IWAIS XI, Montréal, June 2005

Flashover Performance of Station Post Insulators under Icing Conditions based on Electric Field Distribution

V. Jaiswal and M. Farzaneh
NSERC / Hydro-Quebec / UQAC Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE) and
Canada Research Chair on Engineering of Power Network Atmospheric Icing (INGIVRE) at Université du Québec à
Chicoutimi, Québec, Canada, G7H 2B1 (http://cigele.ca)

Abstract— **The main objective of this paper is to study flashover performance based on potential distribution of a standard post insulator for power frequency, lightning impulse (1.2/50 μS) and switching impulse (250/2500 μS) voltages under icing conditions. The potential distribution is computed numerically using the finite element method (FEM) by creating an artificial boundary first far away from the device and then in turn, an open boundary around the insulator is simulated by Kelvin transformation, thus saving considerable memory and computation time. In Kelvin transformation, the region between the domain of interest and infinity is modeled simply by adding a circular boundary, connected to a second mesh of the same size, and boundary constraints to force equivalent boundary potentials to be identical. Infinity lies at the center of the second mesh. Simulation results are confirmed by laboratory experiments, and it has been found that switching impulse is the limiting factor for the design of a semi-conducting glazed insulator under icing conditions. This is contrary to clean conditions, where it has been found that lightning impulse is the limiting factor for the design of a semi-conducting glazed insulator.**

I. INTRODUCTION

FLASHOVER on ice-covered insulators is a complex phenomenon as it involves many processes and mechanisms [1]. Studies of flashover characteristics of insulators are necessary to determine suitable insulator profiles for a particular application. The flashover voltage depends on the electric field distribution, which is mainly distorted by the presence of a water film and air gaps along the ice-covered insulators.

Theoretical models that compute the flashover voltage of ice-covered insulators are useful for two main purposes: (i) to better understand the physical processes responsible for flashover, and (ii) to predict the flashover voltages over a wide range of field conditions, if the model can be shown to be well correlated with field or laboratory experiments. Such a model could help reduce the number of laboratory experiments needed for the better design of insulators.

The ice-covered insulator is an unbounded problem, and hence for studying the effects of semi-conducting glaze coating on the electrical performance by computing potential distributions around the insulator, an artificial boundary, far away from the device where electric fields are effectively zero, has been defined when the mesh is generated. It can take considerable memory and computation time for high voltage (HV) applications.

In Kelvin transformation, the region between the domain of interest and infinity is modelled simply by adding a circular boundary, a second mesh of the same size, and boundary constraints to force equivalent boundary potentials to be identical. Infinity lies at the centre of the second mesh. In effect, the second mesh represents the conformal transformation of all the space exterior to the first mesh into a circle [2]. Using this idea, no deep knowledge of analysis is needed; very little extra computer time is necessary; and frequently fewer elements are required than for most other methods of calculating the potential distributions around ice-covered insulators for high voltage applications.

II. FLASHOVER PERFORMANCE BASED ON POTENTIAL DISTRIBUTION

Flashover performance can be predicted by computing electric field strengths around the insulator. When the electric field strength, at any point, exceeds the corona onset field, discharges occur at that point and may lead to flashover. Computation of the electric field strength involves large error, because of the numerical differentiation of potential at any point. Hence potential distributions along the insulator have been computed in this work. By visible inspection of potential distributions, flashover performances have been predicted.

The general solution for the low frequency electromagnetic fields in insulating systems has been obtained by solving Maxwell's equations.

To apply the finite element method, a functional based on the system energy is defined that can be applied for the stated problem. Minimization of the system energy leads to a system of algebraic equations, whose solution, under the application of corresponding boundary conditions (Dirichlet, Neuman or mixed), supplies the required node potentials.

III. COMPUTATION OF POTENTIAL DISTRIBUTION

Fig. 1 shows the ice-covered station post insulator, simulated in this work.

It is assumed that the ice is accumulated uniformly on the insulator. The potential distributions have been computed on a vertical plane cutting the insulator into four symmetrical parts.

