An AC Arc Discharge Model for Ice-Covered FRP Live-Line Tools

Mona Ghassemi and Masoud Farzaneh
Canada Research Chair on Atmospheric Icing Engineering of Power Networks (INGIVRE)
University of Quebec at Chicoutimi (UQAC)
Chicoutimi, QC, Canada

***Abstract*— Four separate FRP hot-stick flashover incidents have occurred in Canada during live-line working under steady-state system conditions at the peak of the voltage negative half-cycle during cold and freezing conditions. The incidents were reported at 500-kV AC line voltage working stress (95-96 kV/m) in 1997 and 2002 in Manitoba, and at 230-kV AC line voltage working stress (71 kV/m) twice in the neighbouring province, Saskatchewan, in 2012. To the best of our knowledge, the most reliable reproduction of these incidents has been achieved at UQAC Laboratories at a voltage stress of 105 kV/m at -1.04 °C, RH of 109 % with visible fog and 2.8 μg/cm^2 ESDD during a series of "true" cold fog tests. Findings from previous studies could well justify the cold-fog flashover mechanism for the flashovers that occurred on FRP live-line tools especially for the two flashovers that occurred at temperatures down to -13 and -19 °C in Manitoba and Saskatchewan. In the present study, suitable mathematical models for predicting the AC flashover voltage of ice-covered insulators are studied by considering a 1-mm ice layer covering an FRP hot stick. To the best of our knowledge, such modeling has never been attempted so far. By adapting the Obenaus approach, the arc constant parameters in air gaps as well the arc reignition conditions for an ice-covered FRP hot stick should be determined experimentally to develop its AC arc model. However, these issues need to be determined in further research and won't be addressed in this paper. Instead, issues about the present AC arc models developed for ice- or snow-covered insulators as well as various AC arc models developed for pollution flashover are discussed. It should be noted that the arc models developed for polluted or ice-covered insulators may not be adapted adequately for FRP hot-stick flashovers due to the following reasons. The ESDD values measured on the accident sticks in Manitoba and Saskatchewan were 2-3 μg/cm^2. These values are considered to be at typical background level and are ignored in polluted insulator cases. On the other hand, the thickness of ice on a FRP hot stick, e.g. 1 mm, may be much less than that for even light ice-covered insulators. Therefore, arc models developed mainly for heavy ice-covered insulators may not be adapted for FRP hot stick cases. Moreover, the most reliable reproduction of the occurred flashovers was achieved during a series of "true" cold fog tests while none of the present arc models for polluted or ice-covered insulators have been developed for cold fog conditions. Considering the mentioned points, various existing models are considered in order to examine the ones having good concordance with the experimental results obtained at UQAC laboratories.**

Keywords*— *Ice-covered FRP hot-stick, live line work, AC arc discharge model.

I. Introduction

Environmental concerns and lack of new power line construction because of imposed restrictions are making it increasingly difficult for utilities to use planned outages during transmission line construction and maintenance. Power companies and their systems are subjected to a constantly increasing consumer demand. This situation makes energized maintenance or live-line working the only viable solutions, and where the two basic techniques to achieve that are *insulating tool* methods and *bare hand* methods. Having a good surface condition and an insulating length determined by IEEE Std. 516-2009 [1] and IEC 61472-2013 [2] to respect MAD requirements, a FRP hot stick tool provides sufficient impedance between the lineman and the energized components.

Manitoba Hydro and Saskpower experienced four separate FRP hot-stick flashover incidents in spite of respecting the aforementioned standards. The incidents occurred in Canada under steady-state system conditions at the peak of the voltage negative half-cycle during cold and freezing conditions. The incidents were reported at 500-kV AC in an electric field magnitude of 95-96 kV/m in 1997 and 2002 in Manitoba [3-6] and at 230-kV AC in an electric field magnitude of 71 kV/m twice in the neighbouring province, Saskatchewan, in 2012 [7].

In our previous studies reported in [8, 9], a three-dimensional thermo-electrohydrodynamic model based on finite element method was developed for an ice-covered FRP hot-stick. Based on simulation results, the partial discharge current flowing through an ice layer covered the live tool is enough to raise the temperature of an ice layer just below freezing, where the cold-fog flashover mechanism can be justified. Moreover, wind speed and its direction have significant effects on ice temperature increase of an ice-covered FRP live-line tool [9]. These simulation results could well justify the cold-fog flashover mechanism for the two flashovers that occurred on FRP live-line tools at temperatures of -13 and -19 °C in Manitoba and Saskatchewan.

