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The Possibility of Insulation Level Reduction on 110 kV Overhead Line with Built-in Post Insulators Using Line Surge Arresters

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SUMMARY

Installation of line surge arresters (LSA) on overhead lines is normally accomplished with aim of line performance improvement. Co-ordination insulation procedure carried out during the line design in most cases doesn't take into account a suppression of overvoltages by using any overvoltage limiting devices. The decision supported by poor line performance to install LSA is usually made later. The reduction of overvoltage level depends mainly on the number of LSA installed, but in any case it is considerable. It means that insulation regarding dielectric strength might this way be over dimensioned. This fact could be considered for reduction of phase-to-ground and phase-to-phase distances, which lead to greater level of line compaction. This is of the most importance for lines with post insulators, since shorter insulators could be used and consequently narrower right of way achieved. Our target was to investigate the possibility of reducing lightning overvoltages by using LSA's attached parallel to the insulators. For the analyses purpose we implemented a mathematical model of a single-system 110 kV compact overhead line. The Sigma Slp software was used for computer simulations. The line was investigated from the perspective of lightning over-voltages as they are the factors the most severely stressing the insulation. We focused to lightning strikes at a tower top for the case of single-phase (C) LSA installation configuration. The main influencing parameters were varied such as lightning current, surge shape and tower earthing resistance according to their most probable values to obtain overvoltage properties. We concluded, that adoption of LSA's does not only reduce the overvoltage amplitude in that phase but also changes its shape, which has to be taken into account for test impulses generation. The physical model of wooden pole with composite line post insulators was built for testing in high-voltage laboratory. Power frequency and impulse tests were performed on insulators (phase-to-ground) and between phase conductors (phase-to-phase) in dry and wet conditions when necessary. Besides standard also non-standard impulse shape tests were accomplished to obtain withstand voltages for different arching distances. Based on our comparison with the simulation results we concluded that - speaking in terms of lightning overvoltages - it is possible to use insulators for the insulation level U_m = 72,5 kV (140/325 kV), if LSA's in phases A, B and C would be installed. To verify the conclusion in all other respects, further analyses are needed.

KEYWORDS

Compact line, 110 kV, post insulators, overvoltages, insulation level reduction, line arresters, high-voltage laboratory, tests, Sigma SLP, computer simulations.

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1. Introduction

Improvement of the overhead power transmission line (OL) performance is usually accomplished by installation of OL surge arresters (LSA). In majority of cases, the insulation coordination procedure, undertaken in the line design phase, pays no attention to suppression of overvoltages by using any of the currently available overvoltage limiting devices. The decision to cope with the poor OL performance by installing LSA is usually taken much later. Decreasing the overvoltage level depends mainly on the number of LSA's installed. While the decrease is, irrespective of this number, always considerable, there might be cases – speaking in terms of dielectric stress – when insulation can be unnecessarily over-dimensioned. This fact should be considered in order to reduce phase-to-ground and phase-to-phase distances thus allowing for a greater level of line compaction.

The above is particularly important for OL's equipped with post insulators for which shorter insulators can be used assuring numerous advantages (a narrower OL right-of-way, reduced environmental impact, possibility of uprating the MV line to operate on the 110 kV voltage level, etc.). The focus of our study was on a 110 kV single-circuit OL equipped with in-built composite post insulators and ground wire. OL was investigated from the perspective of lightning overvoltages as they are the factors the most severely stressing the OL insulation. On the other hand, temporary voltages are moderate due to the directly grounded neutral (earth-fault factor k_{ef} being less than 1.4 in 94 % of the power stations, earth-fault clearing time $t_{ef} = 1$ s). The same can be said also for switching overvoltages (only single-phase re-closure is used) which can be further suppressed by means, for example, controlled switching. Our target was to investigate the possibility of reducing lightning overvoltages by using LSA's attached parallel to the insulator in the lowest phase C (smallest coupling factor k_c [1]). In order to improve the OL performance, LSA can by all means be installed in two or all the three phases. We investigated only LSA with no serial gap because the residual voltages it produces are lower, meaning that overvoltages can be limited more effectively.

2. Lightning overvoltage simulations

To define the OL insulation level, we analysed any of the possible variations in the lightning overvoltage level. The nature of overvoltages under various OL operating conditions was determined by performing several computer simulations (lightning flash striking at OL), for which we used the Sigma Slp software. Let us mention at the beginning, that "phase-to-ground voltage" in following text is actually related to the tower top, which during transients is not at the ground potential.