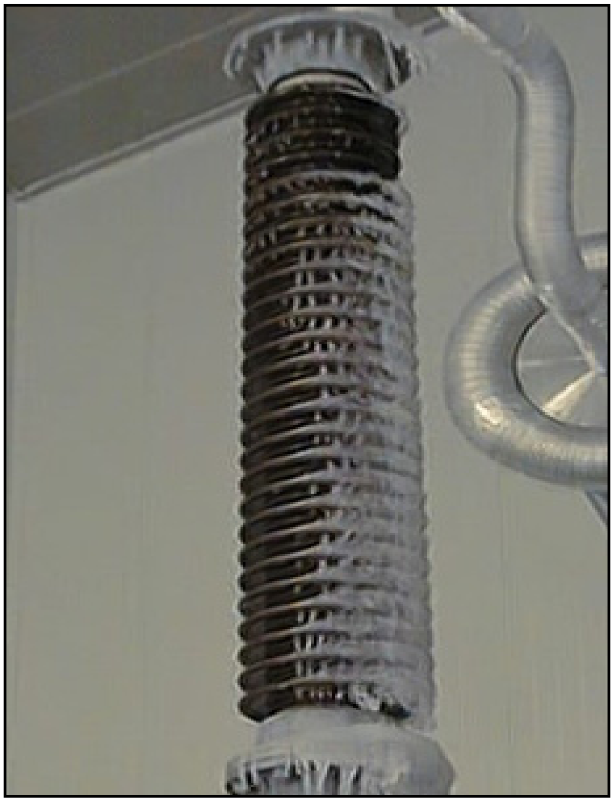

Fig.1. Ice-covered insulator (laboratory model)

A. *Simulation parameters*

TABLE 1 shows the set of parameters used in the simulation work. The conductivities of ice and porcelain are neglected supposing that all the leakage current flows in the semi-conducting glaze and water film.

TABLE 1
SIMULATION PARAMETERS

	Porcelain	Semi-conducting Glaze	Ice-layer	Water film
Permittivity (ε_r)	6.0	16	75.0 for 60 Hz (variable)	81.0 (variable)
Conductivity (µS/cm)	0	0.22 (variable)	0	150-350 (variable)
Thickness (mm)	-	0.5	15	1.0

Since ice-covered insulator is an open boundary problem. There are two methods to compute the potential distribution along the insulator.

B. *Artificial boundary*

Artificial boundary is defined three to four times the device radius away from the device. At this boundary, it is assumed that the electric fields fall off to zero. The position of the artificial boundary is important because the entire interior region up to the boundary must be discretized, and this increases the size of the problem without adding any useful information [3]. Fig. 2 shows the insulator model with artificial boundary.

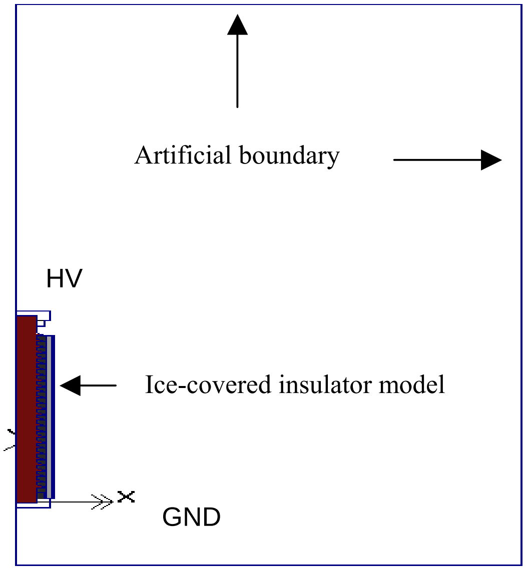

Fig. 2. Ice-covered insulator with artificial boundary

C. *The Open Boundary Simulated by Kelvin Transformation*

The Kelvin transformation only transforms space and, strictly speaking, is not applicable to three-dimensional or rotationally symmetric geometries. It does not of itself in anyway transform the material properties. It is for this reason that an extra step in the derivation is necessary. As a starting point, it is useful to consider the problem in network terms. Imagine a three-dimensional model based on a spherical geometry, with a defined center. The main region of interest lies immediately around the center and extends to a radius "a". Beyond that radius there exists only non-electric, non-conducting material.

The network model is built up as a series of spherical shells. The outer region network could be rebuilt as a network within a sphere of radius "a". The successive radii within the new network are to be the transformed equivalent radii of the original outer network [2].

To complete the model, the extra step is to modify the impedances of the network so that the impedance, looking into the new model from any pair of points, is identical to the impedance seen looking out from those same two points, in the original model. This change in impedance is achieved by applying a transformation to the material properties. This was first done by Ciric and Wong [4, 5]. Their approach was based on algebraic transformations, and they were able to effect great economy of effort in achieving solutions for a range of basic geometries. Later Freeman and Lowther [2] developed the technique to use an all-enveloping sphere that can be applied to the solution of a general range of field problems using finite elements.

