the voltage of a circular element such as the outershed would be spatially equipotential. This provides the justification of incorporating the metallic ring. The validity of this assumption was investigated experimentally. The leakage current wave forms obtained on a standard disc polluted insulator is shown in Figure 2.8 and the leakage current monitored in the presence of a metallic ring on a standard disc insulator is shown in Fig.2.9. It is seen that they are similar.
FIGURE 2-6 EXPERIMENTAL SET UP FOR MEASUREMENT OF LEAKAGE CURRENT

1. H.V. Transformer
2. Disc insulator
3. Resistance
4. Protective gap
FIGURE 2.7 LEAKAGE CURRENT WAVEFORM ON POLLUTED V-J MODEL

FIGURE 2.8 LEAKAGE CURRENT WAVEFORM ON POLLUTED INSULATOR

FIGURE 2.9 LEAKAGE CURRENT WAVEFORM ON POLLUTED INSULATOR WITH A METALLIC RING
The experiment on the standard disc insulator brought into light two leakage current patterns for applied voltages of 2kV and 250V and are shown in Figs.2.8 and 2.10. In the first type, the leakage current abruptly drops after a gradual fall from a peak value. The second characteristic curve is a continuous gradual decrement of the current. The reason being that if the pollution layer around the pin was not uniform, then it is conceivable that a small segment of it dries up while the other portions continue to be wet and conductive. Though the dried segment would preclude the flow of current to pin, the other segments balk the effectiveness of the blocade. Thereafter, another segment of the unevenly polluted layer may dry up leading to further partial preclusion of current paths to pin. If such a situation was to prevail, the leakage current need not fall abruptly over a significant range. In fact, if the regions non-proximate to the pin were to have relatively low levels of moisture, they would dry fast, not lagging much behind the zones adjacent to the pin. Such drying of the periphery would not be conducive to an abrupt drop. A somewhat wet peripheral region and a relatively uniform drying proximate zone would favour abrupt fall of the leakage current.

2.3.3 Location of dry band and measurement of resistance variation due to dry band formation

The locations of dry band observed on the polluted insulator are shown in Fig.2.11. Typical dry band locations obtained on the V-J model are shown in Fig.2.12.

The superimposition of the locations of dry band of the actual insulator and the newly developed V-J model is shown in Fig.2.13 and it is observed that there exists a very close correspondence between the insulator and the newly developed model. The feasibility to locate the dry band and its growth using this new model thus gets established.
FIGURE 2.8 LEAKAGE CURRENT WAVE FORM ON POLLUTED INSULATOR

FIGURE 2.10 LEAKAGE CURRENT WAVE FORM ON POLLUTED INSULATOR WITH LOW VOLTAGE
FIGURE 2-11 DRY BAND LOCATIONS ON STANDARD DISC INSULATOR

1. Pin
2. First rib
3. Outermost rib
FIGURE 2-12 LOCATIONS OF DRY BAND ON THE V-J MODEL

1. Pin
2. First rib (imaginarily equivalent to the radius of the first rib in the insulator)
3. Outer edge
FIGURE 2.13 COMPARISON OF DRY BAND LOCATIONS

Actual insulator
-- V-J Model
1. Pin
2. First rib
3. Outermost rib
Since the primary aim is to investigate the dry band inception, it is instructive to obtain the resistance profile across the segments of the insulator both prior and consequent to the formation of dry band. The segmentation serves as an aid to the measurement and to the analysis. The insulator was demarcated to six segments as shown in Fig.2.14. The point 1 represents the pin and the points A, B, C, D, E and F correspond to the six segments at the outermost rib. The dotted circle marked 2 indicates the first rib closer to pin and 3 denotes the outermost rib of the insulator. A similar figure was also drawn to depict the upper surface with the cap being denoted by 4.

The spatial equivalence between the insulator and the developed V-J model permits an equivalent sketch for this model as shown in Figure 2.15, where the upper and lower surfaces of the model are shown.

Experiments have been conducted on the polluted insulator. The resistance values were measured across the various regions both before and immediately after the formation of dry band. The resistance values in the respective regions like, pin to first rib, first rib to outermost rib, pin to outermost rib and cap to the outermost rib were measured and four sets of data obtained on polluted insulator are shown in Tables 2.1 to 2.4.