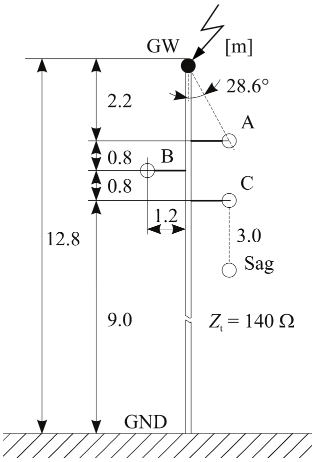

Figure 1: OL dimensions

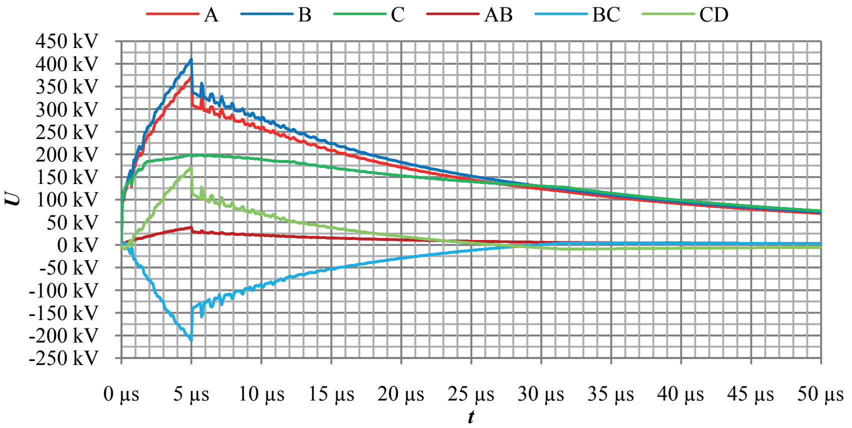

Figure 2: Overvoltages at a lightning flash striking at the tower top ($I_l = 40$ kA, 5/75 µs, $R_g = 10\ \Omega$, line voltage is 0 kV)

For the purpose of our investigation we implemented a mathematical model of a single-system compact OL. The tower was represented with OL with surge impedance $Z_t = 140\ \Omega$ and ionisation footing resistance (IEC 60071-2). The constant value of 10 was taken for low-current resistance R_g to soil resistance ρ [Ωm] ratio. Three OL post insulators were used for conductor attachment. The OL dimensions are shown in Figure 1. As the vertical distances between insulators were short, the tower top wave travelling paths were neglected. We modelled five representative successive towers (the OL span was 92 m). They were terminated so as to ovoid reflections on each side. The line was energized with a three-phase 110 kV voltage, because the total overvoltages, consisting of the OL voltage and lightning overvoltages, have to be considered [1]. As the rated LSA voltage had to be as low as possible (the system parameters being $U_m = 123$ kV, $k_{ef} = 1.4$, $t_{ef} = 1$ s) in order to enable better overvoltage limitation, $U_r = 90$ kA was selected.

Our main interest was to know what happens when a lightning strikes at a tower top for the case of single-phase (C) LSA installation configuration on all towers (Figure 2). The current impulse shape used in our simulations was triangular (linear - front, tail). The main parameters were varied according to their most probable values [1]: lightning current $I_l = 10 \ldots 40$ kA (first stroke), surge front $t_f = 10 \ldots 40$ µs and tail duration $t_t = 30 \ldots 200$ µs, earthing resistance $R_g = 5 \ldots 100\ \Omega$. The most unfavourable parameter values were combined (for example high R_g high I_l taking place at the same time) and examined in more detail. In each case, the operating voltage instant value was added to the overvoltage amplitudes. Figure 3 shows the total overvoltage amplitudes with respect to operating voltage phase angle. Maximum values (U_B, U_{BC}, U_C) for different parameters (R_g , I_l) can be found in Figure 4.