Fig. 3 shows the insulator model for the computation of potential distribution by simulating open boundary by Kelvin transformation.

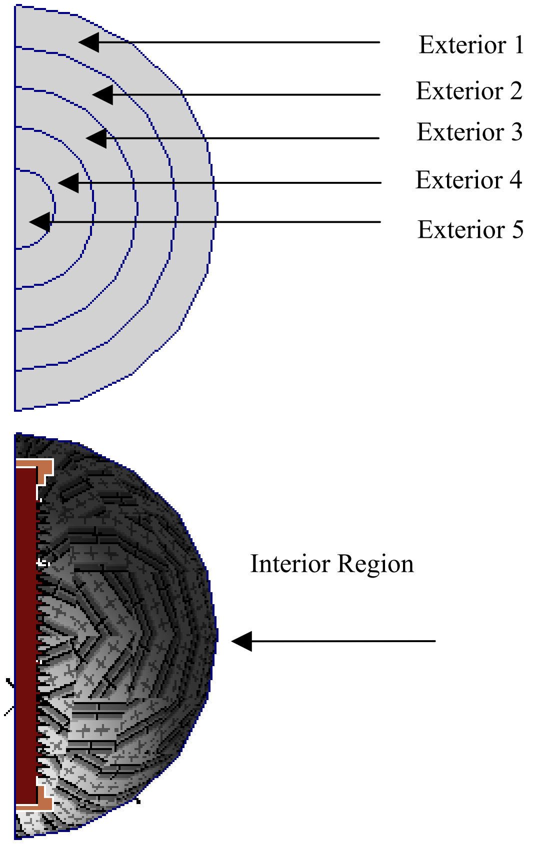

Fig. 3. Insulator model for computation of potential distribution using Kelvin transformation

D. *Clean and ice-covered insulators with a water film*

Computations have been carried out for power frequency, and equivalent sinusoidal voltages of switching impulse (SI) and lightning impulse (LI) voltages. The potential distributions have been computed along the insulator surface from the HV electrode to the grounded electrode for uniform ice accretions.

For switching impulse

$$t_r = 250\mu s$$

$$F_{eq} = 1/\pi t_r = 1.3KHz$$

For lightning impulse

$$t_r = 1\mu s$$

$$F_{eq} = 1/\pi t_r = 320KHz$$

Where t_r is rise time of the impulse.

IV. EXPERIMENTAL VALIDATION

To verify the simulation results, flashover tests have been carried out in a climate room of dimensions 6.2×5.7×3.8 meter on a semi-conducting glazed insulator covered with a glaze ice of thickness 1.5 cm, with a water film and an air gap. The conductivity of the water used to form the glaze ice is taken as 80 µS/cm. Dripping water conductivity was measured after the flashover test and it is found to be 300 µS/cm. Dripping water conductivity is increased to 300 µS/cm from 80 µS/cm because all the salt (NaCl) comes to the surface during the ice accumulation process under service voltage. The length of the tested insulator was 80 cm. Flashover tests were performed for positive lightning impulse and switching impulse voltages.

A. *Experimental Setup*

Fig. 4 shows the experimental setup used during the flashover performance test. Impulse voltages were generated using a Marx generator and shaped to standard lightning impulse voltage (1.2/50µS) and switching impulse voltage (250/2500µS) using external resistors. The test sample was kept in the climate room. The voltage was applied through a bushing.

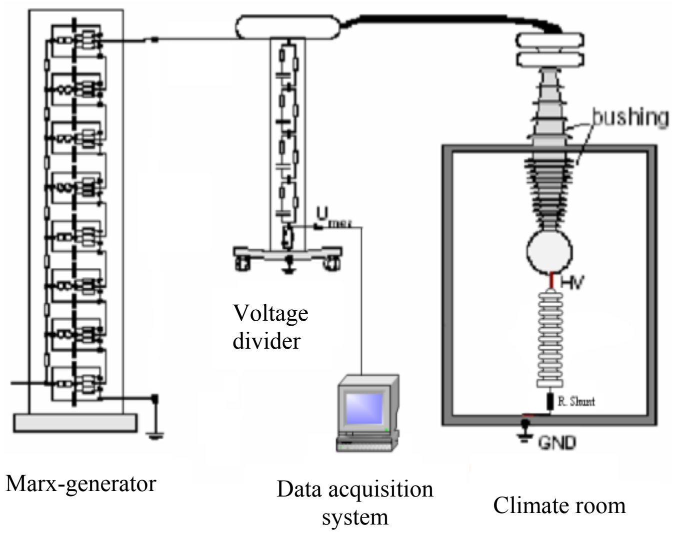

Fig. 4. Impulse flashover performance test

B. *Ice Deposit Method*

Natural conditions were simulated as closely as possible by depositing artificial ice on energized insulators in the climate room. The testing conditions were adjusted to form wet-grown ice on energized insulators. This type of ice is associated with the highest probability of flashover [6]. In the climate room, the parameters such as air temperature and wind velocity, as well as both the vertical and horizontal components of precipitation intensities, are controlled and kept constant following the instructions provided in [7].

