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THE THREAT CAUSED BY FIRES UNDER HIGH VOLTAGE LINES

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The effect of fires on the flashover voltage of power lines has been investigated in Brazil, Mexico, Canada, USA, South Africa, Australia and Poland. The flashover voltage of outdoor insulation is reduced by hot air, conductive flame and colloidal smoke. The paper explains shortly the fire induced flashovers of air gaps. The safety aspect for firemen and other people caused by step potentials at the arcing point was described. The published works about deterioration of aluminum stranded conductors steel reinforced (ACSR) and detection of fire induced corona are briefly reported.

Key words – breakdown voltage, step voltage, ground resistivity

1. INTRODUCTION

The outdoor power lines cross often the forest and agricultural areas where fires sometimes occur. The influence of high flames and intense smoke in the line vicinity on the electrical strength of air and the possibility of ground faults was studied in the Brazil, Mexico, Canada, USA, South Africa, Australia. In these countries the fire of forest, grass, sugar cane or bush ravage large areas, often jeopardizing the reliability of the lines [1, 2]. The special dangerous environmental conditions for overhead lines, electrical or electronic apparatus were noted during the war in Persian Gulf [3]. The line outages due to forest fires were observed in Poland too [4]. The early study of flame in electrical field was started by Malinowski and Haber in 1920s [5]. The influence of localized flame on dielectric strength of air was investigated at Wroclaw University of Technology by Janat [6]. The basic studies explained the mechanisms responsible for lowering the electrical strength of air in the presence of flame. Next, guides for safety of people and firemen were worked out taking into account fire induced flashovers with consequent hazardous step potentials [7].

2. INFLUENCE OF FIRE AND SMOKE ON AIR BREAKDOWN VOLTAGE

The flame is a kind of plasma where air molecules are chemically and thermally ionized. The ion concentration in the propane-air flame is in the range of $10^9 – 10^{12}$ / cm^3 , the most of them have the positive charge [8]. The low concentration of negative ions is probably due to the fact that the most of the negative charge is transferred by free electrons. The main source of ions and electrons in the flame are the molecules with a low ionization potential, e.g. carbon (the ionization potential of graphite amounts to 4.35 eV). The rate of ionization processes increases with temperature. The ion generation rate increases by 2 – 4 times when the temperature increases of 100 K [5]. As it was earlier said, the flame is mostly positive charged, therefore in the dc electrical field it is attracted by the negative electrode (fig. 1b). In the ac field the flame is stretched between electrodes (fig. 1c, 1d). Due to the non-stationary conditions under ac voltage, the flame shift in one direction is lower than under dc voltage (compare fig. 1b and fig. 1c).

The breakdown voltage of plate to plate with 3 cm air gap at normal atmospheric conditions amounts to 61 kVrms. The placement of a candle fire in the middle reduces also the breakdown voltage by 10 times. Additionally, the reduction of breakdown voltage depends on the flame position in the gap and voltage shape. Under dc voltage the smallest reduction is observed when the flame is placed directly at negative electrode. Under the short impulse voltages the reduction of electrical strength is smaller than under the dc or ac voltages.

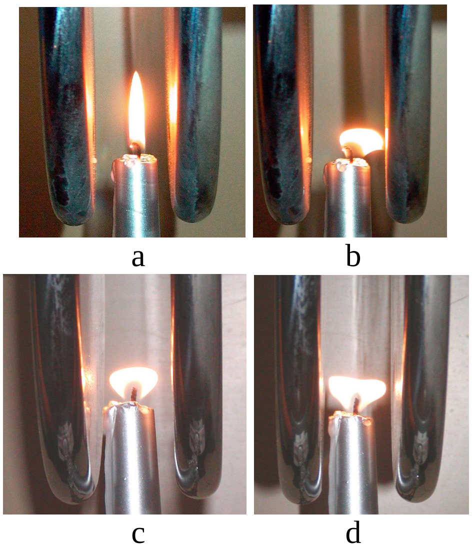

Fig. 1. The flame in an electric field, air gap 3 cm
a – without voltage, b – dc voltage of 3 kV, the right electrode is negative, c – ac voltage of 3 kVrms,
d – ac voltage of 6 kVrms

The electrical strength decrease of air under the influence of flames and smoke can be explained as a result of three factors:

- the high temperature reduces the air density
- the electrical charge is generated in the flame
- the influence of smoke particles.

Mc Mulan and West [9] blew the hot air between the spheres of a horizontal air gap. Compared with the room temperature the electrical strength decreased by two times at the temperature of 350 °C and three times at 700 °C. According to Uhm, the reduced breakdown field E/p decreases with the gas temperature T_g [10].

$$\frac{E}{p} = 25{,}7\frac{T_r}{T_g} \qquad (1)$$

where:
T_r is room temperature and p is the gas pressure.

When the temperature increases in a limited space only, e.g. when the flame does not occupy the whole electrode distance then the temperature influence is smaller. In this case the space charge plays a dominant role. The electrical charge changes the voltage distribution between electrodes. When the charge increases the non-uniformity of the electrical field, then the breakdown voltage decreases.

