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Selection and dimensioning of DC overhead line insulation

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SUMMARY

Selection of DC overhead line insulation in Russia have stemmed from approaches that were developed while generalizing the service experience of the world's first ±400 kV DC Volgograd-Donbass, overhead line and designing of the ±750 kV DC (was constructed, but never been energized) and 1150 kV AC lines from Kazakhstan to Russia. More recently the techniques were supplemented by state-of-the-art findings on comparative breakdown strength and pollution resistance of different insulators.

It can be assumed that the methods of selection of overhead (OH) lines insulation, developed and tested in Russia, will be useful for the development of standards and the implementation of projects of HVDC OH line in the Africa.

The main stages of the selection:

• determination of pollution level (PL) along the OH line route based on field tests, including using the methods of mathematical statistics; statistical analysis methods have been applied in the issues of high voltage engineering, where the phenomenon is characterized by a wide variance of the test results of electrical and climatic influences. A typical example is the pollution performance of insulation, where both pollution and wetting events vary significantly. In Russia statistical methods for selection of external insulation of electrical equipment on the basis of calculating the expected number of trips of overhead lines at normal operation were used for super-long UHV DC and AC OH lines;

• selection of the optimal type of insulator on the basis of laboratory and field studies, pin cap-and-pin insulators and long-rod insulators (porcelain and composite) are considered.

• selection of isolation levels with use of normalized geometrical parameter - specific creepage distance with the with allowance for a number of additional factors, taking into account the operation aspects of insulation at a constant voltage;

• check the electrical strength of insulators, selected with use of geometrical parameter, with test DC voltage under normalized pollution level.

Determination of insulation level is carried out with use of guidelines in dependence of characteristics of sources of pollution and the distance from them to the OH lines. Guidelines also provide for the determination of isolation levels from flashover characteristics of insulators with artificial wet and pollution.

KEYWORDS

Direct current, insulators, pollution level, flashover performance, field measurement, selection.

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1. INTRODUCTION

Both in clean and polluted atmosphere areas, the insulation of overhead lines and switchgear is selected for normal service conditions, i. e. for exposure of wet polluted insulator surface to operating voltage stresses, which assures also reliable performance of the insulation under exposure to internal overvoltages.
Currently in Russia there are no guidelines available for selection HVDC overhead line insulation, so approaches tested in selection of HVAC overhead isolation [1-5], taking into account the specifics of the insulation under direct voltage [6-9] are using.
According to Russian 'Regulations' outdoor isolation levels of OH lines [1,2] are selected from their specific effective creepage distance (λ), which value is depending on the pollution level of the location of electrical equipment.
More informed selection of overhead line insulation is made by using of pollution level maps (PLM) [3]. In this case, the definition of flashover characteristics and natural pollutant layer of insulators are provided [10,15].
Studies of operation experience of outdoor insulation of electrical equipment, located in in the area of the projected overhead line are mainly used in plotting pollution level maps. [10,11].
One of the major insulator selection stages is field pollution level studies of HV OH line route using, among other things, mathematical statistics methods [5,9,12,13].

2. DETERMINATION OF THE POLLUTION LEVEL

2.1. Guidelines for determination of the pollution level

Pollution level (PL) is a quantitative characteristic of the effect of pollution and wetting conditions on the functioning of external insulation at the site of the electrical equipment. According to guidelines, characteristics of pollution sources (salinity of the water, the type of industrial production, production volume, type and ash content of the fuel capacity (MW), the distance from the sources of pollution and some other parameters) are used as initial criterion for determining of PL.
Russian guidelines [1, 2] show the values of PL for various distances from specific sources, depending on the characteristics of these sources. For the important extra HV and UHV OH lines isolation levels are defined not only by the guidelines, but also by PLM.

