Computation of AC flashover voltage of polluted HV insulators using a dynamic arc model

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SUMMARY

Flashover of polluted insulators is still a serious threat to the safe operation of a power transmission system. Despite the extensive investigations carried out on the pollution performance of the insulators, the flashover characteristics are not well understood. Recent theoretical and experimental research on polluted insulators is yet to yield a perfect generalized mathematical model which can accurately predict critical flashover voltage. In this paper, the pollution flashover on the high voltage insulators has been investigated and a new dynamic arc model has been proposed. For this purpose, firstly the concerned insulators’ scaled shapes were partitioned into triangular elements, then finite element method (FEM) was implemented for obtaining potential distribution on the surface of insulator and finally flashover voltages were determined by using the developed arc model. For a number of common insulators of different geometries the computed results of flashover voltages on the selected string insulators have been compared to experimental results of some other research. Pollution flashover behaviors of the insulators have been taken into consideration and the validity of the model was thus verified. Copyright © 2008 John Wiley & Sons, Ltd.

key words: pollution flashover; flashover voltage; dynamic arc model

1. INTRODUCTION

Pollution flashover, observed on insulators used in high voltage transmission, is one of the most important problems for power transmission. Pollution flashover is a very complex problem due to several reasons such as modeling difficulties of the insulator complex shape, different pollution density at different regions, non-homogenous pollution distribution on the surface of insulator, and unknown effect of humidity on the pollution.

Under severe environmental conditions, a pollution layer is deposited on the insulator surface. When the surface of a polluted high voltage insulator is dampened due to dew deposition, fog or rain, a wet conducting film is formed and a leakage current flows through the surface [1,2]. The leakage current begins to dry the pollution layer and the resistivity of the layer rises in certain areas. This leads to dry band formation, usually in the areas where the current density is highest. The dry band supports most of the applied voltage. The air gap flashes over, with the arc spanning the dry band gap which is in series with the wet portion of the insulator. The arc may extinguish at zero current and the insulator may return to working conditions. Dry band formation and rewetting may continue for many hours [3]. These arcs will burn in series with the wet surface resistance. If this resistance is sufficiently low, the partial arcs will elongate along the insulator profile and may eventually cause the full insulator flashover. In this way, the performance of a polluted insulator may be represented by the flashover voltage and the flashover current defined as the maximum leakage current magnitude immediately before flashover [4].

The pollution flashover phenomenon has five main stages:

1. conducting layer build-up,
2. dry band formation,
3. partial arcing,
4. arc elongation,
5. eventual arc spanning the whole insulator followed by flashover [3].

To investigate the pollution problem potential distribution has to be determined and total pollution resistance in series with the discharge has to be computed. Evaluation of the flashover performance of a polluted insulator requires the model simulation of the physical phenomenon taking place on the insulator surface and numerical solution using computer. The validity of this evaluation is dependent on two factors: a clear understanding of the physical mechanism of the problem and the development of a realistic computational model [1].

An alternative to natural and artificial pollution tests is the analytical determination of the flashover performance of the polluted insulators. Due to the complex shapes of the insulators, insufficient knowledge on the physical nature of flashover and lack of computational facilities, sufficiently precise analysis of the phenomenon by analytical or numerical methods has not been possible until the availability of high performance computers and the development of suitable numerical computational techniques. In recent years, the numerical models which simulate physical phenomenon were developed and the computers were widely used in the solution of engineering problems. Consequently, a computer-aided estimation of the flashover performance of the polluted insulators has also drawn more attention. Researchers are trying to devise analytical methods to assess the flashover performance of the polluted high voltage insulators in order to eliminate, as far as possible, the need for expensive test facilities and get rid of tedious and lengthy experiments [5–12].

In literature, some static and dynamic models were developed by making some assumptions and omissions to predict the flashover voltages of the polluted insulators. A review of the theoretical models reveals that most of the existing models are static [13]. As the flashover is a very rapid process it is expected that dynamic models, which take into account the instantaneous changes in the arc parameters, are more representative than static models [14]. The few available dynamic models are either conceptual [15] or statistical [16] and/or require experimental data that are not easily available [17,18]. Also a majority of these models consider only strips of electrolytes rather than an actual insulator [13,17]. This has motivated the present study, the purpose of which is to develop a dynamic model that takes into account the actual geometry of the insulators [19].