The above described processes were demonstrated by the experiment carried out by Janat [6]. The breakdown voltage of the horizontal air gap (sphere diameter 12.5 cm, distance 28 cm) was measured depending on the position of a cold graphite rod (temperature 25 °C). The measurements were repeated with the hot rod (temperature 400 °C). The breakdown voltages were also measured in the low-pressure propane-air flame having similar dimensions to the graphite rod. The experiment showed that the local temperature increase caused by hot rod reduces the breakdown voltage not very much. The flame which generates the space charge and increases temperature reduces the breakdown voltage more considerably (fig. 2). Authors are not convinced about the fact that the rod temperature approached 400 °C. In our opinion the low-pressure propane-air flame temperature was much higher, about 2000 °C [11].

The smoke molecules got charged by attracting electrical charge which is generated in the flame. They can link in strain aggregates which are positioned along electrical lines. The soot is a semi-conductor with a very extended surface. The partial discharges can easily be initiated on the soot edges. Therefore, the smoke decreases the electrical strength of the air in a similar manner like metallic particles lower the breakdown voltage in GIS. The cigarette smoke reduces the breakdown voltage to the half value of pure air. Fig. 3 compares the electrical strength of a pure air in a plate to plate air gap (plate diameter of 4.5 cm) with that of the air contaminated with cigarette smoke.

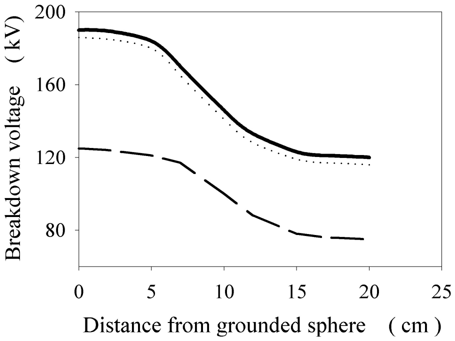

Fig. 2. The breakdown ac voltage of a sphere air gap depending on the flame distance from the grounded sphere (dashed line); graphite rod with the temperature of 25 °C (solid thick line) and graphite rod with temperature of 400 °C (dotted line) [6]

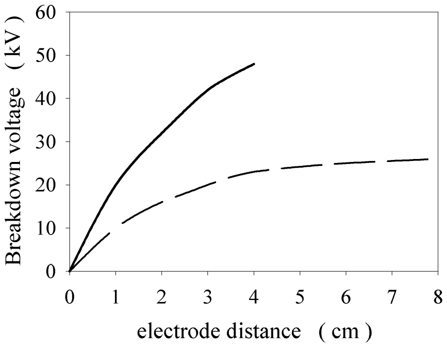

Fig. 3. The breakdown characteristic of a plate to plate air gap under ac voltage [6]. Solid line – pure air, dashed line – air containing a cigarette smoke

3. THE CONDITIONS FOR GROUND FAULT OCCURENCE

The field experiments confirmed that even the densest smoke alone can not cause mid-span flashovers. The ground fault is possible only when the flames occur in the vicinity of phase conductor. However, smoke may contaminate the insulators and lead to insulator flashover in the presence of the moisture generated by fire fighting operation. This would generate hazardous step potentials in the immediate vicinity of towers. Hence, it is advisable to avoid the area within 10 m from the tower at all times [7].

Deno has shown that the ground faults are not possible if the propane-air flames are at least 2 m beneath the phase conductor of 500 kV line [12]. However, when the flames and dense smoke are present together then this minimum safe distance should be greater. It seems that the safe distance of 3 m from phase conductor of 400 kV line could be assumed.

4. STEP VOLTAGE AROUND A FLASHOVER POINT

Fig. 4. shows the one-phase ground fault. The high current I in the immediate vicinity of the arcing point and the associated high voltage gradient cause breakdown of the soil. The discharges develop until they reach the point (the radius a) at which the gradient in the soil is below the critical ionization gradient G amounting about 3 kV/cm [7]. The short current I generates the step voltage U_{SS}. The dangerous zone finishes at the distance d. The step voltage U_{SS} is lower than the tolerable step voltage U_{SSP}. These voltages and the resistance to ground R_g are represented by the following equations [7]:

$$U_{SS} = \frac{I\rho}{2\pi r(r+1)} \qquad (2)$$

$$U_{SSp} = (116 + 0{,}7\rho_S) / \sqrt{t} \qquad (3)$$

$$R_g = \sqrt{\rho G / 2\pi I} \qquad (4)$$

where:

$$I = 0{,}5\beta\left[\sqrt{1 + (2I_O/\beta)^2} - 1\right] \qquad (5)$$

$$\beta = \left(\frac{I_o}{U_n}\right)^2 \cdot \frac{3\rho \cdot G}{2\pi} \qquad (6)$$

U_n is the phase to phase voltage in Volts, I is the fault current available from the system assuming $R_g = 0$, t – time in seconds, ρ - ground resistivity in Ωm, ρ_s – resistivity of the top layer of the soil in Ωm.