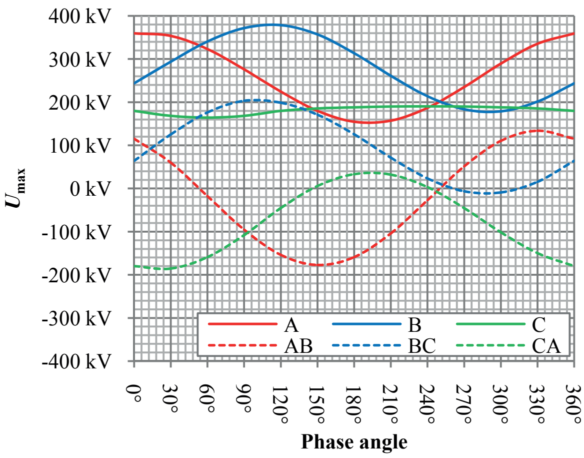

Figure 3: Maximum overvoltages (operating voltage 110 kV included)

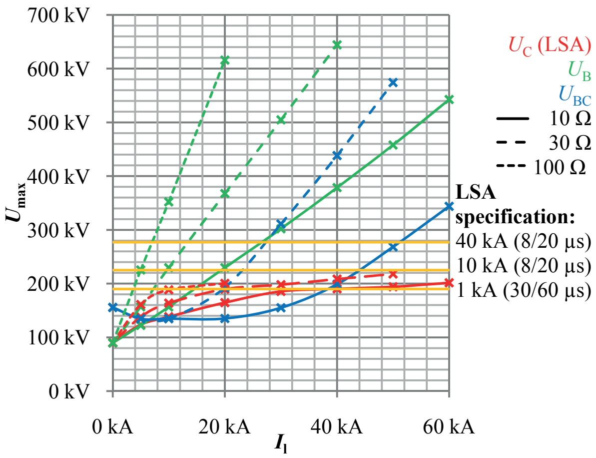

Figure 4: Maximum $U_{max}(I_l , R_g, 5/75\ \mu s)$ with respect to 110 kV

Judging from the results obtained with our simulations of overvoltages involving phases A and B (without LSA), the following conclusions can be drawn:

- The overvoltage amplitudes for typical wave front duration t_f are affected mostly by lightning current peak value I_l and tower footing resistance R_g (Figures 4 and 6).
- Higher lightning current steepness (t_f) increases the overvoltage amplitude (Figures 5 and 6). On the contrary, surge tail duration t_t (time to 50 % amplitude) is of no importance with this respect.
- Overvoltage duration t_t is moderately affected by I_l shape (the descending part) which is the consequence of travelling wave reflections, mainly from the tower grounding [1].
- Phase-to-phase overvoltages are small because of short distances between conductors and thus similar coupling factors k_c. In fact, LSA operation in phase C increases them (Figure 2). Anyway, they are never higher than the phase-to-ground overvoltages.

The overvoltages in phase C (LSA installed) are defined by I_l and U-t arrester characteristics and thus becoming flat with long impulse duration t_t (Figure 2). Except in case of a shielding failure, they take the value of some 200 kV (roughly).

We also considered some other typical cases. The reference values valid for the following statements are: LSA installed in phase C, BIL 550 kV (phase-to-ground and phase-to-phase insulation), I_l shape 5/75 µs, $R_g = 10\ \Omega$, no operating voltage on OL. It should be noted that the shielding failure (lightning stroke to phase A or B) initiates a single-phase flashover even when the current is very low, such as

I_l = 3 kA. An exception is a direct stroke to phase conductor C. Anyway, because of high I_l through the arrester, the overvoltages can increase considerably. In phases A and B, induced voltages are not so high, but the polarity is opposite for high I_l values. This means that phase-to-phase overvoltages become critical reaching 550 kV at approximately I_l =100 kA.

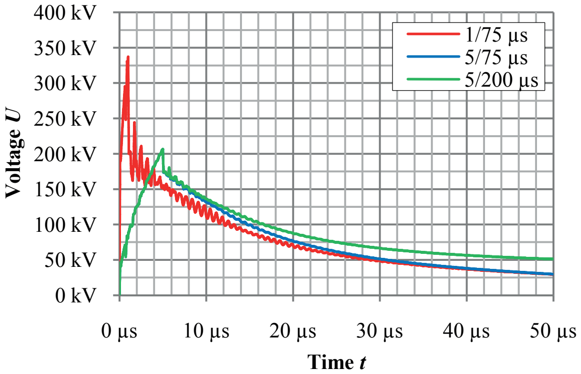

Figure 5: Phase B overvoltages for variable t_f – samples (I_l = 40 kA, R_g = 10 Ω, line voltage is 0 kV)

