The Analysis of Moistening Processes of an Insulator Surface

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Abstract— **Some unexplained outages of overhead transmission line occur due to flashover of dirty and moistening insulator string in early morning time. The processes of a surface insulator wetting are discussed in this paper as the cause of insulation flashover. The explanation is given for the fact that the most frequent outages occur when the wind speed is 2-3 m/s.**

Keywords— Insulator,Flashover, Moistening, Overhead transmission line.

I. Introduction

Nowadays a transport of electrical energy with the help of high voltage overhead transmission lines (OHL) is the most economical decision. Unfortunately, the impact of the environment reduces the reliability of the energy transmission. Unplanned outages of OHLs are most often associated with flashovers of insulation or air gaps between conductor and any grounded part of tower. They occur mainly in the early morning. Usually two causes of morning outages are considered: interference of birds [1-4] and flashover of insulator string due to wetting of contaminated insulators by fog, dew or drizzling rain [5-7]. These causes differ one from other indeed but they are often hardly distinguishable in practice. In some cases, the combined effect of the first and second events or specific cause of outages due to flashover of composite insulators with mycosis [8] is considered [3]. All mentioned causes were studied in details and are well understood now.

By contrast, today's experience shows that a high proportion of outages cannot be explained by known impacts. According to [9] the specific number of OHL outages with unknown cause varies from 15 up to 30 % and more in different countries and for different system voltages. These outages occur due to flashover of insulation mainly in areas with lightly polluted insulators in early morning under normal operating conditions but in presence of dew. Similarly, these outages tend to be single phase with the following successful re-closing. Followed from some facts, the authors of [9] offered the cascade mechanism of flashover, which starts from the partial flashover of dry insulators in string. We also suppose that in any case the initial process starts from the moistening of contamination layer on insulator's surface and increase of leakage current. So, the aim of this work was the consideration of moistening process as the important factor that influences on insulation flashover and OHL outage.

II. Affecting of the Weather Conditions

Data concerning sudden outages of 4 overhead transmission lines of 110 kV voltage with sum length 492 km were analyzed. These lines operate in the South-West Altay region. The analyzed period includes from 2005 up to 2009, i.e. 5 years. The total number of unplanned outages was 275 and 137 from them (almost 50 %) had unknown cause. The insulation level on these lines was about 17mm/kV. All flashed insulators were dismounted and some from them were tested. The average ratio ESDD/NSDD was about 0.01 ± 0.05 / 0.06 ± 0.04 mg/cm2. It has to be noted, that about 5 % of glass insulators were changed on composite ones during the analyzed period and single flashover with bird pollution occurred on them. One insulator string made from 8cap & pin glass insulators with "arc marks" and polymeric insulator with bird pollution were tested in dry and wet conditions. The flashover voltages were 312 and 340 kV in dry condition. In wet condition, both samples withstood 80 and 200 kV step-applied AC voltage. Some glass insulators were also tested in fog chamber according to IEC procedure [10] with control of fog parameters [11]. Moreover, they were tested with application of ultrasonic fog [12]. In all cases, the flashover voltage exceeded the operated voltage two times and more.

In order to understand the cause of line insulation flashover at operated voltage we studied the dependences of outages on weather condition. To find flashover dependence on weather only two meteorological parameters were chosen as arguments: relative humidity and wind speed. Relative humidity is directly connected with the process of moisture condensation on insulator surface. But it is clear that complete saturation of pollution layer requires a large initial content of moisture in the air in absence of rain or fog. Large air absolute humidity occurs after the hot weather in the day before. Evaporation of water from the soil in hot weather results in large absolute air humidity (up to 15 g/m3 and more). The abundant dew can appear at subsequent decrease of air temperature. Therefore, the temperature change can be included as an argument of flashover probability dependence on the weather conditions. But we took into account only relative humidity as a resulting parameter for moistening process. Conversely, wind speed seems to be an independent meteorological factor, which can influence on the interested process. Indeed, there cannot be any dew on insulators at high wind speed. Conversely, a zero wind speed leads to a rapid "draining" of air near insulators due to heating of insulator surface by leakage current. So the further moistening would require additional inflow of humid air. Based on these arguments, the probability of flashover should have a maximum at some velocity of the wind. The meteorological data were provided by the nearest weather stations. The archive included the values of temperature, pressure and relative humidity, wind speed and other parameters recorded 4 times per day. Outage's time does not always coincide with the moment of the weather conditions measurement, so the linear approximation of data was performed between the moments of measurements. All 137 outages were processed with the accompanying weather conditions. Figure 1 shows the dependence of specific number of OHL outages P on both relative humidity f and wind speed v.

