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New mathematical formulations for calculating residual resistance in a static arc model of ice-covered insulators

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ABSTRACT

This paper develops two new mathematical formulations for calculation of the residual resistance in a static arc model to predict ac and dc flashover voltages of heavy ice-covered insulators. In the first formulation, appropriate for dc with a small insulator string, the residual resistance is considered as a resistance between a small circular conductor where it models the arc root and the ground electrode. It is shown that using this new formula for a static dc arc model with heavy ice-covered insulators leads to an improved model to predict flashover voltage. In the second formulation, appropriate for ac and dc with long insulator strings, the residual resistance is considered as a resistance between two small circular conductors modeling two arc roots where the arcs are on air gaps formed near the high voltage and ground electrodes. The method of image charges is used in both formulations. The capability of this improved static arc model is confirmed when it is compared to that of previous static and dynamic models. This improved arc model has a better correspondence with the experimental results than the previous static and dynamic models. It can be used as a powerful tool for the design and selection of insulators subjected to ice accretion.

1. Introduction

In many cold climate regions, a most important challenge is the decrease in outdoor electrical insulation strength of power network insulators under ice and snow conditions. This can sometimes lead to flashover and consequent power outages which have been reported in North America (Charneski et al., 1982; Cherney, 1980; Farzaneh and Kiernicki, 1995; Kawai, 1970; Schneider, 1975) as well as in many cold climate countries of Europe (Fikke et al., 1993, 1994; Meier and Niggli, 1968) and Asia (Fujimura et al., 1979; Matsuda et al., 1991). A detailed industry survey (Yoshida and Naito, 2005) reported that 35 utilities in 18 countries had ice- and snow-related electrical flashover problems. In particular, a total of 83 such events (69 on lines, and 14 in stations) occurred on transmission lines from 400- to 735-kV in relatively clean conditions. From January 2006 to June 2007 only, ice-covered insulators flashovers in China caused failures of 500-kV lines four times (Su et al., 2012). A recent power outage lasting for a long period of time happened in thirteen provinces of southern China early in 2008 where more than 30,000 transmission lines and 8000 towers were damaged, with a direct economic loss of nearly 10 billion RMB (1.6 billion dollars) (Deng et al., 2012; Su et al., 2012). Furthermore, it should be noticed that there were 61 trippings caused by flashover of iced insulators in China in 2012 while the flashovers trippings caused by pollution happened only 11 times (Guan et al., 2014).

Therefore, a great deal of research including field and laboratory tests in controlled conditions and the development of mathematical models has been carried out to understand the flashover process on ice and snow-covered insulators (Farzaneh, 2014). To the best of our knowledge, Farzaneh and Zhang (2000), Farzaneh et al. (1997), and Zhang and Farzaneh (2000) provided the first attempts to model AC and DC arc discharge on an ice surface in order to calculate the flashover voltage of heavy ice-covered insulators where ice accretion, *t*, on a reference rotating cylinder is $t > 10$ mm (Farzaneh and Chisholm, 2009).

Based on a number of tests carried out on ice-covered insulators during the flashover process it was observed that several violet arcs first appeared across the air gaps followed by the extension of one of the arcs along the ice surface forming a white arc. When the white arc reached a certain length, a flashover occurred suddenly. Therefore, the electrical flashover process on an ice surface can be described adequately by adapting the Obenaus approach (Obenaus, 1958) for the polluted insulators as described in Farzaneh and Zhang (2000), Farzaneh et al. (1997), and Zhang and Farzaneh (2000), including the arc discharge on an air gap in series with an ice layer.

Direct laboratory measurements of arc constants, surface conductance, and reignition conditions in Farzaneh and Zhang (2000),

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Farzaneh et al. (1997), and Zhang and Farzaneh (2000) lead to values that differed systematically from those found for flashovers on polluted surfaces. In Farzaneh et al. (2004) and Shu et al. (2012), static arc models were adapted to take into account the influence of air pressure on ac and dc flashover voltage of ice-covered insulator strings. Moreover, static arc models were elaborated in order to model ac and dc flashovers on long-rod ice-covered composite insulators taking into account the influence of different shed configurations and low atmospheric pressure in Hu et al. (2007, 2011, 2012), Jiang et al. (2011), and Shu et al. (2014).

The above mentioned static models, as well as the dynamic models (Farzaneh et al., 2003b; Taheri et al., 2014; Tavakoli, 2004) and the finite element method (FEM) based models (Volat et al., 2011; Yang et al., 2007) were developed, providing powerful tools to predict AC and DC flashover voltage, thus minimizing time consuming experimental laboratory tests (Farzaneh et al., 2003a; IEEE std., 1783, 2009) and the use of equipment.

Although dynamic models can predict the whole temporal evolution of the flashover process, the parameters of a modeled equivalent electrical circuit need to be calculated. Some parameters of the model, particularly the capacitance between the arc tip and the opposite electrode, C, as well as the arc channel inductance, L, may be influenced in service conditions by the presence of corona rings, arcing horns, phase conductors, towers and other metallic structures. So, more complex closed-form formulas or numerical calculations are needed to take those into account. Moreover, the value of the heat dissipation rate, P_0, used in Mayr's equation (Mayr, 1943) to calculate the arc channel resistance should be adjusted for different geometries and different freezing water conductivities in order to obtain good agreement between the simulation and the laboratory test results (Taheri et al., 2014; Tavakoli, 2004).