2.2. Determination of the pollution level with PLM

2.2.1. Allocation of areas with similar operation conditions of isolation

Pollution level map is a special geographic map, containing marked industrial and natural sources of pollution, electrical equipment (OH lines and substations), contours, showing areas with identical pollution levels, taking into account the impact of atmospheric boundary layer pollution on reducing the dielectric strength of electrical equipment. When selecting insulation level using PLM characteristics of pollution sources and characteristics of the location of electrical equipment must be considered. The operation experience of electrical equipment, the study of insulators (flashover performance, specific surface conductivity) located in the study area also must be taken into account. Algorithm of plotting of PLM is shown in Figure 1.When plotting of PLM at the first stage, the allocation of sections with similar degree of potential hazards for insulation performance [3] must be done.
For this purpose, a schematic map of the study area at a scale from 1:10.000 to 1: 100.000 for local maps and from 1:100.000 to 1:600.000 for regional maps has to be prepared. The following objects have to be marked on the map:
• routes of OH lines and areas of switchyards;

• typical climatic region, topography, landscape-climatic regions and subregions;
• sources of industrial pollutions and their borders;
• waterfront of salinas;
• salty soil and cultivated areas, dry and wet dust storms areas, dust non-indigenous areas, bird sitting down on cross-arm areas, etc.

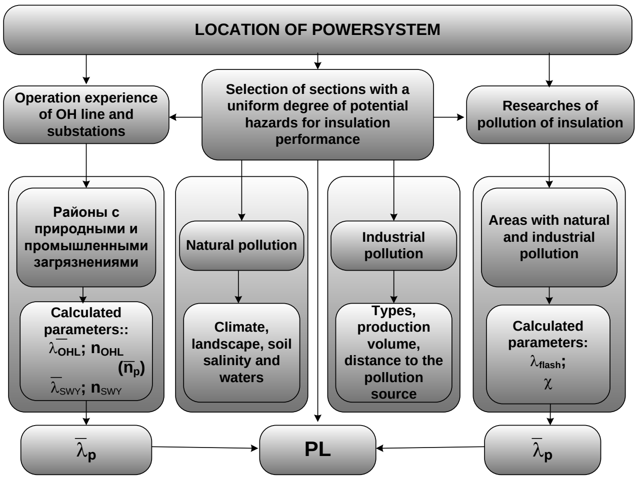

Figure 1 – Algorithm for plotting of PLM

2.2.2. Determination of insulation level by operation experience

UHVDC OH lines usually have a long length (over 1,000 km). Along the route of OH line a few sections with a uniform degree of potential hazards for insulation performance had to be selected. Generalization of operating experience of HVDC OH lines (preferred) or HVAC OH lines with voltage over 110 kV has to be done for every selected uniform section.
Study of failures that cause automatic shutdown of the overhead line and switchyard, is aimed to find connection between sources of pollution of insulation, insulation levels (specific creepage distance λ) and quantitative estimation of the reliability (n_p), ie specific number of trips per year caused by the pollution of insulation.
Average values (for several OH lines and switchyards located in selected uniform section) of specific creepage distance $\bar{\lambda}_{OHL}$ and $\bar{\lambda}_{SWY}$ have to be calculated. To estimate the number of trips $\bar{n}_p$ it is nesessary to know the number of OH line tripping caused by flash-over of polluted insulation.
All automatic tripping of overhead lines are divided into two groups: caused by flash-over of polluted insulation and occurred for unclear reasons. Those trips that coincided with adverse weather conditions (rain, snow, drizzle, dew, etc.) are identified as trips due to pollution.
Ultimately, average specific number of trips ($\bar{n}_p$) for n_{OHL} и n_{SWY} caused by flash-over of polluted insulation has to be calculated for each uniform section. Depending on the value $\bar{n}_p$, insulation level (average specific creepage distance $\bar{\lambda}_p$) is considered to be adequate, otherwise it is necessary to increase the isolation level. For UHV OH lines permissible specific annual number of outages caused by polluted insulation, as a rule, should not exceed 0.1 trip/100 km·year. In the case where $\bar{n}_p > 0.1$, it is necessary to increase the average specific creepage distance $\bar{\lambda}_{OHL}$ by multiplying by the coefficient K_α (Table 1).Required value of specific creepage distance λ_p for each uniform section is defined $\lambda_p = \bar{\lambda}_{OHL} \cdot K_\alpha$.