By using three-dimensional FEM models elaborated in [10-13], the voltage and electric field distributions around an FRP hot stick were calculated and assessed. The simulation geometries were similar to that of the flashover tests at UQAC [10, 11] and that of the Manitoba site incidents [12, 13] in a three-dimensional domain and could well explain some features of the flashover.

In another investigation [14], the authors studied the Minimum Approach Distance required for the hot sticks used in Manitoba. In this regard, the MADs obtained by IEEE Std. 516-2009 [1] and IEC 61472-2013 [2] for various conditions were compared and analyzed. In this regard and by using the laboratory investigations reported in [14, 15], a new formula for MAD calculation under cold and freezing conditions was introduced.

In this paper, the present mathematical models for predicting the AC flashover voltage of ice-covered insulators or contaminated insulators are examined to explore suitable arc models for FRP hot-sticks for extremely light levels of ESDD contamination, having a good concordance with the experimental results obtained at UQAC.

II. Experimental Investigations

The aforementioned four incidents occurred on FRP hot sticks during live line work in Canada led to a series of tests at Manitoba Hydro, Hydro-Quebec Research Institute (IREQ), Kinectrics and UQAC to investigate factors that may have contributed to the flashovers. To the best of our knowledge, the most reliable reproduction of the incidents has been achieved at UQAC[7] at a voltage stress of 105 kV/m at -1.04 °C, RH of 109 % with visible fog and 2.8 μg/cm^2 ESDD during a series of "true" cold fog tests reported in this section.

A. Test Set-up and Facilities

Fig. 1 shows the overall layout of the cold fog tests. A horizontal HV conductor was placed between two vertical 1.4-m station post insulators. A third insulator, forming a triangle, was used to support the base of the FRP hot stick on a pivot as seen in Fig. 1. An air cylinder and Teflon roller were used to push up near the base of the tool, below the ground connection.

B. Test Results

The first six tests used a new, unwaxed 32-mm diameter A.B. Chance universal stick mounted horizontally. Tests 7-10 used a waxed, 38-mm diameter link stick provided by SaskPower, known as the “Sister Stick” to the stick that flashed over on 12 December 2012. Tests 9 and 10 also made use of a new link stick with 32-mm diameter, hung down from the cylindrical bus at an angle of 60°. Table I gives additional details of the tests.

ESDD levels in the range from 1 to 16 μg/cm^2 were obtained by wiping the tool surfaces with the thumb of a leather work glove, saturated with a NaCl solution of 50 mS/cm. To obtain higher levels of ESDD, the tool surface was wiped repeatedly, with each pass adding more contamination. No NSDD (kaolin) was used in the solution.

Preliminary testing established that the smoothest temperature profiles and best regulation of relative humidity were achieved in the UQAC chamber by:

- Pre-chilling the chamber to a low temperature
- Turning off the chillers, and turning on the wind generator system
- Allowing temperature to rise, usually following a $1 - e^{-kt}$ profile, faster at first and slower during the transition points from -2°C to +1°C.

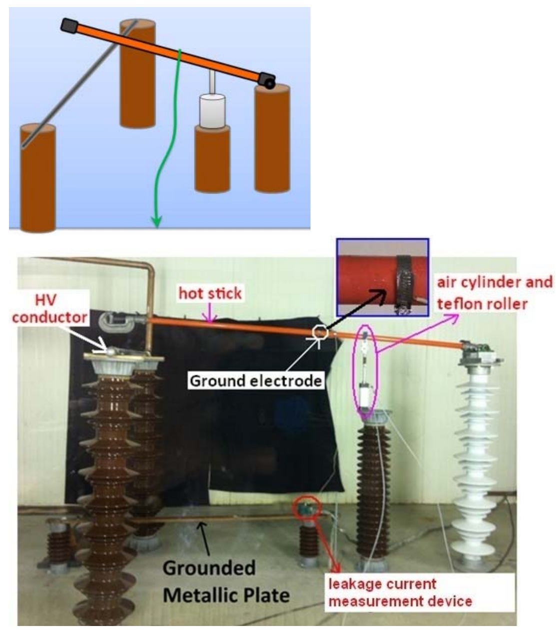

Fig. 1. Overall arrangement of live line tool testing in cold fog tests.