In this study, a dynamic arc model which considers original shape of an insulator and adds variation of pollution resistance in series with the discharge to calculations in every step has been developed and alternating current flashover voltages of the polluted insulators have been computed.

2. DYNAMIC ARC MODEL

The occurring partial discharges in the dry bands and the variations of pollution layer resistance are important during the flashover phenomenon on the high voltage insulators. In this study, a polluted insulator which generates the partial discharges in the pollution layer has been modeled by using AR model proposed by Rumeli [20,21]. AR model represents a polluted insulator with a resistance in series with the discharge as given in Figure 1. The pollution layer resistance has been computed by using AR model. The resistance represents the pollution layer in the proposed dynamic arc model. The dynamic arc model has been obtained by making the following assumptions:

1. formation of partial discharges on the leakage path,
2. the increment of these discharges with covering completely the leakage length and formation of the flashover,
3. having a homogeneous structure of pollution distribution on the insulator surface.

Additionally, the variations of temperature on the pollution layer during the discharge and effect of humidity were neglected. First, scaled shape of the insulators is drawn and the points on the leakage length of the insulator are determined. The number of these points must be high enough so that they can represent the real shape of the insulator. Then the points on and around the insulator are determined and all of the points are drawn by lines which allows us to obtain the triangles for finite element method (FEM) solution. The number of these triangles can be increased by the help of the MESH program. Therefore, a point on the middle of every side of every triangle is determined in the MESH program automatically. Then AR model of the insulator is obtained by another computer application.
Both the potential distribution and field strengths on and in the selected external area of the insulator were computed by using FEM, where the dynamic arc model is also obtained. Then the values and positions of field strength were determined in the surface of the insulator along the leakage length. The values of pollution resistance in series with the discharge were computed by using AR model and FEM. In order to calculate the variation of the pollution resistance by using the potentials on the AR model, the solution zone was finally meshed by triangular elements. The initial conditions were applied to pin and cap of the insulator and the solution was attained. The meshed case by triangular elements of AR half-model for 80F140W insulator is shown in Figure 2. The quadrangles which divided to triangles were used in the zone that is quite near to the cap. The total resistance between two electrodes was calculated as follows [22].

The total pollution resistance between the pin electrode which is system voltage applied on the point \( (i, 2) \) and the cap electrode on the zero potential \((m, j; j = 2, \ldots, n)\) is calculated from solution of equation \( \nabla^2 U = 0 \) under determined boundary conditions in Figure 3. Rumeli [20] calculated variation of resistance by moving ahead the arc root on the model from pin to cap by definite distances along the leakage length. On the other hand, the values of the potential belong to points on the leakage length in this developed model has been replaced by arc root. The field strength values of the points on the \( i = m - 1 \) vertical line that is quite near to the cap \((\varepsilon \approx 0.1 \text{ cm}, k = 1 \text{ cm})\) is

\[
E(m - 1, j) = \frac{U(m - 1,j)}{\varepsilon}, \quad j = 2, \ldots, n
\]

(1)

where \( E \) is the electric field.

\[
J_j = \sigma \cdot E_j = \sigma \frac{E(m - 1,j - 1) + E(m - 1,j)}{2}
\]

(2)
where \( J \) is the current density and \( \sigma \) is the specific conductivity of the pollution.

or

\[
J_j = \sigma \frac{U(m-1,j-1)UV(m-1,j)}{2} = \frac{\sigma}{\varepsilon} \cdot U_{AV}
\]

(3)

where \( U_{AV} \) is the average of potentials of two neighbor node points belong to triangles with dense meshed that is near to ground electrode.

The flowing current towards ground electrode is computed by

\[
I_T = 2 \sum_{j=2}^{n} h \cdot k \cdot J_j
\]

(4)

where \( h \) is the thickness of the pollution layer.

\[
I_T = \frac{\sigma \cdot k}{\varepsilon} \left[ U(m-1,2) + U(m-1,n) + 2 \sum_{j=3}^{n-1} U(m-1,j) \right]
\]

(5)

Total resistance between the electrode which is system voltage applied and the ground electrode is

\[
R_T = \frac{U}{I_T}
\]

(6)

The calculations were done considering the half of the insulator model. Because of the symmetry, the calculations for one side of the insulator validate for its other side too.