Table 1 – K_α depending on n_p

n_p, trip/100 km·year	0,1	0,5	1,0	2,0	5,0
K_α	1	1,1	1,15	1,20	1,25

2.2.3. Determination of insulation level by the results of studies

Using the results of studies of insulators with natural pollutant layer for each uniform section, values of flashover voltage (U_{flash}), specific surface conductivity (χ), and specific flashover creepage distance λ_{flash} have to be determined. The specific flashover creepage distance λ_{flash} is determined by the equation:

$$\lambda_{flash} = \frac{\nu \cdot L_1}{U_{flash} \cdot K_L}, \tag{1}$$

where: U_{flash}, the average (or 50%) flashover voltage of the test insulator (test time-averaged for steady-state conditions), kV; K_L– usage factor of creepage distance of test insulator; ν -number of insulators in the string; L_1 – creepage distance of single insulator.

An average ($\overline{\lambda}_{flash}$) of the lowest values measured at different points of uniform section at different times of the year has to be determined using the individual values λ_{flash}.

An average $\overline{\chi}$ of the highest values measured at different points of uniform section at different times of the year has to be determined. Using calculated values $\overline{\lambda}_{flash}$ and $\overline{\chi}$ the insulation levels $\overline{\lambda}_{\text{p}}$ and PL has to be determined for OH lines in uniform section. The guidelines for selection of insulation levels with using of $\overline{n}_p$, $\overline{\lambda}_{flash}$, $\overline{\chi}$ was developed in JSC "NIIPT" on the base of long-term research of insulation in areas with different pollution levels. Using the methods of mathematical statistics, quantitative relationships between the insulation levels (λ) (defined on the basis of studies) and HV OH lines and switchgears insulation operational reliability (n_{p}) were determined.

The desired value $\overline{\lambda}_{\text{p}}$ is defined by the flashover voltage of naturally polluted insulators and statistical safety factor K_s:

$$\overline{\lambda}_{\text{p}} = K_s \cdot \overline{\lambda}_{flash}, \tag{2}$$

where K_s is the safety margin of insulation showing the ratio of the average dielectric strength of a single insulator string to the string withstand voltage assuring the specified reliability level of the line.

K_s is determined using the methods of mathematical statistics [12]. Probability of a flashover per hazardous wetting per string is:

$$P_{\text{s}} = F\left(\frac{1-K_s}{C_p \cdot K_s}\right) = \frac{n_p}{m \cdot \xi} = F(x), \tag{3}$$

where n_p – is specific annual number of flashovers; m – number of strings per 100 km of the line; ξ – average number of wet insulation hazards; C_p – flashover voltage variability ratio for insulators that were polluted on the planned line route; F – integral normal distribution function; x - argument of the normal distribution function $x = \left(\frac{1-K_{\text{s}}}{C_p \cdot K_{\text{s}}}\right)$.

From the equation (3) the safety margin is determined:

$$K_s = \frac{1}{1 - x \cdot C_p}. \tag{4}$$

Using the field measurements the flashover characteristic (λ_{flash}) and specific surface conductivity (χ) are determined. Using table 2 and figures 2 and 3, pollution level is determined.

Determination of demanded λ_{p} in dependence of λ_{flash} is shown in Figure 2, determination of demanded λ_p in dependence of χ is shown in Figure 3.

Table 2 - Determination of PL from field measurements of λ flash and χ

Average specific alternating flashover voltage for standard-make cap-and-pin insulator the insulating height $\overline{\lambda}_{flash}$, cm/kV	Average specific surface conductivity $\overline{\chi}$, μS	Standard specific creepage distance λ, cm/kV		PL
		λ_{ac}	λ_{dc}	
>1.2 to 1.5	>1 to 3	1.6	2.8	1
>1.5 to 1.9	>3 to 6	2.0	3.5	2
>1.9 to 2.3	>6 to 12	2.5	4.3	3
>2.3 to 2.7	>12 to 20	3.1	5.4	4
>2.7 to 3.3	>20 to 30	3.7	6.4	>4