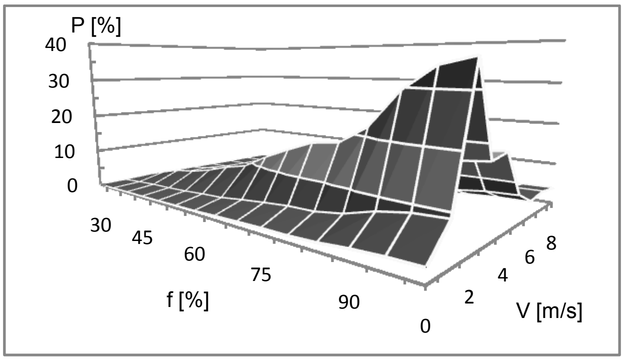

Fig. 1. The specific number of outages vs relative humidity and wind speed

It can be seen that the maximum number of outages occurred at a wind speed of 2 m/s and more than 80% of all outages occurred at a wind speed of up to 4 m/s. Finally the analysis showed that the maximum probability of line outage correlates with the following combination of weather factors:

– decrease of the air temperature after the hot weather that has took place at day time and continued until night time;
– relative humidity of air more than 82 %;
– wind speed about (2 – 3) m/s.

This conclusion must be accompanied by the following note. The used meteorological conditions are valid only at the location of weather stations. For this reason, it is necessary to take into account the possible local increases of relative air humidity in lowlands, marshes or glades in forest. The same is for the wind speed. In the lowlands or in forest glades it can be less than on the weather station.

Indirect confirmation of possible "dew on cold surface" cause of insulation flashover was given by the UV-inspection data. They showed heavy increase of discharge intensity on insulators at the morning hours.

III. Droplet Model

The fact of flashover or withstanding of the line insulator can be considered as the result of the confrontation between the moistening of contamination layer on insulator by any meteorological factor and drying of the same layer due to the heating by leakage currents. It was experimentally established that the highest moisture content in contamination layer corresponds to the minimum flashover voltage. It is clear that the moistening process depends on the rating of moisture entry from the ambient air to insulator surface. First of all, let us consider the processes of the surface moistening by any fog. Problems of heating and mass changing in two-phase flows were examined in detail by author [13]. A simplified model of the insulator moistening by two-phase flow of fog was proposed in [14]. It is based on mechanism of inertial precipitation of fog droplets. The real insulator was replaced by a sphere of radius R = 10 cm in order to simplify calculations. Process of inertial precipitation of water droplets from fog depends on the nature of the air flow around the obstacle: its characteristic dimension R, droplet radius r, and air humidity W.

Figure 2 shows the results of calculations of water flow on the insulator surface during fog and drizzle at different wind speeds [14].