The service voltage was applied to the test insulator during the whole icing period. This is necessary for a more realistic simulation of the natural icing of insulator equipment in the field [7]. In fact, the electric field affects ice accretion during its formation [8], particularly the progression of icicles and, consequently, the formation of the air gaps. The location, number, and length of these air gaps are major factors in electric field distortion [9], and consequently, flashover voltage level.

C. *Ice Test Preparation Prior to Flashover*

A preparation period is needed between the end of the ice accretions at subzero air temperature and the moment when the test voltage is applied for the flashover voltage evaluation. The procedure may be adjusted according to two approaches, that is, performing the test under the "icing regime" or under the "melting regime" [7].

In this work, testing is done under the "icing regime." The test insulator is exposed to conditions as close as possible to those in the field (e.g. freezing rain conditions).

Testing under the "icing regime" corresponds to the case where the flashover performance test is carried out shortly after the ice accretion is completed and a water film is still present on the ice surface [8]. In such a case, the preparation period is short, typically about 2 to 3 minutes. This gives enough time for taking pictures, adjusting the test setup, installing/removing the collector receiving dripping water from the test insulator, and measuring ice thickness. Immediately after this period, the flashover test voltage is applied.

TABLE 2 shows the test conditions, used for the experiments.

TABLE 2

Chamber dimensions	6.2×5.7×3.8 m
Accumulation voltage	64 kV, 60 Hz, AC
Test voltages	Lightning and Switching Impulse, up-and-down method ($V_{50\%}$)
Accumulation temperature	-12°C
Ice thickness	15 mm
Type of ice	Glaze
Conductivity	80 µS/cm at 20°C

EXPERIMENTAL TEST CONDITIONS

D. *Ice Test Flashover Performance Evaluation*

High leakage currents from an appropriate power supply, including both partial and flashover arcs, generally change the length and shape of air gaps i.e. ice free areas formed along the ice covered insulator, modify the ice surface conductivity, and will sometimes totally shed the ice deposit. These changes will affect the flashover voltage of test insulators [7]. Therefore, only one flashover test was achieved for any ice accretion sequence.

V. RESULTS AND DISCUSSION

Potential distributions were computed around insulators by a commercially available program based on the finite element method. For each simulation, the voltage applied was 100 kV peak. Using an artificial boundary, time taken for the computation of potential distribution on Pentium 4 computer for polynomial order 4 and Conjugate gradient tolerance 0.0001%, was 68 hours 45 minutes. Time taken for the computation of potential distribution using Kelvin transformation was 25 hours 57 minutes only. Potential distributions along the semi-conducting glazed insulator, computed by both methods, are compared, and are found to be in agreement.

Fig. 5 shows the potential distributions along an insulator at the tip of the sheds at a distance of 15.0 cm, radially out from the center of the insulator, down the length of the insulator, coated with a semi-conducting glaze of thickness 0.5 mm with conductivity 22 x 10^{-6} S/m for an equivalent lightning impulse, an equivalent switching impulse and power frequency voltages, covered with wet glaze ice in presence of an air gap of length 7.5 cm. It is observed that the potential distribution is more linear for a lightning impulse voltage than that for a switching impulse voltage.