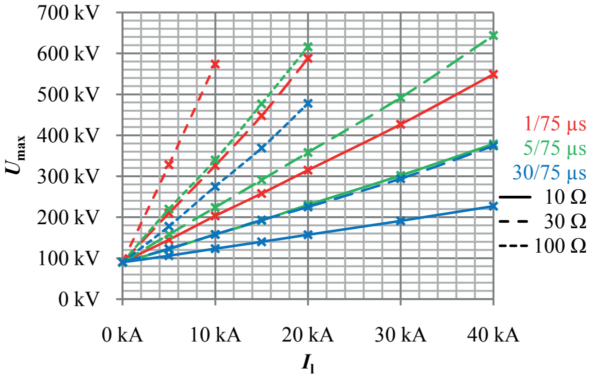

Figure 6: $U_C(t_f, I_l, 240°)$ characteristics

The best line performance for the standard case is to be expected with LSA installed in phases A, B and C resulting in low overvoltages in any of them. Again, the insulators are dielectrically stressed by the arrester residual voltage. In this way, the phase-to-phase overvoltages are practically zero. The shielding failure causes no flashover even at I_l =100 kA and R_g = 50 Ω despite higher overvoltages for which the highest phase-to-phase values were obtained as a result of the reasons given above.

Speaking in terms of the OL insulation dielectric stress, we can in general conclude that shapes of the phase-to-ground and phase-to-phase overvoltage are well matched with the standard lightning impulse of 1.2/50 µs. Adoption of LSA's does not only reduce the overvoltage amplitude in that phase but also changes its shape. The top is flattened and surge duration t_t is longer especially under unfavourable operating conditions, for example at high I_l and long t_t. Since the dielectric strength in air gaps depends on overvoltage characteristics [2] [3], the test voltage shape for this last case has to be adapted accordingly. For any other overvoltage level, the standard lightning impulse is appropriate.

3. High-voltage tests

The crucial characteristics for an insulator is its withstand voltage U_w. We began our measurements with standard dialectic tests performed on the entire insulator. As a reference we took the withstand voltages U_w for the insulation level U_m = 72.5 kV. For this purpose we made a physical model of the compact line tower equipped with line post composite insulators. They were attached in a vertical delta configuration. The conductor was represented with a 3 m long aluminium pipe and hanged up on the insulator with suspension and coupling fittings. The electric field was evenly distributed with spheres at both ends of the pipe. Thus developed model (Figure 7) provided the basis for our testing.

Figure 7: Model of compact line tower with line post composite insulators

We preformed a standard dielectric positive and negative lightning impulse voltage test in dry and alternating voltage test in dry and wet according to specifications of the IEC 60060-1 standard. Our investigation began with lightning-impulse voltage tests (entire insulator). The methods up-and-down (UDM) and multi-level (MLM), each preformed 50 times were used to obtain needed results. 50 %

disruptive discharge voltage U_{50} and the overall discharge characteristics were determined with a statistical analysis of the obtained test results on the basis of the maximum likelihood method [4].

The insulators U_{50} at a positive (649 kV) lightning impulse test is lower than at a negative (689 kV) one. We therefore preformed tests at a shorter phase-to-ground arcing distances l_{ad} only for positive lightning impulses. The insulator creepage distance sheds were bridged with a copper ring connected to the ground and in this way l_{ad} was shorter. An equivalent to the shorter insulator was thus achieved and the impact to U_{50} assessed. The obtained results are shown in Figure 8.