In Test 10, which is the most reliable reproduction of the incidents, after the 32-mm link stick at an angle of 60° withstood -84 kV$_{peak}$ across 80 cm (105 kV/m) for several minutes, the air pressure system was used to drop the 38-mm SaskPower stick onto the energized conductor as seen in Fig. 2(a).

TABLE I. Cold fog test parameters for 80-cm tool length

Parameter	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Initial Temperature (°C)	-4	-10	-12	-14	-16	-17	-16	-17	-9	-9
Chill Hours	2	2	2	4	4	4	2	12	12	12
dT/dt (C°/hour) -2 to +1°C	6.7	7.2	5.6	3.7	3.5	2.1	3.6	0.9	2.9	2
Fog Nozzles (#), σ_W (μS/cm)	1 head, 80	2 heads, 80 μS/cm					2 heads, 300 μS/cm			
Tool Diameter (mm)	32 mm Universal Stick						38	38	38, 32	38, 32
ESDD (μg/cm^2) after test	7.6	1.3	3.8	2.9	4.6	7.6	12.7	4.8	15.6	2.8
Applied Voltage (kV)	120	120	120	120	111	102	111	120	91	84
Stress Levels (kV/m)	150	150	150	150	139	128	139	150	114	105
Results	W/S	W/S	W/S	W/S	W/S	W/S	W/S	W/S	5 F/O	1 F/O
Comments (peak-to-peak	70	130	100	NA	Stick	45	-500	Stick	10	F/O

Leakage Current, mA)	-1°C	-8.4°C	-7°C		Up/Dn	-1°C	many	Up/Dn		on contact

There were discharges from the head of the tool to the conductor even with the tool in its up position, as seen in Fig. 2(b). The discharge activity was initiated at the band as ground electrode, which has the highest electric field, as seen in Fig. 2(c). The video frame rate in Fig. 2 is 30 FPS and Fig. 2(a) is considered as reference time. Fig. 2(b)-(d) show the sequences for arc propagation at t=1/30, 19/30 and 20/30 s, respectively. The partial discharge activity takes four video frames (0.13 s) to move about 40 cm, a speed extension of 3 m/s. The final jump to flashover is at least four times faster than a single video frame (Fig. 2(c) and 2(d)).