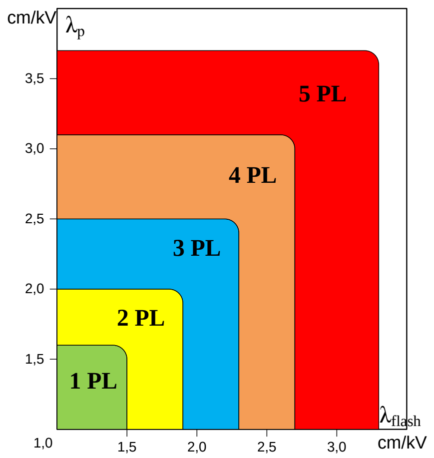

Figure 2 – Determination of demanded λ_p in dependence of λ_{flash}

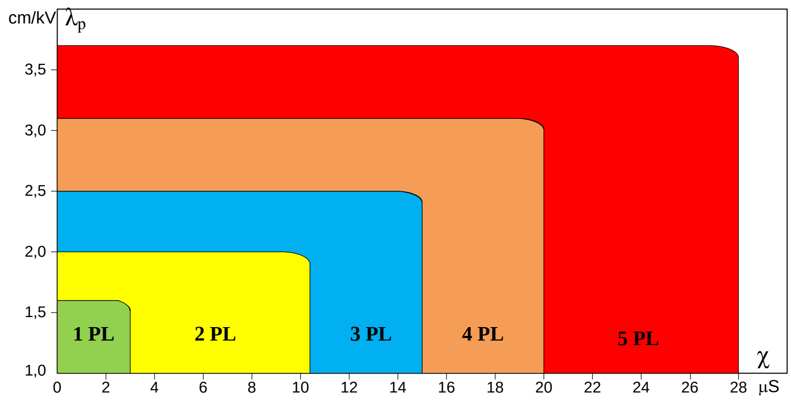

Figure 3 – Determination of demanded λ_p in dependence of χ

3. SELECTION OF THE INSULATOR TYPE

Three basically different line insulators can be considered as likely candidates of use on UHVDC overhead lines: cap-and-pins glass and porcelain, long-rods porcelain and composite insulators.

Each of these types has its own advantages as regards reliability, weight, cost, ease of transportation, installation and maintenance, diagnostics etc. Still, quite a number of engineering and economical factors have to be taken into account when planning use of this or that type on a UHVDC lines.

The guiding principle of selecting optimum insulator type is to make allowance for standard hazardous service conditions, i. e. exposure of wet polluted insulation to the operating voltage. On the final account, it is this exposure that determines the string length, the tower height, and thus the cost of the line as a whole.

It is recommended to use OH line insulators which assure the needed reliability of the line at a minimum string length, costs of operation and diagnosis. For a given set of pollution conditions, the practical criterion of an optimum insulator configuration is to have the highest possible specific flashover voltage (E_h), over the insulator's construction length the lowest possible pollutability and good self-cleaning. AC and DC tests of artificially polluted cap-and-pin, long-rod porcelain and composite insulators have made it possible to compare their dielectric strength at identical pollution levels and to find a number of coefficients that are taken into account when dimensioning insulators or insulation sets for UHV DC overhead lines.

In areas with high pollution level (3rd and 4th PL) application of composite insulators has a significant effect on the reduction of the length of the strings due to higher value of parameter E_h (Figure 4).

In areas with mild to moderate pollution level (1st and 2nd PL), despite the higher value of E_h for composite insulators, it is difficult to significantly reduce the length of the strings made of composite materials because it is necessary to fulfill the requirements to the length of the air gap of the wire-traverse, limited by overvoltages.