Similarly, for the V-J model, the respective regions are pin to halfway point and half way point to outer edge. The resistance values in the segments were measured and four sets of data obtained on the V-J model are shown in Tables 2.5 to 2.8. These tabulated data of resistance profiles measured across the segments of the insulator and on the V-J model both prior and immediately after the formation of dry band revealed accurately the formation of dry band in the specific segment and enabled to trace its growth as discussed below:
FIGURE 2.14 SEGMENTATION OF THE INSULATOR FOR RESISTANCE PROFILE MEASUREMENT

(a) Cap and outermost rib
(b) Pin and outermost rib

1. Pin
2. First rib closer to pin
3. Outermost rib
4. Cap
FIGURE 2.15 SEGMENTATION OF V-J MODEL FOR RESISTANCE PROFILE MEASUREMENT

(a) Upper surface
(b) Lower surface

1 Pin
2 Outer edge
3 Cap
### TABLE 2.1 RESISTANCE PROFILE ON INSULATOR 1

<table>
<thead>
<tr>
<th></th>
<th>Before the dry band formation</th>
<th>After the formation of dry band</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Pin to First rib</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>First rib to Outermost rib</td>
<td>200</td>
<td>180</td>
</tr>
<tr>
<td>Pin to Outermost rib</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>Cap to Outermost rib</td>
<td>150</td>
<td>175</td>
</tr>
</tbody>
</table>

All values are in kΩ.

### TABLE 2.2 RESISTANCE PROFILE ON INSULATOR 2

<table>
<thead>
<tr>
<th></th>
<th>Before the dry band formation</th>
<th>After the formation of dry band</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Pin to First rib</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>First rib to Outermost rib</td>
<td>200</td>
<td>190</td>
</tr>
<tr>
<td>Pin to Outermost rib</td>
<td>250</td>
<td>240</td>
</tr>
<tr>
<td>Cap to Outermost rib</td>
<td>180</td>
<td>200</td>
</tr>
</tbody>
</table>

All values are in kΩ.
### TABLE 2.3 RESISTANCE PROFILE ON INSULATOR 3

<table>
<thead>
<tr>
<th>Before the dry band formation</th>
<th>After the formation of dry band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin to First rib</td>
<td>Pin to Outermost rib</td>
</tr>
<tr>
<td>60 A 80 B 60 C 50 D 50 E 60 F</td>
<td>90 A 250 B 200 C 80 D 70 E 60 F</td>
</tr>
<tr>
<td>First rib to Outermost rib</td>
<td>180 A 140 B 190 C 200 D 190 E 200 F</td>
</tr>
<tr>
<td>240 A 220 B 240 C 250 D 250 E 250 F</td>
<td>300 A 470 B 470 C 470 D 300 E 290 F</td>
</tr>
<tr>
<td>Pin to Outermost rib</td>
<td>200 A 190 B 180 C 200 D 180 E 200 F</td>
</tr>
<tr>
<td>Cap to Outermost rib</td>
<td>210 A 200 B 190 C 190 D 200 E 220 F</td>
</tr>
</tbody>
</table>

All values are in kΩ.

### TABLE 2.4 RESISTANCE PROFILE ON INSULATOR 4

<table>
<thead>
<tr>
<th>Before the dry band formation</th>
<th>After the formation of dry band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin to First rib</td>
<td>Pin to Outermost rib</td>
</tr>
<tr>
<td>30 A 50 B 80 C 60 D 70 E 90 F</td>
<td>350 A 70 B 90 C 90 D 80 E 90 F</td>
</tr>
<tr>
<td>First rib to Outermost rib</td>
<td>200 A 180 B 210 C 190 D 200 E 210 F</td>
</tr>
<tr>
<td>210 A 250 B 260 C 270 D 240 E 280 F</td>
<td>610 A 290 B 310 C 290 D 300 E 330 F</td>
</tr>
<tr>
<td>Pin to Outermost rib</td>
<td>200 A 210 B 180 C 190 D 180 E 200 F</td>
</tr>
<tr>
<td>Cap to Outermost rib</td>
<td>210 A 230 B 200 C 190 D 200 E 210 F</td>
</tr>
</tbody>
</table>

All values are in kΩ.
TABLE 2.5 RESISTANCE PROFILE ON THE MODEL (TEST NO.1)

<table>
<thead>
<tr>
<th></th>
<th>Before the dry band formation</th>
<th>After the formation of dry band</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Pin to Half way point to outer edge</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>Half way point to outer edge</td>
<td>4.4</td>
<td>4.4</td>
</tr>
</tbody>
</table>

All values are in kΩ.