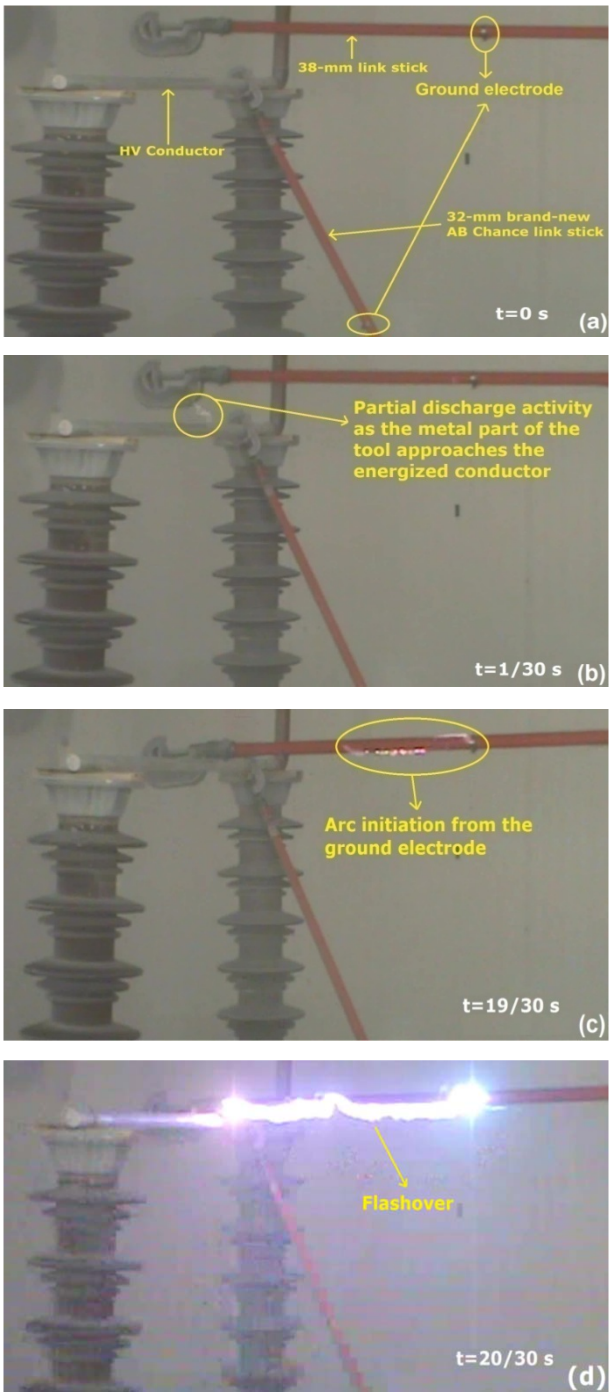

Fig. 2. FRP live-line tool flashover

III. The Model

In this section, present mathematical models for predicting the AC flashover voltage of ice-covered or contaminated insulators are examined for the FRP hot-stick for extremely light levels of ESDD contamination.

The AC flashover process on an ice surface can be considered as an arc discharge on an air gap in series with an ice layer given by:

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

where V(V) and I (A) are peak values of the applied voltage and leakage current, $A = 204.7$ and $n = 0.5607$ [18] are the arc constants, x (cm) is the length of the arc, $V_e = 0\ V$ [18] is the electrode voltage drop. $R_p(x)$ is the residual resistance of the ice section not bridged by the arc and which is given by the formula initially developed in [19] for a narrow flat model of polluted insulators and then used in [18] for ice-covered insulators as follows:

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

where γ_e is the surface conductivity. Since the ice layer only covers the windward side of the insulator string, as reported in [20], the ice deposit can be 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. $R_p(x)$ can then be obtained from a new formula developed in [21, 22] as follows:

$$R_p(x) = \frac{10^6}{\pi\gamma_e}\ln\left[(L-x)/2r + \sqrt{((L-x)/2r)^2 - 1}\right]$$
$$= \frac{10^6}{\pi\gamma_e}\operatorname{csch}^{-1}((L-x)/2r)\ (\Omega) \tag{4}$$

r in (2) and (4) is the radius of the arc root on an ice surface (cm) which can be expressed by [18]:

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

where $B = 0.875$. 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 [18]:

$$V = \frac{kx}{I^b} \qquad (6)$$

where $k = 1118$ for an upward arc propagation [18], $k = 1300$ for a downward arc propagation [23] and $b = 0.5277$ [18] are reignition constants. In [24] for AC flashover of polluted insulators $A = 140$, $n = 0.67$, $k = 1050$, $b = 1$ and $B = 1.45$ were determined and $R_p(x)$ was given by

$$R_p(x) = \frac{10^6}{\pi \times 1.25\gamma_e} \ln{(L - x)/r} \, (\Omega) \qquad (7)$$

In Test 10, we have $L = 80\ cm$, $D = 38\ mm$, and ESDD=2.8 μg/cm^2 corresponding to approximately 0.56 μS in a solid layer test according to CIGRE Monograph 158 [25] and the flashover voltage $V = 84\ kV$. Fig. 3 shows simulation results obtained from the aforementioned models for different surface conductivities.

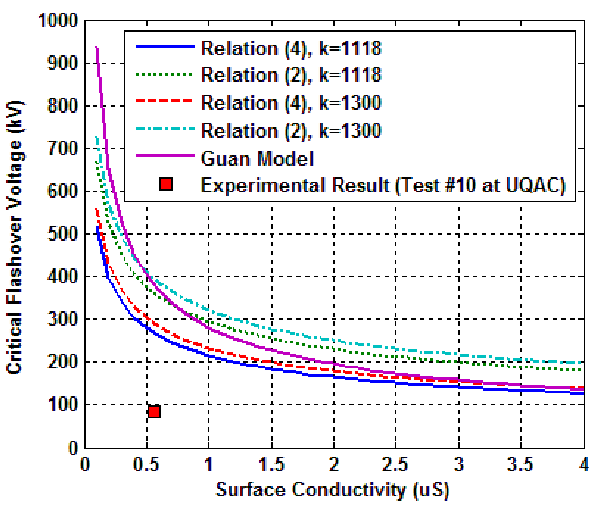

Fig. 3. Simulation and experimental results for the FRP tool flashover tests carried out at UQAC.