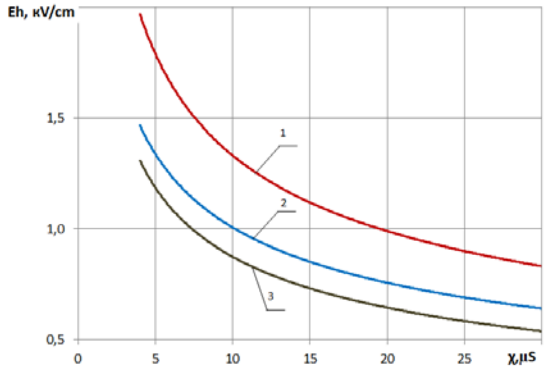

Figure 4 - Specific voltage E_h for the insulating height for cap-and-pin glass, long-rod porcelain and rod composite insulators *as a function of the* specific surface conductivity χ under artificial pollution. 1- rod composite insulators ; 2-long rod porcelain insulators; 3- cap-and-pin glass insulator

Long-rod porcelain (LRP) insulators are promising for application on HVDC OH lines. Flashover characteristics of artificially polluted long-rod porcelain insulators as good as those of cap-and-pin insulators (Figure 4). LRP do not suffer from electrical breakdown consequently, no replacement of broken units is needed, which makes unnecessary the live line maintenance of lines with such insulators.

According to findings of the DC tests of LRP mock-up, configuration of the insulating bushing and the relations between its main geometrical dimensions (for example, the ratio of the distance between the ribs to the rib overhang) have an effect on dielectric strength of the insulator [14].

Insulator with a variable diameter of rib overhang had the highest flashover voltage. Burning partial arcs at DC voltage leads to the blowing of the arc from the surface of the insulator. This way of arc progression causes a partial bypass of section of the insulator with closely spaced ribs, so creepage distance is not fully utilized. It can be assumed that the most effective for heavy pollution level areas (3rd and 4th PL) will be LRP which have rib overhang with large and small diameters. In some cases, LRP which have two small ribs between large ribs.

In recent years there has been a trend towards the use of long-rod porcelain insulators for operating DC OH lines (Australia, China), as well as the projected DC OH line ± 300 kV in Russia [15]. It can be assumed that a deterrent to widespread use of these insulators for DC OH line was a lack of study of electric corrosion characteristics at DC voltage in pollution and humidity conditions.

Electric corrosive resistance test at DC voltage was carried out by NIIPT. Long-rod units were tested with reference to cap-and-pin insulators [16].

Long-rod insulator mock-ups had real caps, construction and material (lead) of armouring. Tests were performed in an artificial corrosion environment of two kinds (Fig. 5). In one case, solid wet polluted surface (clay with salt) was formed on the surface of the insulator. In the second case test objects were placed into a weak electrolyte (salt solution).

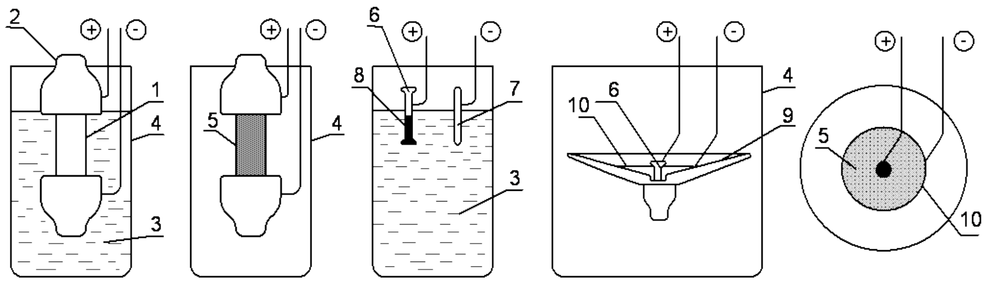

Figure 5 - Electric corrosive resistance test of insulator mock-ups: 1-porcelain; 2-cap (iron); 3-electrolyte (NaCl dissolved in water); 4 - a container (glass); 5-pollution layer (kaolin + NaCl); 6-pin

of cap-and-pin insulator (iron); 7-electrode (copper); 8-protective coating of the pin; 9- cap-and-pin insulator; 10 - ring-shaped electrode (copper)