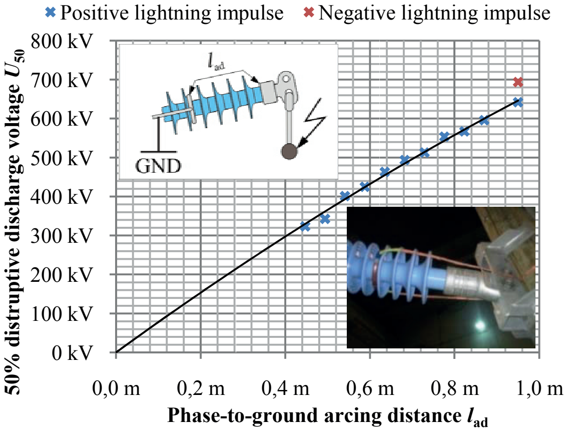

Figure 8: U_{50} as a function of phase-to-ground l_{ad}

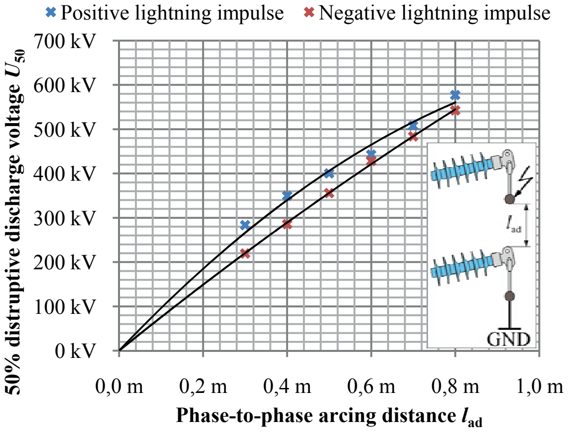

Figure 9: U_{50} as a function of phase-to-phase l_{ad}

We then determined U_{50} as a function of phase-to-phase l_{ad}. The conductor was at both phases replaced by an aluminium pipe. Shortest l_{ad} was found to be between phases that are one above the other. The lower phase was connected to the ground and the upper to the impulse generator. The obtained results are given in Figure 9. It can be seen that the worst case scenario is the one with the negative lightning impulse. The required lightning impulse withstand voltage for $U_m = 72.5$ kV is $U_w = 325$ kV and is equal to 10 % disruptive discharge voltage U_{10}.

Our next step was determination of alternating withstand voltage U_w as a function of phase-to-ground and phase-to-phase l_{ad} in dry or wet conditions. The obtained results are presented in Figure 10 and 11. The required alternating withstand voltage (50 Hz, 1 min.) for $U_m = 72.5$ kV is $U_w = 140$ kV.

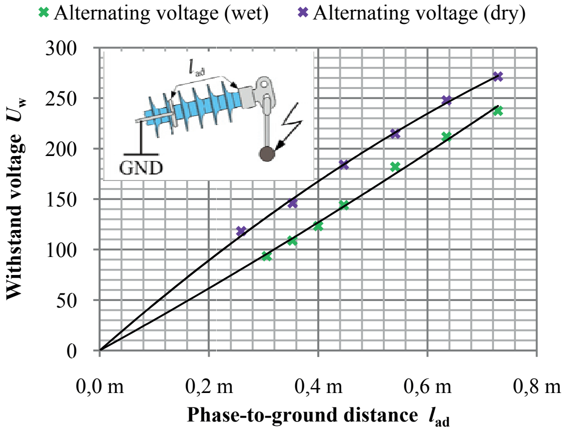

Figure 10: U_w as a function of phase-to-phase l_{ad}

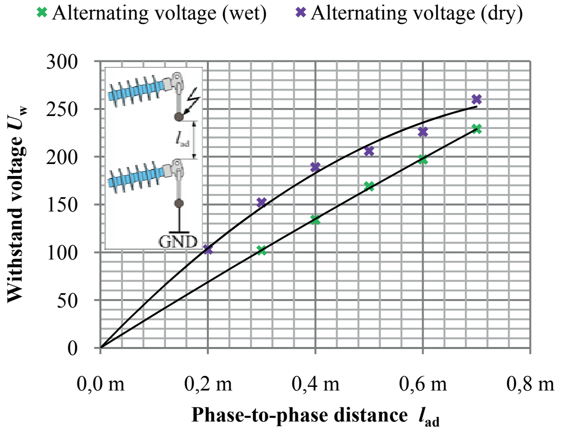

Figure 11: U_w as a function of phase-to-phase l_{ad}

U_{50} being dependent on the impulse descending part [2], the impulse-generator discharge resistors were changed so as to achieve longer times to the half-value, i.e. approximately 900 µs, with the front time remaining the same. From this point onwards it is described as a 1.2/900 µs impulse. The results obtained with 1.2/900 µs positive impulse tests are shown in Figure 12. U_{50} decreases if the length of the wave increases.

As it was established by computer simulation results the overvoltage shape in phases with LSA installed is specific, i.e. flat top and longer durations (Figure 2). We took an effort to achieve a similar overvoltage shape by varying the flat top width and peak voltage. A certain impulse width and peak voltage are achieved by placing the surge arrester parallel with the insulator. To adapt the parameters, we changed the arresters rated voltage. This requires fine adjustment which can be achieved by a different number of zinc oxide ZnO blocks connected in series. Using the testing UDM method was found inappropriate. Namely, the ZnO surge arresters and blocks heated up upon each lightning impulse for which reason their characteristics altered. We therefore used another approach in which the charging voltage was changed in small steps. We wrote down the last peak voltage and width t_{90} (at 90 % peak value) of withstand prior to discharge. Figure 13 shows the dependence of the peak value on t_{90}.

