Hygroscopic Properties of Pollutants on HV Insulators

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ABSTRACT

The mechanism of moisture absorption by an insulator surface contaminated with different salts was described. A list of some salts depending on their hygroscopicity was given. Measurements of surface conductivity and leakage current on flat insulator models at different relative humidities and with different types of salt were carried out. At natural atmospheric conditions the flashover voltage of cap and pin insulators subjected to 250/2500 μs switching impulses was evaluated.

INTRODUCTION

SINCE the resistivity of dry pollution layers is very high, the electrical strentgh of even considerably contaminated insulators at low air humidities reaches that of clean insulators. Only when the pollution layer is wetted, the surface resistance decreases heavily and can lead to a pollution flashover. Thus the wetting of pollution layers is the first stage of flashover development.

Some papers [1-3] deal with the process of moisture absorption by pollution layers containing sodium chloride, NaCl. Pollution layers formed under natural conditions may contain a varyity of other chemical compounds of different properties [4-6]. For this reason the flashover voltage in natural conditions may be different from that evaluated in laboratory pollution tests where the pollution layers only contain sodium chloride [7,8]. Since the periods of increased air humidity and fogs are the most dangerous conditions, the hygroscopicity of pollution layers is a very important factor. Recent tests have shown that hygroscopicity can influence not only the ac flashover voltage, but also the flashover voltage for switching impulses.

MOISTURE ABSORPTION BY POLLUTIONS ON INSULATOR SURFACE

THE wetting of pollution layer on an insulator can occur through condensation, mechanically (as a result of a collision of rain droplets with deposits on insulator surfaces), and through moisture absorption by insoluble and soluble components of the pollution layer.

G. Karady [9] considered in detail the wetting mechanism by condensation and that resulting from rain droplet impacts. At the same time, the process of absorptive wetting seems equally important for the stability of layer wetting. It thus merits special consideration.

The evaporation rate from an aqueous solution is proportional to the difference between water vapor pressure of the solution and that of atmosphere

$$\frac{dn}{dt} = K(p - p_s) \qquad (1)$$

where n is the quantity of water molecules per 1 cm^2 (moles), t the time, p the vapor pressure in atmosphere, p_s the solution vapor pressure, and K is a constant.

If the vapor pressure in the atmosphere is higher than that of solution vapor pressure, the solution absorbs moisture. The vapor pressure above solutions is always lower than above pure water. According to Raoult's law, it is proportional to the mole fraction of water in solution

$$p_s = X p_0 \qquad (2)$$

where X is the mole fraction of water in a solution, and p_0 the vapor pressure above pure water.

For dissociating electrolytes the mole fraction of water in a solution is calculated as

$$x = \frac{n_1}{n_1 + i n_2} \qquad (3)$$

where n_1 is the water concentration (moles), n_2 the electrolyte concentration (moles), i is Van't Hoff coefficient,

$$i = (1 - \alpha) + z\alpha \qquad (4)$$

z is the quantity of ions formed as a result of the dissociation of a single electrolyte molecule, α the degree of dissociation: $\alpha = \Lambda/\Lambda_\infty$, Λ the equivalent conductivity by a given concentration of the solution, and Λ_∞ is the equivalent conductivity at an infinity degree of dilution.

It was shown in test [2,3] where only NaCl and kaolin were used that surface conductivity began to increase > 75% RH. Above that air humidity, the difference $(p - p_s)$ in the Equation (1) becomes positive since the vapor pressure of a saturated NaCl solution at 20°C corresponds to the relative humidity of 75%. Thus a saturated NaCl solution absorbs water from air at relative humidities > 75%. As shown in Table 1, the vapor pressure above saturated solutions of other electrolytes can however differ considerably from the vapor pressure above a NaCl solution.