Corrosion resistance was characterized by the quantity of electricity Q, passing over tested object determined be specified service life T = 30 years.
The value of quantity of electricity Q, passing over tested insulator during the year was estimated on the basis of published data on the leakage current and the duration of periods of the year with different moisture conditions [17,18,19]. According these data the quantity of electricity passing over insulators of an HVDC overhead line in a heavily polluted area can be estimated, with an accuracy sufficient for all practical purposes, to be Q = 1 A·h/year.
The surface area in contact with a corrosive environment of the cap-and-pin insulator is about 20 times smaller than the contact zone of the long-rod insulator. That's why cap of long-rod insulator has less value of specific quantity of electricity per unit surface per year ($A \cdot h/cm^2 \cdot$ year anode surface) in comparison with rod of cap-and-pin insulator. Metal flow from rod (pestle) anode unit surface area is also 20 times higher than from anode in the form of a cap of rod insulator.
Because the cap insulator rod leakage is dispersed over a large area, the depth of corrosion is relatively small (about 2 mm), which does not affect the mechanical strength of the insulator.
Furthermore, sealing (armoring) of antimony lead has good corrosion resistance due to films composed of corrosion products, e.g., PbO_2 on the armoring outer surface firmly connected to the metal.
Corrosion damage of the pin cap-and-pin insulators is much more dangerous than corrosion damage of cap of long-rod insulator. Since the extension strength of the pin is determined by the minimum cross-sectional area, it is necessary to prevent reduction of cross-sectional area to a critical value which can be estimated from Figure 6.
Figure 6 shows the dependence of the depth of corrosion damage of long-rod insulator cap Δh (curve 1) and the pin of cap-and-pin insulator Δd (curve 2), and Figures 7-8 show photographs of these insulators with visible corrosion after passing electricity quantity about 20 A·h, which corresponds to 20 years long operation in high pollution areas.

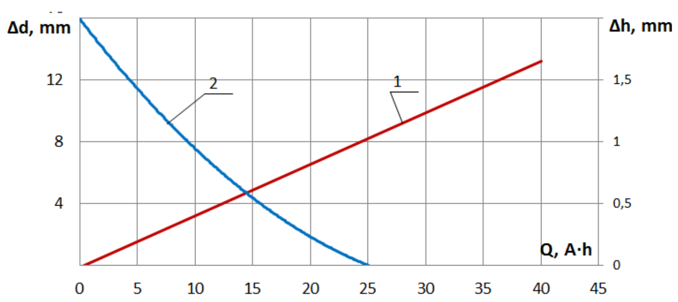

Figure 6 - Depth of corrosion damage of long-rod insulator cap Δh (curve 1) and pin-and-cap insulator pin Δd (curve 1) as functions *of the* electricity quantity Q.

Comparative Electric corrosive resistance test showed the advantage of long rod porcelain insulators in comparison with the pin-and-cap insulator.