In Fig. 3, four AC arc flashover models developed for ice-covered insulators were examined for the FRP live-line tool flashover that occurred at UQAC where $R_p(x)$ was calculated from (2) or (4), considering k for the upward or downward arc propagation. Also, the simulation results of the AC arc model developed for polluted insulators in [24] based on (7) and the aforementioned constants was elaborated for FRP live-line tool flashover in Fig. 3 under "Guan Model". It can be seen in Fig. 3 that the predictions from these models have significant error compared to the test results. Some causes of this significant error are as follows:

- The constants k and b measured for ice-covered insulators are for suspension line insulators where the arc propagates mainly upwards [18] or for post insulators where the arc propagates downwards [23]. However, the flashover studied at UQAC laboratory, as shown in Fig. 2, occurred on the horizontal FRP tool where the reignition constants should have been determined for this situation.
- The ice on a FRP hot stick during live line work in freezing conditions is much less thick than that of even light ice-covered insulators. Therefore, arc models developed essentially for heavy ice-covered insulators cannot be adapted for a FRP hot stick.
- ESDD measured on accident sticks in Canada were in a range of 2-3 μg/cm^2. Typically such values are generally ignored in the case of polluted insulators.

Therefore, further research is needed to develop suitable arc models for predicting flashover voltage for FRP hot sticks.

The computations carried out in [26] showed that the variation of the critical flashover voltage $V\ (kV)$ upon ESDD $C\ (mg/cm^2)$ follows the analytical expression of the following power function:

$$V = a \cdot C^{-b} \qquad (8)$$

Experimental investigations in [26] showed that exponent $b$is independent of the insulator dimensions (the maximum diameter of the insulator disc, D_m, and the leakage distance of the insulator, L and that it changes only with the insulator form factor, F. Its value has been reported to be between 0.35 and 0.37 for stab-type insulators in [26]. The following relation between $a$and L was determined in [26].

$$a = 0.13L + 1.947 \qquad (9)$$

where L is in cm.

Fig. 4 shows simulation results obtained from (8) considering $b = 0.35,\ 0.36$ and 0.37 for the FRP tool of Test 10 carried out at UQAC.

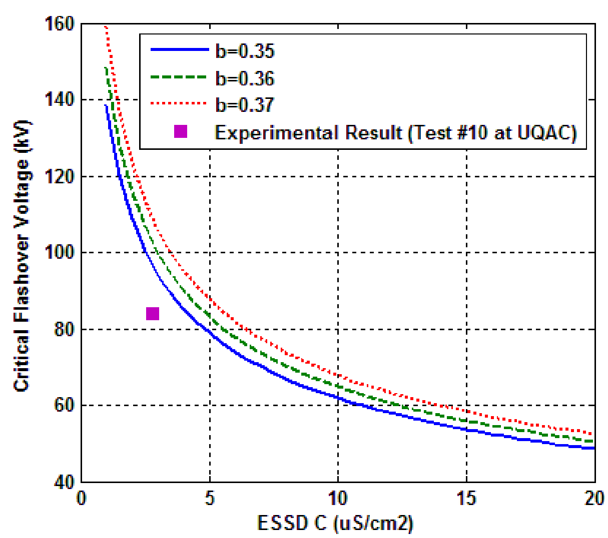

Fig. 4. Simulation and experimental results for FRP tool flashover tests carried at UQAC.

It can be seen that for $b = 0.35$ relation (8) has an error of 15% for the most reliable reproduction of the incidents, Test

10. However, in order to validate the relation developed in (8) for FRP tools during cold-fog tests further experimental research is needed for different ESDD and different dimensions of hot sticks.

IV. CNCLUSIONS

Present mathematical models for predicting the AC flashover voltage of ice-covered insulators as well contaminated insulators were analyzed for FRP hot-stick applications for extremely light levels of ESDD contamination. It was found that the errors from these models for predicting the flashover voltage of FRP hot sticks, based on the experimental results obtained, are too large to be useful. However, it was suggested that the analytical relationship defined in [26] between the critical flashover voltage and the ESDD for polluted insulators may works well in the case of FRP hot sticks.

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