Leakage current on insulators can increase not earlier than after the conditions allowing a stable (continuous) wetting have occurred, *i.e.* after the above mentioned air humidity limit has been exceeded, this value

being dependent upon the chemical constitution of the pollution. This air humidity limit, as found by different authors, amounts to 78–90%, depending upon the type of impurities [11–13].

MEASURING PROCEDURE

IN order to test the hygroscopic properties of different salts, measurements of surface conductivity and leakage current on flat models placed in a fog chamber of 1.2 m^3 volume were carried out. The measurements were conducted at relative humidities of 66, 75, 81, 92 and 100% at 20°C. Particular humidities were obtained by means of saturated NaNO$_3$, NaCl, (NH$_4$)$_2$SO$_4$, Na$_2$CO$_3$ solutions, and that of distilled water placed on the chamber floor. Air motion was provoked in the chamber by a small fan, which accelerated the achievement of the equilibrium humidity.

For the measurement of surface conductivity, flat rectangular glass plates were used, having two aluminum electrodes with a distance of 1.5 cm, using 7 V 50 Hz voltage. Surface conductivity was measured from the moment of placing the plate in the chamber to the moment when its value had settled. For the leakage current measurement however, a round glass plate of 25 cm diameter was used, with a HV electrode of 2 cm diameter in the middle. After 30 min of wetting, a 6 kV ac voltage was applied to the plate located in the chamber. The phenomenon was observed and the leakage current measured.

To form a permanent coat, a mixture containing 40 g kaolin in 1 liter of distilled water was used, to which a selected salt was added so that the conductivity amounted to 5000 μS/cm. Wetting agent were not used. The mixture was coated uniformly over the plates in such quantity that ESDD amounted to 0.03 mg/cm^2. Contaminated plates were dried in an oven and after they had been cooled down to the ambient temperature of 20°C, they were placed in the chamber. Therefore the condensation process did not influence the measurement results. For the tests, the following salts were selected: ZnCl$_2$, CaCl$_2$, NaCl + KNO$_3$ + NaNO$_3$, NaCl, Na$_2$SO$_3$. 7 H$_2$O, CaSO$_4$·2H$_2$O, whose vapor pressures above their saturated solutions corresponded respectively to 15, 31, 32, 75, 95, and 98% RH. Switching impulse performance of 21 glass cap and pin insulators (PS 160 B) used on 400 kV lines was tested. To strings hung on a post outside a building in natural environmental conditions, 250/2500 μs positive and negative switching surges were applied. The tests were carried out according to the up-and-down

method with 30 impulses per test using a 5 MV, 375 kJ generator manufactured by Haefely. During the tests RH, temperature, atmospheric pressure, and surface resistance of insulators were measured. It was found that the value of surface conductivity had never exceeded 5 μS.

TEST RESULTS

MEASUREMENTS OF SURFACE CONDUCTIVITY

AFTER a contaminated plate had been placed in a constant humidity chamber, the surface conductivity increased until a constant value had been reached. Both the time until saturation of the layer during the wetting process and the value of conductivity reached at this time depended upon the salt type. Figure 1 shows the dependence of surface conductivity at saturation point on relative humidity for some salts. The most hygroscopic salts are calcium chloride and zinc chloride, for which the surface conductivity at saturation amounted respectively to 8 and 4 μS already at 66% RH; $Na_2SO_3 \cdot 7H_2O$ and $CaSO_4 \cdot 2H_2O$ absorb water at much higher humidities.