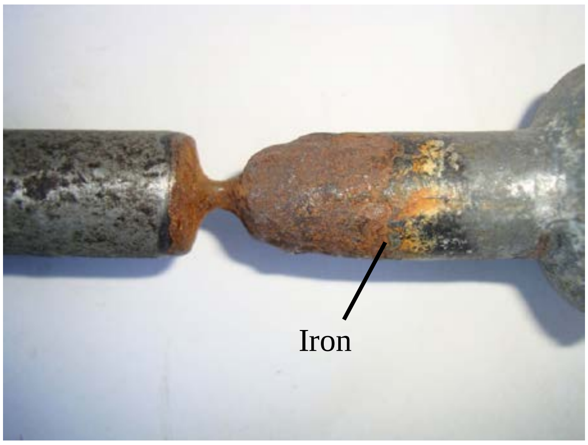

Figure 7 – Corrosive damage of the pin cap-and-pin insulator

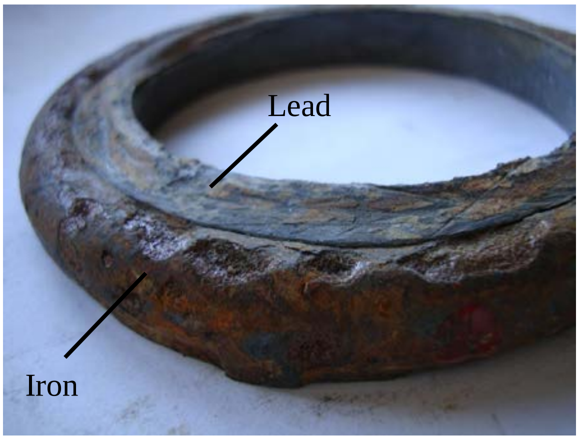

Figure 8 – Corrosive damage of the pin long-rod insulator

4. SELECTION OF INSULATION LEVELS

Levels of external insulation of electrical equipment are selected from specific creepage distance λ, i.e. creepage distance divided by the maximum operating voltage pole-to-earth for HVDC OH lines by phase voltage for AC OH lines.

According to the operating experience [5,8], specific number of tripping n_p of HV AC and DC OH lines, caused by pollution of insulators, decreases with increasing λ (fig. 9). An increase 17-19% λ result in a decrease in n_p by 10 times, both for HVDC and HVAC OH lines.

Recommendation for selection HVDC OH lines isolation can be formulated as the following: compile and synthesize the operation experience of HVAC OH lines near future route of the HVDC OH line, preevaluate its value λ, which can then be corrected by introducing correction factors which take into account the specific conditions of operation at DC voltage.

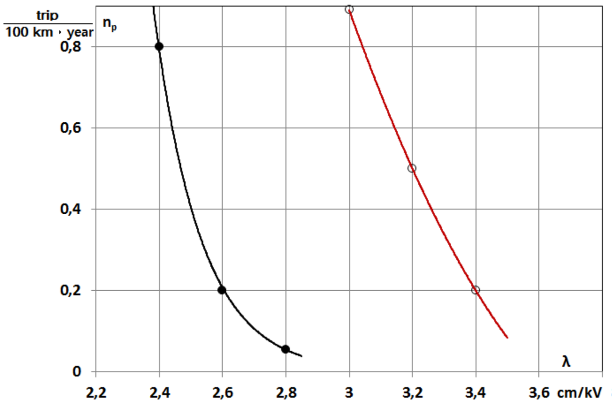

Figure 9 - Specific number of tripping n_p for HVDC (•) and HVAC (o) OH lines, caused by pollution of insulators, as a function of λ.

Depending on potential hazard of pollution of DC OH line insulating strings five pollution levels are defined. Each PL corresponds to a normalized value of specific creepage distance λ (Table 3).

Table 3– Specific creepage distance λ of DC OH line insulating strings depending on the pollution level of the areas

Pollution Level (PL)	1	2	3	4	5
λ, cm/kV (no less)	2,8	3,5	4,4	5,5	6,5

Creepage distance L with allowance for the type of insulator or set of single insulating units, conditions along the OH line would be obtained from:

$$L = \lambda \cdot U_{mo} \cdot K = \lambda \cdot U_{mo} \cdot K_L \cdot K_n \cdot K_{dc} \cdot K_s \cdot K_p \cdot K_t, \quad (5)$$

where U_{mo} – maximum operating voltage pole-earth, kV;
λ – determined in dependence of PL using table 3;
K_L – correction factor making allowance for structural features of the insulating part, including the effect of the elaborate surface of a wet polluted insulator on its flashover performance [1,2];
K_n – correction factor making allowance for the non-linear relationship between flashover voltages of wet polluted insulators (and strings thereof) and their length [8];
K_{dc} – correction factor making allowance for the difference between DC and AC flashover voltages of insulators that have an identical pollution level, $K_{dc} = E_{h\sim} / E_{h=}$ [8];
K_s – correction factor making allowance for the shape of a multiple-unit insulating structure [1];
K_p – correction factor making allowance for different pollution resistance of different insulating materials [20];
K_t – correction factor making allowance for different pollution at DC and AS voltage [21];
K – resultant correction factor $K = K_L \cdot K_n \cdot K_{dc} \cdot K_s \cdot K_p \cdot K_t$.
Creepage distance $L_h = L \cdot K_h$, where Kh - correction factor making allowance for different levels above sea [1].