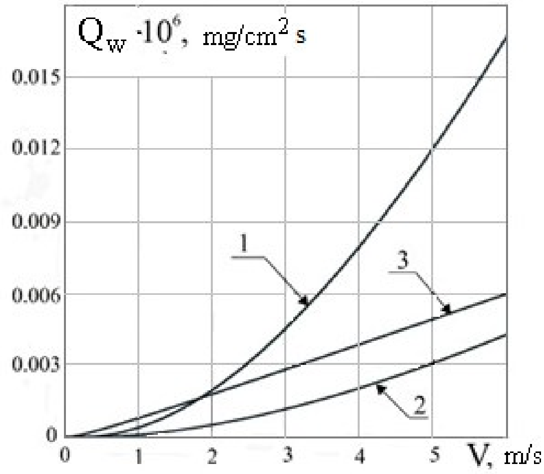

Fig. 2. The water flow on the insulator surface during fogs and drizzle at different wind speeds: 1 – strong advection fog (W = 0.43 g/m^3); 2 – moderate advection fog (W =0.11 g/m^3); 3 – drizzle (W =0.045 g/m^3)

The calculations were performed for different types of fog: advection fog, which is formed due to the flow of warm and humid air over the cold surface and radiation fog, which appears above the soil surface, cooled by means of radiation in previous hours. It is seen that the intensity of surface moistening increases with the wind speed growth and particularly in the case of strong advection fog.

From the dependencies shown in Figure 2, it also follows that in the range of wind speed from 0 to 2 m/s the moistening intensity during the drizzle is more than at strong advection fog, despite of lesser water content in drizzle. This is because an integrated capture ratio of drizzle increases much faster than integrated capture ratio of fog in the specified range of wind speed.

Radiation fogs appear, in general, when the weather is calm. These fogs have typical water content of about 0.08 g/m3. So at wind velocity of 0.5 m/s the moistening intensity is 25·10-10 mg/cm^2·s, i.e. negligible. For this reason, radiation fogs cannot be considered as moistening factor along with the opinion of author [14]. You can agree with this conclusion, if you stay within the classical mechanism of flashover of contaminated and moistening insulator. But in practice there were many cases of insulation flashovers like analyzed above (section 2), which occurred in the absence of such explicit moisturizing factors as drizzle or fog. It is also noticed that flashovers occurred when air relative humidity was less than the dew point but more than 82 % (see fig. 1).

Thus the dependence of the probability of flashover on wind speed, obtained in the analysis of practical operating experience is contrary to the dependencies in figure 2. The probability of flashover has maximum at wind speed of (2 - 3) m/s.

IV. Condensation Model

This contradiction can be solved if we create another model of the insulator surface moistening. In the early morning hours moisture condensates on insulator surface because the air is already heated, but insulators did not have time to warm up. The mechanism of condensation could be interpreted as follows. Because the surface of the insulator has a lower temperature, the moisture will condensate if the partial pressure of water vapor in the incoming air P (H2O) will be more than the saturating pressure of water vapor, Psat, at a temperature equal to the surface temperature of the insulator Tins

$$P\ (\mathrm{H_2O}) \geq P_{sat}(T = T_{ins}) \tag{1}$$

The condensation of the vapor that exists in the moving air stream was considered in [15]. It is shown that the dimensionless flow of water to the surface (so called Stenton number) can be determined from the expression

$$St_D = \frac{\left(-\rho \cdot D \cdot \frac{\partial C_1}{\partial y}\right)_{st}}{\rho_0 \cdot U_0 \cdot \Delta C_1} \tag{2}$$

Here D is the diffusion coefficient of water molecules in the air; ρ - air density; U0 is the velocity of air stream; C1 - mass content of water in air; ΔC1 - difference between water mass contents in the incoming air stream and in the air after moisture condensation on the surface of the cold insulator.

The Stenton number changes a little with increasing of Reynolds number, which defines the transition from laminar flow to turbulent regime. In order to estimate the moistening rate one needs to use some values: the air viscosity, η = 1.8·10-5Pa·s; characteristic size of the insulator, d ~ 0.1 m; the air density, ρ = 1.3 kg/m3 and the diffusion coefficient D = 2·10-5 m2/s [16].The Reynolds number, Re, is about 104 for air flow velocity of 2 m/s and the characteristic size of the insulator. Note that this Re value closely corresponds to the transition from laminar to turbulent regime of air flow around the insulator. In addition, one should evaluate the ΔC1. If one assumes that the insulator has a temperature of 5 °C, the temperature of the incoming air 15°C and its relative humidity of 80 %, so, the relative mass concentration of water ΔC1/ C1will be about 6·10-3.