The moisture absorption mechanism and that of increase in conductivity on contaminated surfaces are however rather complicated. The dilution of salts can be an exothermal process (as in the case of $ZnCl_2$, $MgCl_2$) or an endothermal process (as in the case of $Na_2SO_3 \cdot 7H_2O$, KNO_3). Even a minimal decrease or increase in the layer temperature influences the wetting process. An increase in surface conductivity at a given air humidity depends not only on the water absorption rate but also on the value of conductivity of the salt solution, especially at higher concentrations. In Figure 2 the conductivity of NaCl, $CaCl_2$, $Na_2SO_3 \cdot 7H_2O$ and $ZnCl_2$ solutions depending on salt concentration is shown. The curves end at the point of saturation. The conductivity of a $ZnCl_2$ solution at a concentration of 40 g/100 g H_2O is about 91 mS/cm. However, at the same concentration the conductivity of $CaCl_2$ solution is almost twice as high. This is probably the reason why at a air humidity of 66% the conductivity of a $CaCl_2$ layer is about twice as high as the conductivity of a $ZnCl_2$ layer despite a similar hygroscopicity of both salts.

The rate of increase in surface conductivity during wetting not only depends on the salt hygroscopicity. Figure 3 shows that the surface conductivity of a
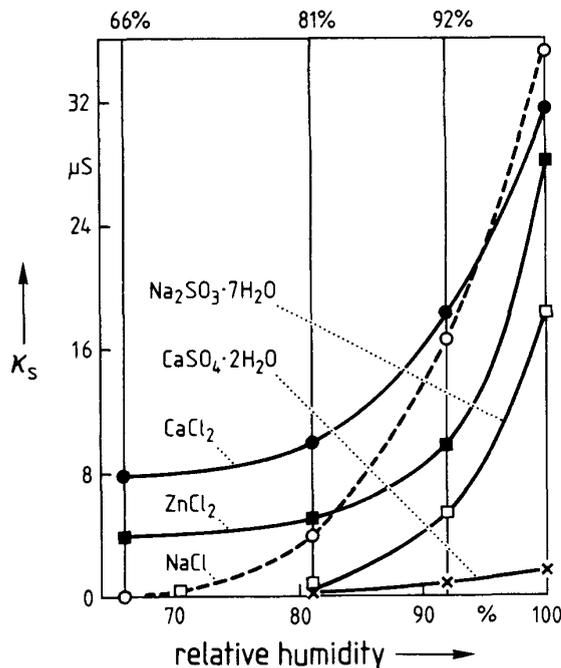

Figure 1.

Equilibrium surface conductivity values at constant ESDD=0.03 mg/cm^2 on a plate contaminated with different salts depending upon RH.

layer with NaCl, which is characterized by a considerably lower hygroscopicity than $ZnCl_2$, increases much faster than those of the $ZnCl_2$ layer.

LEAKAGE CURRENT

AFTER voltage has been applied to the round plate, for a short time of about 1 s, a sinusoidal current flows. Since the current density at the central electrode is the highest one, a dry zone forms around it and the discharge phase begins. After a lapse of a few s, the dry zone spreads to such a size (2 to 3 cm) that discharges extinguish. For pollution of low hygroscopicity (NaCl, Na_2SO_3) this state remains even at 100% RH. Hygroscopic salts ($ZnCl_2$, $CaCl_2$) absorb however moisture with such a rate that after some time, already at 66% RH, around the central electrode the dry zone diminishes to a few mm. This provokes a repeated ignition of discharges shown in Figure 4, which are constant in time. The leakage current connected to these discharges is however many times smaller than the initial current just after the application of the voltage.
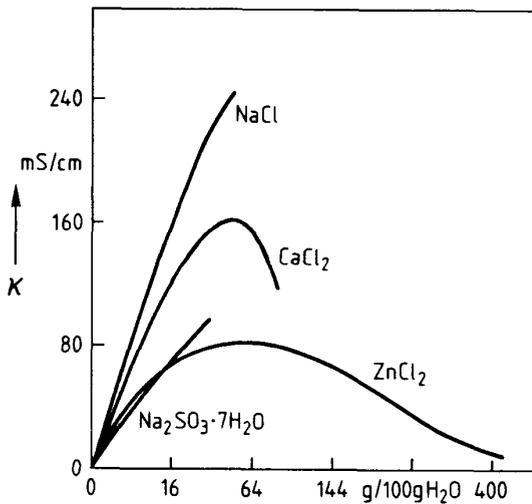
Figure 2.