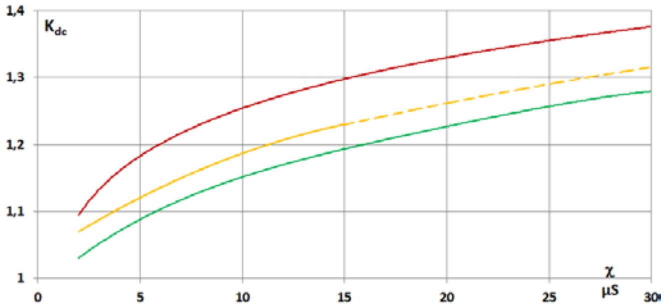

Figure 10 – Factor K_{dc} as a function of χ for cap-and-pin, long-rod porcelain and composite insulators: 1- Long- rod composite insulator; 2- Long- rod porcelain insulator, 3- Cap-and-pin insulator (glass, porcelain)

Table 4 shows the raw data for the estimation of the resulting coefficient K.

Table 4 - Evaluation of the correction factors

Correction factor	Type of insulator	Determination of the coefficients
K_L	Cap-and-pin (glass, porcelain) L/D≤1.6	1 for L/D<1.1
		K_L = 1+0.6(L/D-1.1) for L/D from 1.1 ro 1.6
	Long- rod (porcelain)	1 for L/h<2.5
		K_L = 1+0.2(L/h–2.5) for L/h от 2.5 до 4
	Long- rod (composite)	1 for L/h<3
		K_L = 1+0.15(L/h–3) for L/h от 3 до 4
K_n	Cap-and-pin (glass, porcelain)	1 for χ>5 μS
		K_n = 0.865 + 0.0054n (n – number of units in the string more than 25 for χ≤5 μS)
	Long- rod (porcelain, composite)	1
K_{dc}	Cap-and-pin (glass, porcelain)	Curve 1 (fig.10)
	Long- rod (porcelain)	Curve 2 (fig.10)
	Long- rod (composite)	Curve 3 (fig.10)

Correction factor	Type of insulator	Determination of the coefficients
K_s	Cap-and-pin (glass, porcelain) Long- rod (porcelain, composite)	By analogy with AC OH line: 1.05 for s=2 1.08 for s=3 1.10 for s=4 s – the number of parallel circuits in the string of identical insulators
K_p	Cap-and-pin (glass, porcelain)	1.0 in the areas of 1-st PL
	Long- rod (porcelain)	1.0–1.4 in the areas of 2nd - 4th PL
	Long- rod (composite)	Additional information is required
K_t	Cap-and-pin (glass, porcelain) Long- rod (porcelain, composite)	Field study is required . Approximately it is possible to determine the value from[21]
K_h	Cap-and-pin (glass, porcelain) Long- rod (porcelain, composite)	By analogy with AC OH line: 1.05 from 1000 to 2000 m above sea level; 1.1 from 2000 to 3000 m above sea level; 1.15 from 3000 to 4000 m above sea level.

5. SELECTION OF INSULATORS ON THE BASIS OF THEIR WET POLLUTED FLASHOVER PERFORMANCE

Dimensioning of insulation by the geometrical parameter, i. e. the creepage distance L, must be checked by results of wet polluted tests. The 50% DC flashover voltages of a wet polluted string must not be below the specified test voltage U_{test} at the specified test specific surface conductivity χ_{test} of the pollutant layer.

The test voltage U_{test} is applied to wet polluted insulation continuously. Its value is found from the expression

$$U_{test} = K_s \cdot U_{m0} = 1.5\ U_{m0}\ ,$$

where K_s = 1.5 is the safety factor expressing the increase in dielectric strength of a single unit (or string) with respect to a totality of units (strings) involved in operation of the UHV DC line in question.

Values of χ_{test} are found in Table 5 with allowance for the PL and the material of the insulating body.

Table 5 - Values of χtest

PL	χ_{test}, μS	
	Porcelain and glass units	Composite insulators
1	5	2
2	10	5
3	20	10
4	30	20

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