Several criteria are used to control the arc propagation on the insulator surface; one of them is to analyze the arc dynamics till flashover is established by the equivalent impedance [2,5]. The difference between the arc gradient and the pollution gradient on the discharge root (\( \Delta E \)) with respect to electric field criterion is the most important factor to control the flashover [19,20,23–25]. The others include current/arc length criterion [26], the geometric shape criterion [27], and the energy criterion [18]. Furthermore, the pollution resistance in series with the arc that varies with time (\( dR/dt \)) is also considered [13,17,20,28].

Although some old studies assume that the arc propagation starts from the pin and elongate toward the cap the predischarges not only elongate by starting from one point, but can also occur on several points at the same instant depending on the state of the dry bands [20,24,28]. This fact has encouraged our investigation to develop this presented dynamic model having the actual insulator geometry including both the arc formation and propagation on the different zones of the leakage distance.
COMPUTATION OF AC FLASHOVER VOLTAGE

The points on the insulator surface where partial discharges occur are determined. These points provide arc propagation criterion ($E > E_{arc}$). In this step, arc voltage gradient is

$$E_{arc} = A I_T^n$$  \hspace{1cm} (7)

Values of the coefficients $A$ and $n$ change due to the environment conditions where the arc is ignited. When the arc is ignited in air, $A = 63$ and $n = 0.76$ are used for AC [24,25,29].

According to arc propagation criterion which was proposed in this study, electric field of the pollution layer is greater than electric field of the arc ($E > E_{arc}$). If the voltage gradient of the pollution layer is greater than the arc gradient, ionization in the arc strip will occur due to an increase in the current. In this case, the arc will propagate because of the leading voltage gradient. Otherwise, the arc will extinguish [19]. If the arc length is equal to the leakage length of the insulator for an applied voltage and a pollution level, the flashover occurs in the case $E > E_{arc}$ [30]. If the arc length is less than the leakage length and the arc criterion is provided, the dynamic change in the arc resistance is calculated. In this state, the values of electric field strength and current density change. Consequently, the flowing current towards ground electrode changes as well. This current is recalculated. So, the new arc resistance is calculated and the same processes are repeated for a new resistance. If arc criterion is not still provided, the applied voltage is increased and these steps are repeated. When the arc occurs between any two points on the insulator surface, the values and positions of the field strength along the leakage length on the insulator surface is redetermined by using values of the new pollution resistance. The same processes are repeated until the arc occurs at all the points on the leakage length. Because of formation of the dry band in the zone between two points on which the arc occurs, this situation was considered at calculation of the pollution resistance in series with the arc [31].

3. COMPUTER PROGRAM

FLASHOVER program has six subprograms, if it is generalized. These subprograms make use of 27 subprograms. Diameter, leakage length and profile of the insulator, pollution density of region to be used, atmospheric conditions, level and type of the voltage, etc. were used in the initial data for determination of surface flashover performance of a polluted insulator.

A general flowchart of FLASHOVER program is shown in Figure 4. In FLASHOVER program, the nodes on the leakage length and their coordinates are first read. By using the coordinates of the nodes on a line along the leakage length because of insulator's symmetry, all the nodes are rotated 360° by increasing step by step as much as a predetermined angle. In each step, the coordinates of all the nodes along the insulator surface are obtained and these coordinates are arranged in a suitable formation for the FEM solution. Then, the coordinates of all the nodes belonging to a mesh are constructed manually. Consequently, the three node numbers for each triangle (element), the nodes which define the function and their potentials, the nodes on the leakage length and their coordinates, the dielectric constants of each element, and the coordinates which belong to the boundary points describing the insulator are read. Afterwards, dielectric constant of the air ($\varepsilon_0$), dielectric constant of the pollution layer ($\varepsilon_r$), conductivity ($\sigma$), $\pi$, frequency ($f$), etc. are assigned by the user. Finally, the potentials of all the nodes are computed. After flowing current from the pollution layer is computed, field strengths of all the nodes are computed. Differences in the field strength between every two nodes ($\Delta E$) are checked along the leakage path. If the arc occurs between two nodes, the potential values of these nodes are computed. The node numbers and potential values are added to the series which has been constructed by nodes whose potentials are known. After that the process comes back to the section where the potentials of the nodes have obtained and the potential value is increased. Checking field strength values between the nodes allows us to see whether the arc occurs or not. If the arc occurs between all the nodes, the flashover occurs along the insulator surface.