TABLE 2.6 RESISTANCE PROFILE ON THE MODEL (TEST NO.2)

<table>
<thead>
<tr>
<th></th>
<th>Before the dry band formation</th>
<th>After the formation of dry band</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Pin to Half way point to outer edge</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Half way point to outer edge</td>
<td>4.5</td>
<td>4.2</td>
</tr>
</tbody>
</table>

All values are in kΩ.
### TABLE 2.7 RESISTANCE PROFILE ON THE MODEL (TEST NO. 3)

<table>
<thead>
<tr>
<th></th>
<th>Before the dry band formation</th>
<th>After the formation of dry band</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Pin to Half way point to outer edge</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>Half way point to outer edge</td>
<td>4.0</td>
<td>4.4</td>
</tr>
</tbody>
</table>

All values are in KΩ.

### TABLE 2.8 RESISTANCE PROFILE ON THE MODEL (TEST NO. 4)

<table>
<thead>
<tr>
<th></th>
<th>Before the dry band formation</th>
<th>After the formation of dry band</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Pin to Half way point to outer edge</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Half way point to outer edge</td>
<td>4.2</td>
<td>4.0</td>
</tr>
</tbody>
</table>

All values are in KΩ.
For example, in Table 2.1, the resistance value in segment A prior to the dry band formation is 50 kΩ and it got increased to 150 kΩ subsequent to the formation of dry band. The corresponding change in segment B is from 80 kΩ to 90 kΩ. This is much smaller than that in segment A and hence it could be stated that the dry band exists in segment A and does not spread to segment B. A similar observation of values of each segment reveals that the dry band would also lie in segment F, since this segment also has a change in resistance value from 70 kΩ to 250 kΩ.

It is obvious that the percentage change is much greater in segment F than in A, yielding a vital clue to the nature, shape and growth of dry band in that segment. As segment F predominantly shows the variation in resistance, it is clear that drying is more in that segment compared to the neighbouring segments and hence the dry band is initiated in the segment F and the neighbouring segments continue to be relatively wet and conductive. The larger change in resistance in segment F confines the leakage current path to be closer to the pin and the arc is parallel to the circumference of the pin, which is clearly seen in Figure 2.16, whereas from Table 2.5, it is observed that the change in segmental resistance is lesser, suggesting that the drying is nearly uniform in all the segments and amongst these segments, whichever has the maximum change in resistance has the dry band formed and it is confined only to that segment since the neighbouring segments are also dry and does not allow conduction of leakage current and hence the arc traverse away from the pin elongating radially as shown in Fig.2.17.

Further, the second row of Tables 2.1 to 2.4 depict the behaviour of the region from first rib to outermost rib. It is seen that the change in resistance values are nowhere in comparison to those in the region namely, the pin to first rib. The small change in resistance is explicable as a smaller amount of drying.

The segment D of Table 3.1, shows that there is no noteworthy change in resistance, which implies that the region would continue to remain wet and the principal reason for this wetness is the minimum current density in the outer region.
FIGURE 2.16 RESISTANCE VARIATIONS BETWEEN PIN AND FIRST RIB OF INSULATOR AND LOCATION OF DRY BAND

1. Pin
2. First rib

- Resistance before dry band formation
- Resistance after dry band formation
- Location of dry band
FIGURE 2.17 RESISTANCE VARIATIONS BETWEEN PIN AND HALF WAY POINT TO OUTER EDGE ON V-J MODEL AND LOCATION OF DRY BAND

1. Pin
2. Half way point to outer edge

- Resistance before dry band formation
- Resistance after dry band formation
- Location of dry band
The change in resistance values from the cap to the outermost rib as recorded by the fourth row of Tables 2.1 to 2.4 proves that drying also occurs on the upper surface. However, the change is not presumably in the vicinity of the cap. Dry bands do not occur here as the current density is lower than that near the pin.