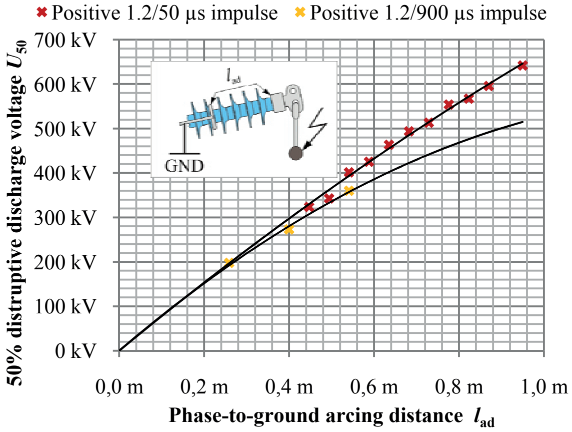

Figure 12: U_{50} as a function of phase-to-ground l_{ad}

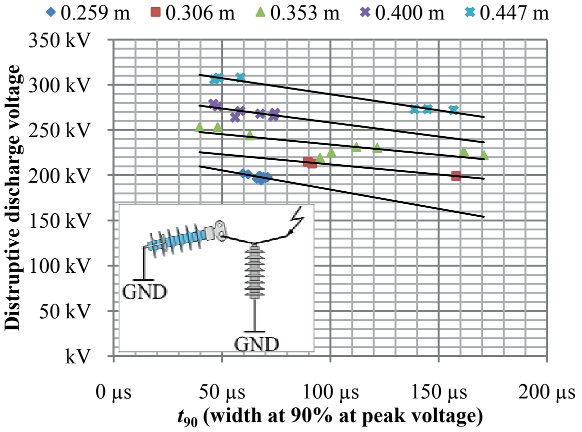

Figure 13: Voltage and shape dependency on discharge

The purpose of our next test was to determine the impact of the potential rings on U_W and U_{50}. We bridged nine sheds and l_{ad} was 0.494 m regarding the copper ring and upper metal part of the insulator. The test was preformed with a 1.2/900 µs positive impulse in dry and alternating voltage in dry and wet. The results are shown in Figures 14 and 15. We were also searching the point where the arc changes its sink or origin position. This transition point for different test types is at different distances d. Value d = 0.00 m is reached when the potential ring is aligned with the copper ring.

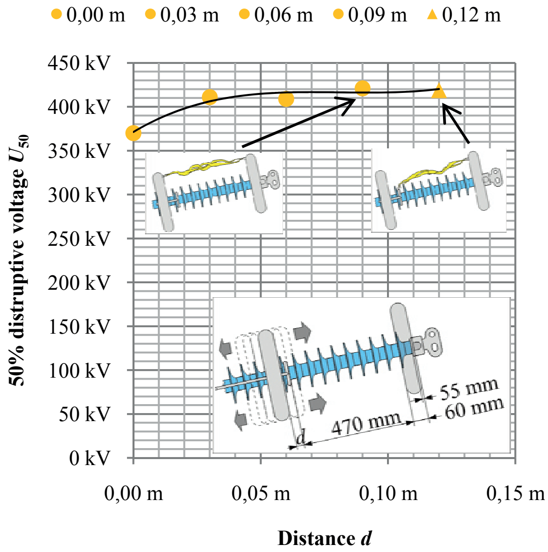

Figure 14: Searching for optimum with positive 1.2/900 µs impulse test

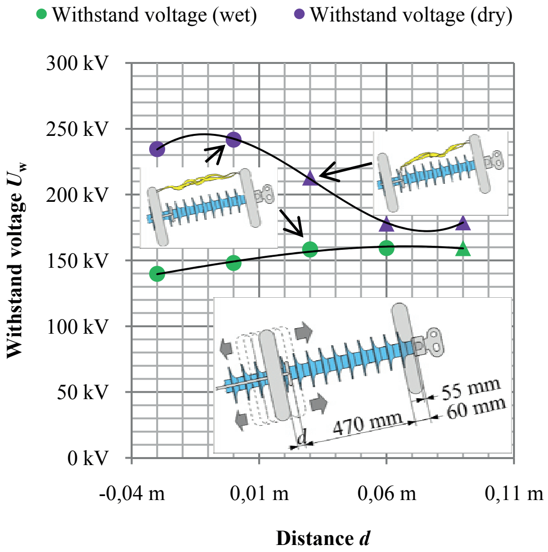

Figure 15: Searching for optimum with alternating voltage test

When shortened insulators are used, surface dielectric stresses caused by the operational voltage are increased. To detect any possible partial discharges under different operational states, we used a corona camera. No surface corona activity at normal voltages in dry was observed.