The potentials of the nodes on the model and flowing currents from pieces of the pollution layer between these nodes and ground electrode have been computed. Surface conductivity values of these pieces are known. As the resistance value is computed, the applied voltage to pin is divided to total current which flows to ground electrode from the points on the leakage length. Zero volt to nodes on the cap and system voltage to nodes on the pin are applied. Coefficients matrix and right side matrix are made zero before the solution started. Then, initial values of the function are placed into the coefficients matrix assuming that the potentials of the nodes on the cap are equal. The system matrix equation formed by using FEM is solved with successive over relaxation (SOR) method.
4. APPLICATION

In this study, MESH and FLASHOVER programs have been used for computing the flashover voltages. In addition, other special programs have been used for drawing AR model and preparing the finite element mesh of the insulator.

First, the scaled shape of the considered insulator was meshed by triangular elements and the shape was drawn to millimetric paper and so initial file was prepared. The corner coordinates of all the triangles, dielectric constants, the pollution conductivity values, etc. were located in this file. Then, MESH program was run. Note that if it is desired, the number of triangular elements can be increased by MESH program. This program determines the coordinates of the nodes on the leakage length of the insulator, the coordinates of the boundary points of the material, and electrical characteristics of all the elements. Finally, the values of potential and electric field strength, the pollution resistance in series with the arc, and the flashover voltage were computed by the FLASHOVER program. Similar computations for the flashover voltages of different types of insulators were obtained.

The scaled shapes of the insulators considered are shown in Figure 5 and the characteristic values of the insulators are given in Table I. Hi, d, L, and n are height (mm), diameter (mm), leakage length of the insulator for an element (mm), and the number of element on a chain in Table I, respectively.
The air around the insulator and pollution layer on the insulator surface was meshed. Finite element mesh generation for one of the polluted insulators considered (80 F 140 W—E type) is shown in Figure 6.

The values of AC flashover voltage computed by using the dynamic model proposed in this study for all the insulators in Table I are shown in Figures 7 and 8. The computed flashover voltages for an element are in Figure 7 and the computed flashover voltages for a total chain (Table I) are in Figure 8. It can be seen from these figures that in response to an increase in the surface conductivity, the flashover voltage decreases. Variations of electric field strength against the leakage length for different pollution conductivities for C insulator are shown in Figure 9.

Flashover performance of the insulators has been compared under different pollution severity levels. Pollution levels are classified by IEC [32] according to surface conductivity \( \sigma_s \) of the pollution layer on the insulator surface as follows:

1. no significant pollution, \( 5 \mu \text{s} < \sigma_s < 10 \mu \text{s} \),
2. light pollution, \( 10 \mu \text{s} < \sigma_s < 20 \mu \text{s} \).

<table>
<thead>
<tr>
<th>Insulator type</th>
<th>( H_i ) (mm)</th>
<th>( D ) (mm)</th>
<th>( L ) (mm)</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>F7</td>
<td>146</td>
<td>255</td>
<td>311</td>
</tr>
<tr>
<td>B</td>
<td>7K3</td>
<td>185</td>
<td>288</td>
<td>304</td>
</tr>
<tr>
<td>C</td>
<td>BULLERS</td>
<td>140</td>
<td>290</td>
<td>418</td>
</tr>
<tr>
<td>D</td>
<td>80AL146W</td>
<td>146</td>
<td>355</td>
<td>415</td>
</tr>
<tr>
<td>E</td>
<td>80F140W</td>
<td>140</td>
<td>280</td>
<td>415</td>
</tr>
<tr>
<td>F</td>
<td>U100L</td>
<td>146</td>
<td>255</td>
<td>300</td>
</tr>
<tr>
<td>G</td>
<td>U40BL</td>
<td>110</td>
<td>175</td>
<td>185</td>
</tr>
<tr>
<td>H</td>
<td>U70BL</td>
<td>146</td>
<td>255</td>
<td>280</td>
</tr>
<tr>
<td>I</td>
<td>U160BL</td>
<td>170</td>
<td>280</td>
<td>390</td>
</tr>
<tr>
<td>J</td>
<td>U100BLP</td>
<td>146</td>
<td>280</td>
<td>432</td>
</tr>
</tbody>
</table>

Table I. Characteristic values of the insulators which computed flashover voltages.
3. heavy pollution, $20 \mu s < \sigma_s < 40 \mu s$,
4. very heavy pollution, $\sigma_s > 50 \mu s$.