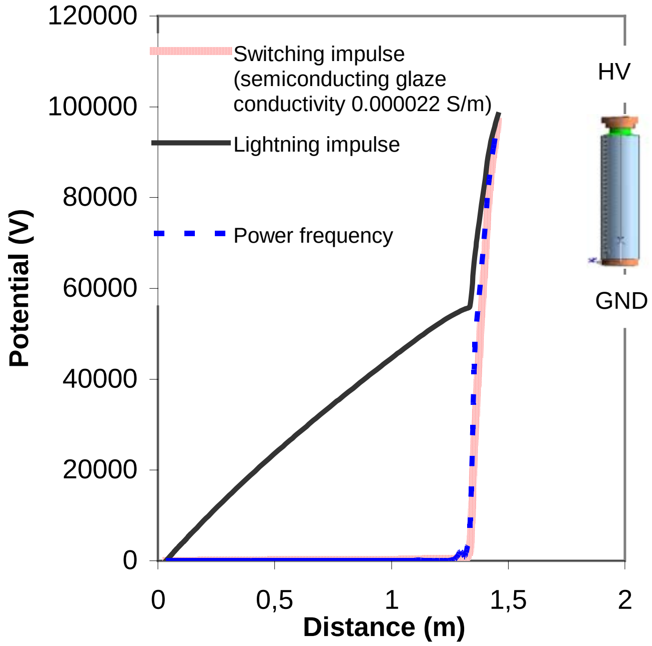

Fig. 5. Potential distributions along a wet ice-covered insulator coated with semi-conducting glaze for equivalent switching impulse, equivalent lightning impulse and power frequency voltages

Fig. 6 shows the potential distributions along the clean insulator at the tip of the sheds at a distance of 15.0 cm, radially out from the center of the insulator, down the length of the insulator, coated with semi-conducting glaze of thickness 0.5 mm with conductivity 22 x 10^{-6} S/m, for 320 KHz and 1.3 KHz sinusoidal voltages, equivalent to lightning and switching impulse voltages, respectively. It is observed that the potential distribution is more linear for switching impulse voltage than for lightning impulse voltage.

Fig. 7 shows the flashover voltages measured under icing and clean conditions for the test conditions mentioned in the previous section. It is observed that the switching impulse is the limiting factor in the design of the semi-conducting glazed insulator under icing conditions, as predicted by the simulation results. This is contrary to clean conditions where it is observed that the lightning impulse is the limiting factor for the design of the semi-conducting glazed insulator, as predicted by the simulation results.

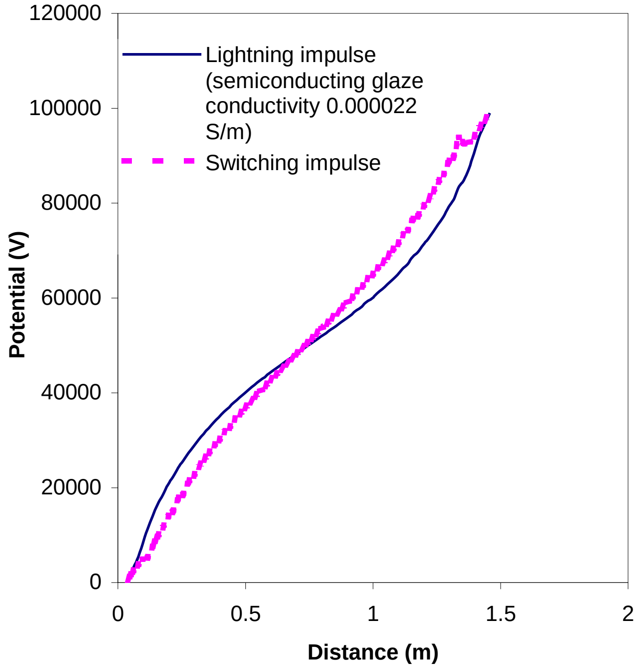

Fig. 6. Potential distributions along a clean standard insulator coated with semi-conducting glaze for equivalent lightning and equivalent switching impulse voltages

Fig. 7 also shows that the ice, accumulated on the insulator, has little effect on the flashover voltage of the semi-conducting glazed insulator for lightning impulse voltage. This is in agreement with our simulation results, as shown in Figs. 5 and 6, that the potential distributions for a lightning impulse voltage, along the wet ice-covered semi-conducting glazed insulator with an air gap, and the potential distribution along clean semi-conducting glazed insulator, are both almost linear.

Fig. 7 further shows that the ice significantly reduces the flashover voltage of the semi-conducting glazed insulator for switching impulse voltage. This is also in agreement with the simulation results shown in Figs. 5 and 6, where the potential distribution for a switching impulse voltage is not linear along the insulator when the insulator is covered with wet ice with an air gap formed along the insulator, but the potential distribution along the clean insulator is linear.

VI. CONCLUSIONS

The following conclusions have been drawn from this work:

1. In the case of an open boundary, simulated by Kelvin transformation, computation time for the computation of potential distribution along a wet ice-covered semi-conducting glazed station post insulator with an air gap is much less than that by taking an artificial boundary.