Conductivity of solutions NaCl, CaCl$_2$, Na$_2$SO$_3\cdot$7H$_2$O and ZnCl$_2$ depending upon the solution concentration at 20°C.
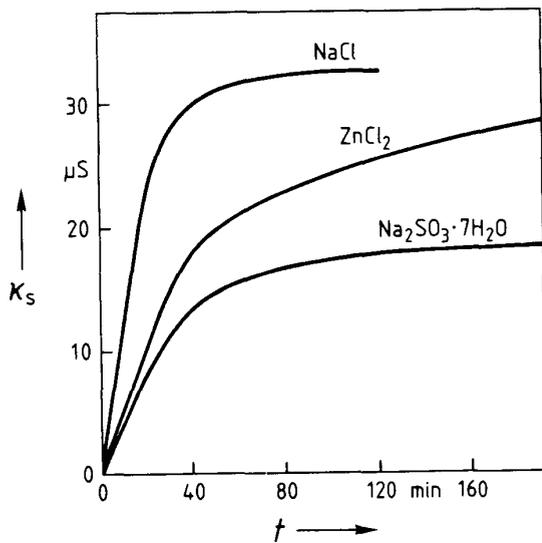

Figure 3.

Increase in the surface conductivity value of a layer contaminated with NaCl, ZnCl$_2$, NaSO$_3$ at 100% RH depending upon wetting time. ESDD=0.03 mg/cm^2, 20°C.

Figure 5 presents the highest current values after 6 kV has been applied on to the model of an insulator covered with layers containing different salts, as mea-

Figure 4.

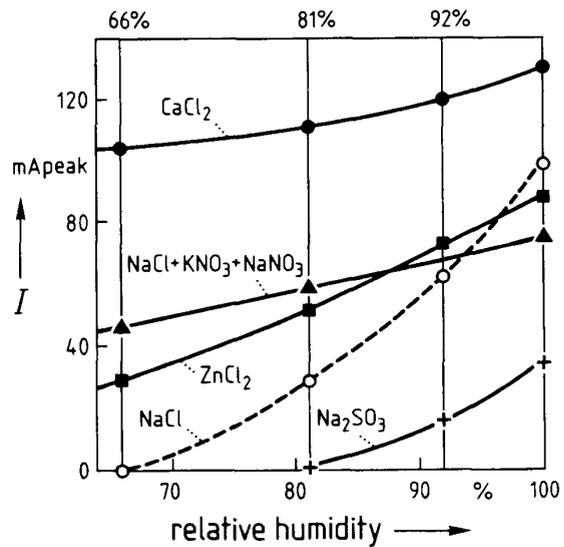Surface discharges by a pollution with CaCl$_2$, burning at 66% RH.

Figure 5.

Maximal current values after applying 6 kV voltage to an insulator model polluted with different salts. The plate was wetted for 30 min before switching on voltage. ESDD=0.03 mg/cm^2.

sured at different relative humidities. The highest current values were recorded for the layer with CaCl$_2$. After the voltage has been switched on, the layer heats up considerably. For this reason the solubility at boiling point, boiling point temperature, and solution conductivity which also vary along with temperature [5] are

important features of a salt. For instance, a saturated $CaCl_2$ solution boils at a temperature as high as 178°C and its solubility is then 305 g/100 g H_2O. For a saturated NaCl solution these values are respectively 109°C and 40.7 g/100 g H_2O.