Let's use data presented in [15] for Re =104 in the form of

$$St_D \cdot Sc^n \cdot 10^2 \approx 0.4 \tag{3}$$

where Sc is the Schmidt number (it is the ratio of the kinematic viscosity coefficient to the diffusion coefficient); n = 0.66 for laminar flow and n= 0.6 for turbulent flow

$$Sc = \frac{\eta}{D \cdot \rho} \tag{4}$$

Substituting the value of the Schmidt number for air Sc~ 0.69 one can estimate from (2) the flow of condensate per unit area of the insulator surface

$$J \approx 0.4 \frac{\rho \cdot U_0 \cdot \Delta C_1}{100 \cdot 0.8} \approx 80 \frac{\mathrm{mg}}{\mathrm{s \cdot m^2}} \tag{5}$$

The resulting value is great enough, e.g. both the top and bottom surface of insulator could be covered by the water layer about 0.3 mm during one hour. It indirectly proves the possibility of flashover insulation from the condensation mechanism point of view. We emphasize, however, that the flow of condensed moisture is highly dependent on air relative humidity and the temperature difference between air and insulator.

In this mechanism the dependence on the incoming water flow on velocity exists but it is not too significant. In the laminar flow mode there is very little change of condensed water with increasing flow velocity; in the turbulent regime condensation slightly increases, E.G, the two times increase in wind velocity leads to an increase in the rate of condensation of about 1.5 times.

Now let's consider the possibility of water desorption from the insulator surface. In our opinion, the following processes should occur in this case. First, if the moisture condenses in the form of drops, the air flow will tear drops due to the force associated with air movement. This force applies to the surface and may tear a drop at the sufficient air velocity. Secondly, if moisture condenses on the particles of dirt on the surface, the wind will tear the particles together with moisture. Thus, at a certain speed the wind may start reducing of the water amount on the insulator surface.

The forces that tear drop or particle have the same nature. When the air flow is laminar, this force is determined by the viscosity of air. In order to estimate its value we can assume that the air flows around the sphere body of water drop. The value of the resistance can be estimated from the well-known expression for the Stokes force related to the drop size r

$$F_{lam} = 6\pi \cdot \eta \cdot r \cdot U_0 \quad (6)$$

If the movement of air around the insulator becomes turbulent, the force of resistance changes [17]

$$F_{turb} = \rho \cdot U_0^2 \cdot S \cdot k \quad (7)$$

where S is the part of particle area which is perpendicular to the flow S~ πr2 and k is a coefficient of order k ≈ 0.5.

Comparison of values of the forces in laminar and turbulent modes shows that in the latter case the breaking force is two orders of magnitude exceed the force acting in the laminar mode. The detachment of contamination particle (and water droplets) from insulator surface will occur when the breaking force will begin to exceed the weight of the particles (or droplets). The estimation shows that in laminar mode this condition cannot be achieved, whereas in the turbulent regime, at a speed of about (2 - 3) m/s, the possible separation of particles having sizes even in tenths of a millimeter can be achieved. If there is perfect wetting of insulator surface, then force which increases at turbulent regime will promote moisture decrease due to water movement in the force direction and faster water draining by the gravity force. It concerns the bottom part of insulator with hanging drops too.

V. CONCLUSIONS

In accordance with the considered phenomena and their quantitative estimation, the amount of moisture that falls to the surface, increases with wind velocity from zero to a certain value. But when the wind velocity reaches V ~ (2 - 3) m/s the process of separation of water droplets from the surface of the insulator sharply increases. As a consequence, the maximum value of condensed water is to be expected at this wind speed that is almost identical to the wind speed, which corresponds to maximum probability of OHL outage.

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