2. From the simulation results, confirmed by the experimental results, it has been found that a switching impulse is the limiting factor in the design of a semi-conducting glazed insulator under icing conditions, because the potential distribution is linear along the semi-conducting glazed insulator studied for an equivalent lightning impulse voltage under icing conditions.

3. This is opposite to clean conditions where it has been found that a lightning impulse is the limiting factor in the design of the semi-conducting glazed insulator under clean conditions, because the potential distribution is more linear along the studied semi-conducting glazed insulator for an equivalent switching impulse voltage under clean conditions.

4. From the simulation results, confirmed by the experimental results, it has been found that accumulation of ice on the insulator does not have a major effect on its flashover voltage for a lightning impulse voltage, but ice significantly reduces the flashover voltage of the semi-conducting glazed insulator for switching impulse voltage.

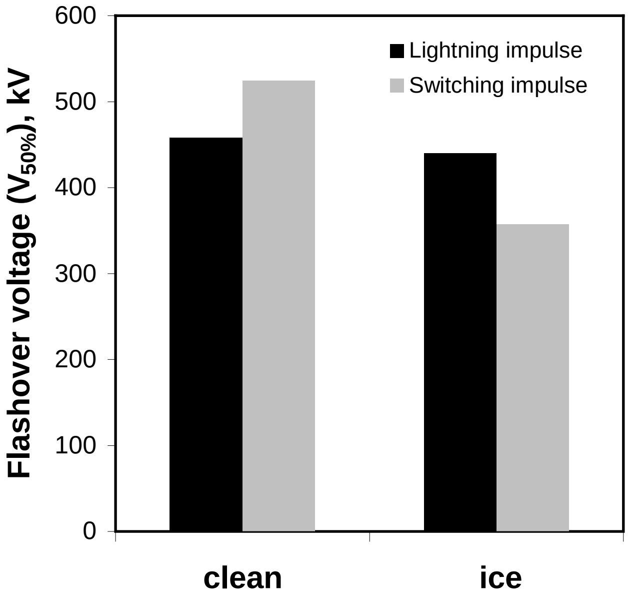

Fig. 7. Impulse flashover performance of a semi-conducting glazed standard post insulator (experimental results)

VII. ACKNOWLEDGMENT

This work was carried out within the framework of the NSERC/Hydro-Quebec/UQAC Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE) and Canada Research Chair on Engineering of Power Network Atmospheric Icing (INGIVRE) at the University of Quebec at Chicoutimi. The authors would like to thank all the sponsors of the project.

VIII. REFERENCES

1. M. Farzaneh, “Ice Accretion on H.V. Conductors and Insulators and Related Phenomena,” Invited article, Philosophical Transactions, The Royal Society, Londres, no. 358, pp. 1-35, 2000.

2. E.M. Freeman and D.A. Lowther, “An Open Boundary Technique for Axisymmetric and Three Dimensional Magnetic and Electric Field Problems,” *IEEE T-MAG,* MAG-25, pp. 4135-4137, September 1989.
3. Vinay Jaiswal and M Joy Thomas, “Finite Element Modeling of Ionized Field Quantities around a Monopolar HVDC Transmission Line,” *Journal of Physics D: Applied Physics,* vol. 36, no 23, pp. 3089-3094, December 2003.
4. S. H. Wong and I. R. Ciric, “Method of Conformal Transformation for the Finite Element Solution of Axisymmetric Exterior Field Problems,” *COMPEL,* pp. 123- 135, 4, 1985.
5. I. R. Ciric and S. H. Wong, “Inversion Transformations for Finite Element Solutions of Three Dimensional Exterior Field Problems,” *COMPEL,* pp. 109-119, 5, 1986.
6. M. Farzaneh and J. Kiernicki, “Flashover performance of IEEE standard insulators under icing conditions,” *IEEE Trans. Power Delivery*, vol. 12, pp. 1602-1613, October 1997.
7. M. Farzaneh et al, “Insulator Icing Test Methods and Procedures,” *IEEE Trans. Power Delivery,* vol. 18, pp. 1503-1515, October 2003.
8. M. Farzaneh, “Ice accretion on high-voltage conductors and insulators and related phenomena,” *Philos. Trans. Roy. Soc.,* vol. 358, no. 1776, pp. 2971-3005, Nov. 2000.
9. M. Farzaneh, C. Volat and A. Gakwaya, “Electric Field Calculation around Ice-covered Insulator Using Boundary Element Method,” *IEEE International Symposium on Electrical Insulation,* Anaheim, California, pp. 349-355 April 2000.