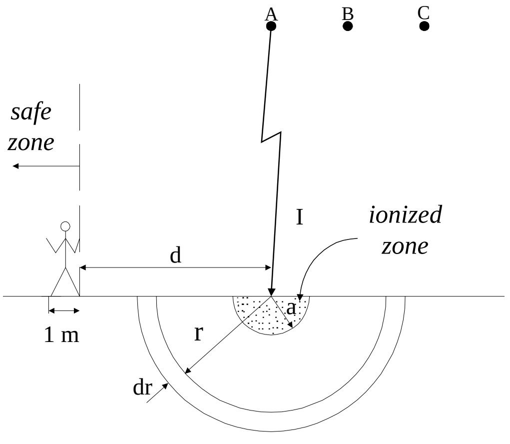

Fig. 4. Step voltage around a flashover point [7]

In overhead 400 kV transmission lines the ground fault is usually switched off after 0.1 s. However, in the lines with lower voltages this time is longer because of the use of less sophisticated equipment. In safety calculations, the fault duration is usually taken equal to 0.5 second [7]. Taking ρ_s equal to 100 Ωm and $t = 0.5$ second the tolerable step voltage U_{SSP} is calculated from (3). This value is only a bit higher than the tolerable touching voltage which equals 200 V (fig. 6). Assuming:

- fault duration t = 0,5 s
- resistivity of the top layer of the soil $\rho_s = 100$ Ωm
- critical ionization gradient G = 3 kV/cm

the distance d from the arcing point beyond which the step voltage drops to a safe value U_{SSP} can be calculated from the approximate equation

$$d = 0{,}5\left[\sqrt{1 + 0{,}0169 \cdot U_n^2} - 1\right] \qquad (7)$$

where the voltage U is in kV and the distance d in m.

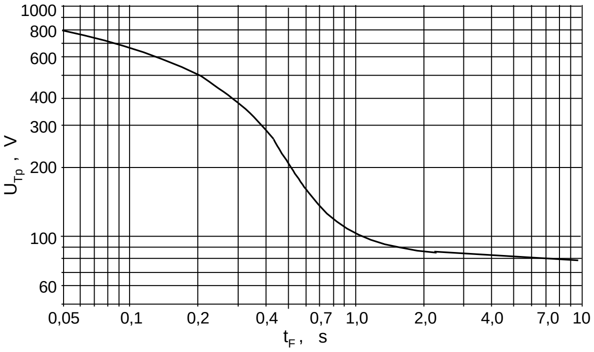

Fig. 6. Permissible touch voltages depending on fault time (according to and IEC 60479-1 [13])

Table 1 contains the safe distances from the ground fault for different high voltage lines as derived from (7).

Tab. 1. Safe distances from the ground fault of high voltage lines

Line voltage (kV)	Safe distance from the ground fault (m)
10	0,4
20	0,9
110	7
220	14
400	21

5. DETERIORATION OF ACSR CONDUCTORS

When aluminum stranded steel reinforced conductors (ACSR) are exposed or heated by fires, their mechanical strength is reduced below the rated values of new conductors [14]. Moreover, the zinc layer on the steel strand would be removed and galvanic corrosion could be accelerated. This tends to corrode the aluminum strand in the interior layers as well as the bare steel strands. Any blaze like forest fires could be an important factor in reducing the life of aged ACSR conductors in service.

6. DETECTION OF FIRE INDUCED CORONA

The numbers of flashovers caused by sugar cane fires amounted several hundred per year in South Africa. One of the strategies being used to avoid or mitigate this problem is the development of a means for detecting the presence of a fire under a line prior to possible flashover. The extreme temperatures and floating particles introduced by the fire under or near an energized line initiate enhanced corona discharges, and as a result, significant levels of radio frequency noise [15]. There is a need of discrimination between radio noise generated by fires, conductor corona and noise from polluted insulators during dry and wet weather conditions. In the most favourable dry weather conditions, the high noise levels generated by fire are distinguishable from those produced by conductor corona and polluted insulators. In heavy rain conditions, fire noise generated more than 30 to 40 km away will not be detectable at the termination.

7. CONCLUSIONS

Fires under power lines can cause mid-span flashovers with consequent hazardous step potentials. During a fire fighting action the guidelines for safety of firemen are as follows:

- The fire fighting action in the vicinity of operating power line (without de-energizing the line) is permissible if :
  - the fire has not reached the ground area beneath the wires,
  - the fire is burning under the wires – the gap between the wires and the top of the flames is greater than 3 m (this is valid for 400 kV lines)

- If a fire with high flames is detected in direct vicinity of operating line, the utility should be requested to de-energize the affected power line. For the period the line remains energized, the hazardous step potential zone should be evaluated based on the table 1.

- The area within 10 m from towers should be avoided at all times to protect against the risk of flashovers of insulators under the wet polluted conditions generated by the flames, the dense smoke and fire fighting action.

- The mechanical and electrical deterioration of line conductors should be taken into account

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