FEM models need commercial FEM software, like COMSOL Multiphysics®, to compute the electric field and the leakage current (Volat et al., 2011; Yang et al., 2007).

The equation used for calculating the residual resistance both for the static (Farzaneh and Zhang, 2000, 2007; Farzaneh et al., 1997; Zhang and Farzaneh, 2000) and dynamic models (Farzaneh et al., 2003b; Taheri et al., 2014; Tavakoli, 2004) is based on the formula developed by Wilkins (1969) for a flat model of polluted insulators. In this paper, two new equations are formulated for the residual resistance. As compared to the present static and dynamics models, the improved static model developed in the present paper, where these new equations are used instead of Wilkins's equation, provides a better fit with laboratory test results.

2. Static model description

The mathematical model for analyzing the flashover on ice-covered insulating surfaces (Fig. 1) is given by:

$$V = AxI^{-n} + V_e + IR_p(x) \tag{1}$$

where V(V) and I (A) are the applied voltage and leakage current (in AC case there are peak values), A and n are the arc constants, x (cm) is the length of the arc, V_e is the electrodevoltage drop, and $R_p(x)$ (Ω) is the residual resistance of ice section not bridged by the arc.

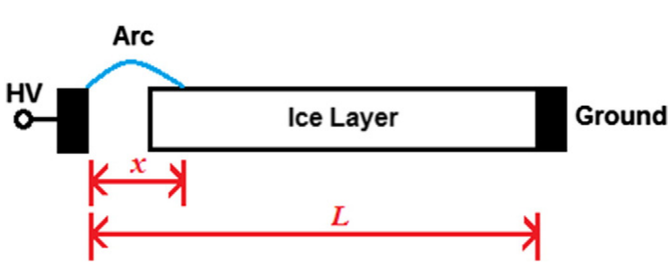

Fig. 1. Physical model of an arc on an ice surface.

Under AC conditions, in order to maintain an arc burning on a dielectric surface, another equation with regards to arc reignition condition must also be satisfied:

$$V = \frac{kx}{I^b} \tag{2}$$

where k and b are reignition constants. Experimental investigations at CIGELE established the parameters of Eqs. (1) and (2) as those presented in Table 1 (Farzaneh and Zhang, 2000, 2007; Farzaneh et al., 1997; Farzaneh-Dehkordi et al., 2004; Zhang and Farzaneh, 2000).

Since the ice layer only covers the windward side of insulator string, as reported in (Drapeau and Faraneh, 1993), the ice deposit was considered as a half cylinder with rectangular surface of length L(cm)and width W(cm) given by:

$$W = \frac{\pi(D + 2\varepsilon)}{2} \tag{3}$$

where D is the insulator diameter and ε is the thickness of the ice layer. Then, the residual resistance $R_p(x)$ can be calculated from the following equation for a narrow ice layer ($W \ll L$) as developed first in Wilkins (1969):

$$R_p(x) = \frac{10^6}{\pi\gamma_e}\left[\frac{\pi(L-x)}{W} + \ln\left(\frac{W}{2\pi r}\right)\right](\Omega) \tag{4}$$

where r is the radius of the arc root on an ice surface (cm) and γ_e (μS) is the equivalent surface conductivity. The relation between the arc channel radius and leakage current can be expressed by Wilkins (1969)

$$r = \sqrt{\frac{I}{\pi B}} \tag{5}$$

where the values of B for both inner and outer AC and DC arcs were estimated experimentally (Farzaneh and Zhang, 2000; Zhang and Farzaneh, 2000) as presented in Table 2.

As well, γ_e may be calculated as a function of conductivity of the water ($\sigma(\mu S/cm)$) at 20 °C used to form the ice (Farzaneh and Zhang, 2000; Farzaneh et al., 1997; Zhang and Farzaneh, 2000):

$$\gamma_e = 0.0675\sigma + 2.45 \; for \; AC \; arc \tag{6}$$

$$\gamma_e = 0.0599\sigma + 2.59 \; for \; DC- \; arc \tag{7}$$

$$\gamma_e = 0.082\sigma + 1.79 \; for \; DC+ \; arc. \tag{8}$$

Using Eqs. (1)–(8) the critical flashover voltage can be calculated by a trial and error numerical method used in Farzaneh and Zhang (2000), Farzaneh et al. (1997), and Zhang and Farzaneh (2000) or by the following theoretical formulae developed by Wilkins in Wilkins (1969):

$$V_c = A^{1/(n+1)} r_p{}^{n/(n+1)}\left(L + \frac{W}{2\pi}\ln\frac{BW^2}{4\pi i_c}\right) + V_e \quad for \; a \; narrow \; layer \tag{9}$$

Table 1
Arc discharge parameters on an ice surface.

Arc type	A	n	k	b	V_e
AC (60 Hz)	204.7	0.5607	1118 (for the arc propagation upward) 1300 (for the arc propagation downward)	0.5277	0
DC−	84.6	0.772	–	–	526
DC+	208.9	0.449	–	–	799