Variations of the computed AC flashover voltages for an element based on the insulator types are drawn in Figure 10 for light pollution ($\sigma_s = 15 \mu s$). The effect of height, diameter, and leakage length of the insulators to flashover voltage is shown in Figure 10. The comparison of AC flashover voltages computed by using the dynamic model with the theoretical or experimental results of other researchers for C insulator is given in Figure 11 and the comparison for B insulator is given in Figure 12. It can be seen from these figures that the difference between flashover voltages is very small for light and heavy pollution, but the difference is bigger for no significant pollution. Separately, while flashover voltage of Cron [33] is smallest for $\sigma_s = 5 \mu s$, the flashover voltage is biggest for
$\sigma_s > 40 \mu s$ in Figure 11. This state is interesting. Consequently, the calculated curves based on the proposed dynamic model give better agreement with the experimental and theoretical curves.

Long rod insulators are used for medium and high voltage overhead distribution and transmission lines for suspension or tension of conductor to the posts. Long rod porcelain insulators provide better operation conditions in comparison to cap and pin type insulators and other composite long rod insulators on polluted and sea-side areas.

The cross-section of the long rod insulator type VKL 75/14 which has 1270 mm of height, 157 mm of diameter, and 1876 mm of leakage length, is given in Figure 13. The flashover voltages have been computed by using dynamic model for VKL 75/14 insulator and the results have been compared with results obtained from other researches. The comparison of modeled results of flashover voltage against the surface conductivity with the experimental and theoretical results of earlier researches for long rod insulator type VKL 75/14 is shown in Figure 14. All of the curves are theoretical except for c curve in Figure 14. It can be seen that computed flashover voltage values are rather similar to the theoretical and experimental results of other researchers.

Figure 8. The computed flashover voltages (for total of a chain).

Figure 9. Variations of electric field strength along the leakage length for C insulator.
Figure 10. The computed flashover voltages according to insulator type (for an element).

Figure 11. Comparison of flashover voltages for C insulator (for a chain of nine elements) (a, Rumeli [21]; b, Cron [33]; c, Özbek [1]; d, dynamic model).

Figure 12. Comparison of flashover voltages for B insulator (for a chain of seven elements). (a, Rumeli [21]; b, Cron [33]; c, Özbek [1]; d, dynamic model; e, Wilkins [33]; f, Sundararajan [19]).
5. CONCLUSION

The flashover characteristics have an important practical value since they can be used by design engineers for proper selection of insulators for power systems operating in polluted regions. They also have special importance in the development of new insulator shapes for polluted localities as they provide quick evaluations. However, the reliability and validity of the flashover characteristics in measuring the flashover performance of high voltage insulators should still be checked by natural and artificial tests for some
time. When the flashover characteristics are improved and established well, this will eliminate the burden of natural and artificial pollution tests for the assessment of insulator flashover performance.

The use of a dynamic arc model that calculates the pollution flashover voltage of insulators with various profiles has been demonstrated. The model predictions correlate well with the experimental results. The diameter and leakage length has strong influence on the flashover voltage. In addition, the length of the underribs or skirts and the distance between them also play a major role on contamination.

The values of computed flashover voltages show that J insulator has the biggest flashover voltage and G insulator has the smallest flashover voltage. It should be noted that J insulator has the longest leakage length and G insulator has the shortest leakage length. J insulator has the best flashover performance. G insulator which has the smallest height and diameter and the shortest leakage length shows the worst performance from the flashover performance perspective. J, C, and E insulators which show similarity based on the insulator geometry and dimensions, and B, A, I, D, F, and H insulators whose leakage lengths are very close show the similar flashover behaviors.

It is seen that computed flashover characteristics by using the proposed dynamic model in this study are similar to the results of different researches in Figures 11 and 12. The developed dynamic arc model can be used confidently for calculation of the flashover voltages of polluted string insulators. It is expected that this model will help reduce the number of experiments. The same calculations must be done for non-uniform pollution distribution as well.

6. LIST OF SYMBOLS AND ABBREVIATIONS

6.1. Symbols

- \( d \): diameter
- \( E \): electric field
- \( E_{\text{arc}} \): arc voltage gradient
- \( f \): frequency
- \( h \): thickness
- \( H_i \): height
- \( I \): current
- \( J \): current density
- \( L \): leakage length
- \( n \): number of element
- \( R_T \): total resistance
- \( U \): potential
- \( U_{\text{avg}} \): average of potentials
- \( \sigma \): conductivity
- \( \varepsilon \): dielectric constant

6.2. Abbreviations

- FEM: finite element method
- SOR: successive over relaxation

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