Table 1.
Relative humidity above saturated solutions at 20°C [10]

Saturated aqueous solution	Air humidity above a solution %
$ZnCl_2 \cdot 1/2H_2O$	10
$NaCl + KNO_3 + NaNO_3$	30.5
$CaCl_2 \cdot 6H_2O$	32
$MgCl_2$	33 (30°C)
$NaCl + KNO_3$	32.5 (16°C)
K_2CO_3	45
$Ca(NO_3)_2 \cdot 4H_2O$	53.4
$NaNO_3$	66
$NaCl$	75
Na_2CO_3	92
$CaSO_4 \cdot 2H_2O$	98

The tests show the importance of the chemical constitution of pollution layers. Hygroscopic salts are most dangerous among the soluble components of pollution. Such components are, among others,: $CaCl_2$, $MgCl_2$, K_2CO_3, $Ca(NO_3)_2 \cdot 4H_2O$. They can cause considerable pollution severity during energizing of transmission lines in periods of increased humidity (even without fog or drizzle occurrence). Since the hygroscopicity of pollution layers consisting of several chemical components (e.g. $NaCl + KNO_3 + NaNO_3$, Table 1) can be higher than those of each component separately, certain types of natural layers can have a high capability of moisture absorption. This can be a reason for a surprisingly bad pollution performance of outdoor insulations in some industrial regions [14].

SWITCHING IMPULSE PERFORMANCE

I T was found that there is a non-linear dependence of 50% flashover voltage (U_{50}) on relative humidity at switching impulses of negative polarity. These results are presented in Figure 6. The electrical strength increases slightly with RH from low values up to about 60%. When the relative humidity exceeds 70%, sometimes a considerable drop in U_{50} is observed.
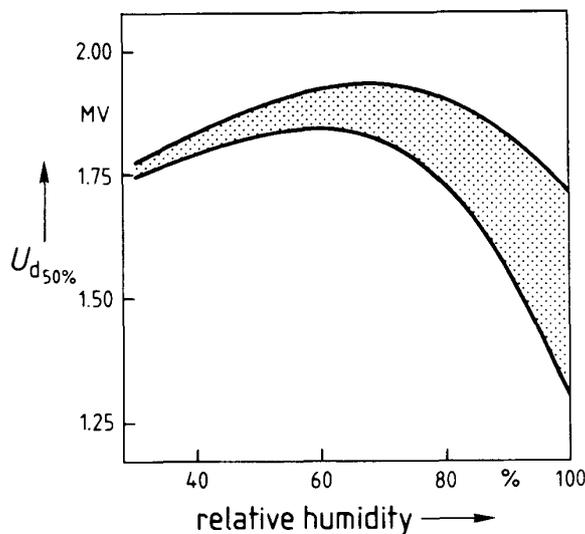

Figure 6.
50% flashover voltage of 21 cap-and-pin insulators as tested with negative switching surges as function of RH.

Such a dependence is striking, the more it occurs at negative polarity only, when flashover develops directly at the dielectric surface. At positive polarity however, when a discharge develops freely in the space around an insulator, no dependence of U_{50} on relative humidity was found. Other papers [15,16] confirm these results.

In the interval from 70 to 100% RH, the dependence of U_{50} on RH is subjected to a rather large scatter (different values of U_{50} correspond to the same RH values). This results from the measurement that surface resistance is a parameter determining changes of flashover voltage at negative surges. The effect that surface resistance decreases if RH increases occurs to a degree much lower than after the insulator was washed during a rainfall just before. For that reason, the resistance of clean insulators at high humidities is higher than that of insulators after a longer rainless period. It was found that at a high humidity and lowest surface resistances U_{50} of

insulators for the negative impulse could be about 20% lower than for positive surges. A similar effect was also observed on strings of porcelain long-rod insulators LG 75/24 sv.

CONCLUSIONS

THE intensity of moisture absorption on insulator surface depends upon the chemical constitution of the pollution.

The effect of intense and continuous moisture absorption can cause long-lasting surface discharges at operating voltage or can be a reason for flashovers a short time after the voltage has been switched on to a line.

The periods of high air humidity and hygroscopic properties of pollution layers are very important in switching impulse performance of insulators.

The flashover voltage at negative switching impulses depends on the state of the insulator surface and can be even lower than flashover voltage at positive switching impulses.

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