Everyone of these aspects is seen in the V-J model as recorded in the Tables 2.5 to 2.8 which clearly reveal these facts.

The distinct variations in the resistance profiles in the segmented regions between the two points of observations reveal noteworthy conclusions discussed in the following section.

2.4 DRY BAND FORMATION AS ON ACTUAL INSULATOR

The agreement of the dry band formation is based on the following results obtained from experimental analysis on the newly developed V-J model and the actual insulator:

i. The drying process originate from the pin region due to the maximum current density and traverse outward.

ii. The dry band is precisely located in the specific segmental region and its growth is determined.

iii. Drying takes place from the pin region and the dry band formation is confined to the first rib, which is similar to the ‘active area’ reported by L.J. Williams et al., (1974) and is shown in Fig.2.18.

iv. From the first rib to the outermost rib, appreciable increase in resistance value is not present and infact two of the segments continue to remain wet, the reason attributed for this effect is the lesser current density.
FIGURE 2.18 IDENTIFICATION OF ZONES

(a) Locations of dry band obtained on V-J model
(b) Results of L.J.Williams et.al [1974]
v. Dry band does not form on the upper surface since the current density is lesser than that of the pin region.

vi. From initial resistance values on different zones it is understood that the pollution coating is fairly uniform.

vii. A striking feature is observed in the change in resistance value and the pattern of dry band. A larger change in resistance value corresponds to a pattern which is closer to the pin and follows an arc parallel to the circumference of the pin and relatively lesser change indicates an arc traversing away from the pin elongating radically.

2.5 VALIDATION OF THE V-J MODEL

Based on the experiments conducted on the V-J model, the model gets validated on the following grounds:

The leakage current variation recorded on this model is similar to that obtained for an insulator and is in agreement with the literature.

The dry band locations obtained on the V-J model reveal the fact of feasibility of obtaining them. On superimposition of these locations with that of the insulators it is observed that there exists a closer correspondence between the insulator and the model.

The qualitative analysis of the model is obtained based on the measurements of the segmented resistance profiles obtained before and after the formation of dry band and its behaviour is characterised.

The wind effects can be simulated to the upper and lower surfaces of this model and studied to a very high degree of accuracy in this model.
2.6 CONCLUSION

In this chapter a new physical geometrical model developed equivalent to a standard disc insulator is discussed. Its circular shape exploits the main feature of the actual insulator. The design and development of this new model has taken into consideration the shape factor of the standard disc insulator with its protected and unprotected creepage lengths equivalent to the lower and upper surfaces of the insulator, the non-uniform current density, the leakage current pattern, and the surface resistance values. The model is so designed and developed that it takes into account the contribution of wind effects in its profiles and the surface area of the model truly depicts the surface area of the insulator. The experimental studies conducted on this newly developed model are highlighted and the outcome of the studies are summarised.

The pattern of leakage current variation obtained on the V-J model is similar to that of the standard disc insulator and is in accordance with the literature. The current density variations in the pin region and the outermost rib region are explicitly revealed through the drying pattern.

The dry band is accurately located and its growth is determined in the specific segmental region. The correlation of the locations of dry band on the model and the insulator is exposed when the superimposition of these locations are made.

The behaviour of this new model is qualitatively characterised and compared with the actual insulator through the measurement of segmental resistance profiles before and immediately after the formation of dry band.
It is possible to implement the deposition of contamination on the upper and lower surfaces of this model similar to that obtainable on an insulator. The wind directed with an appropriate velocity could create effects similar to those on the windward and leeward regions of the surface of the insulator.

The major advantage of this new model lies in its spatial similarity to the actual insulator. This permits an easy one-to-one correspondence between a point on the insulator and on the model. The versatility of this newly developed physical geometrical model is thus validated and its viability in the mathematical modelling is assessed in the subsequent chapter.