4. Conclusions

Our investigation of the 110 kV compact OL was based on the assumption that the greatest stress the OL insulation has to withstand is the one caused by lightning overvoltages. To have them defined, we first made several sample overvoltage simulations at lightning strokes for various OL parameters (LSA number, flashover current I_l, wave shape, various grounding resistances R_g). By taking into account the determined overvoltages (amplitude, shape) we then made on a physical model of the OL tower a series of dielectric tests in our high-voltage laboratory. The final target of our investigation was to establish the extent to which the phase-to-ground (support insulators) and phase-to-phase distances can be reduced by applying LSA's.

Based on our investigation results, the following conclusions can be drawn for the case envisaging installation of LSA on each OL tower in the lowest OL phase, i.e. phase C, and under assumption that BIL (phase-to-ground and phase-to-phase) is 550 kV:

- The most unfavorable lightning overvoltages take place at lightning flashes directly striking into the OL tower if shielding failures are avoided.
- The increase in the phase-to-ground overvoltage levels is mostly affected by higher amplitude values or front duration t_f of flashover current I_l and tower grounding resistance R_g . Also to be taken into account is the momentary value of the operating voltage.
- In majority of cases the lightning flash that strikes into either conductor A or B (with no surge arrester) gives rise to unwanted flashover.
- The phase-to-phase overvoltages are lower than the phase-to-ground ones except at the time of a shielding failure occurrence, in which the lightning strikes into phase C (phase with LSA).
- The overvoltage in the phase with LSA is determined with the *U-I* arrester characteristic.
- The highest possible OL operational reliability rate (close to 100 %) is obtained by installing LSA's in all the three phases, i.e. phase A, B and C.

To provide for a comparison, Figure 16 lists the required flashover lengths l_{ad} at the insulator and between two phases with regard to the observed insulation level U_m = 72.5 kV (140/325 kV), the first one being lower related to U_m = 123 kV (IEC 60071-1).

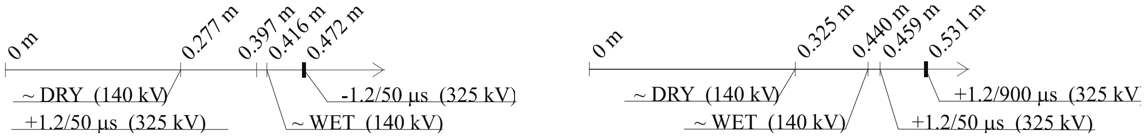

Figure 16. Flashover *clearing* distance l_{ad} at the insulator and between two phases with regard to the insulation level U_m = 72,5 kV (140/325 kV).

Based on our comparison with the simulation results we can see that - speaking in terms of lightning overvoltages - the insulators for insulation level U_m = 72,5 kV (140/325 kV) might be used, if LSA's in phases A, B and C would be installed. The insulators could then be substantially shortened. Off course l_{ad} = 0,54 m is not the lowest level since for insulator dimensioning we have to take into consideration at least the insulation co-ordination correction factors. On the other hand using potential rings, this distance could again be considerably shortened. The same applies for the phase-to-phase distances. To determine criteria allowing for reliable operation of such designed OL, a considerable number of simulations of overvoltage phenomena should be accomplished, to obtain statistical results. Such analyses for OL with reduced number of LSA (i.e. phase C only) would probably show poor line performance. The investigation should address also temporary and switching overvoltages.

It should herewith be well noted that by doing so one of the basic insulation co-ordination rules has been violated, namely, $U_m = 72{,}5$ kV does not correspond to the system operating voltage ($U_m = 123$ kV). This gives rise to an increase in the dielectric stress on the insulator surface which - particularly at the time when pollution is critical - may result in accelerated material ageing (silicone rubber) and eventual flashovers at the time of temporary overvoltages and even during normal operation. Though the investigation made with a corona camera in our high-voltage laboratory revealed no occurrence of partial discharges, the issue of insulation ageing under the condition of strong electric field should be dealt with under a special research.

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