TRANSIENT OVERVOLTAGES ON DISTRIBUTION UNDERGROUND CABLE INSERTED IN OVERHEAD LINE

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ABSTRACT
In recent years, an increased number of windstorms has led to a surge in damage of 22 kV and 35 kV lines caused by fallen trees. Those incidents result frequently in long power outages and increased maintenance costs of distribution networks. This paper is inspired by a recent trend consisting in the replacement of concerned sections of overhead lines by cables. Such an approach is called “cable sections inserted in overhead lines” or, simply, “cables inserted in lines”. This solution brings numerous changes concerning the operation of distribution networks and it can be a potential source of faults due to the increased danger of the penetration of lightning overvoltage to the cable and of the subsequent breakdown of its insulation.

INTRODUCTION
The analysis of overvoltages due to a lightning stroke is based on simulations in the EMTP-ATP program. The aim of the simulating model was to create the less favourable situation in an MV distribution network with inserted cable sections that would lead to an increased risk of faults due to overvoltage. To do so, a part of a real 22 kV distribution network in a mountain region in the proximity of an already installed power cable in direction to the Lysá hora mountain where some parts of the overhead line were replaced by cables in the model. This results in three cable sections separated by only two spans of overhead line of a length of 60 m each while keeping the actual network configuration (Fig. 1). It can be expected that the effects of the lightning hitting the overhead line phase conductor and the subsequent overvoltages along the cables will be considerable in such a model. The electrical stress of the inserted cables due to overvoltage will be analysed by means of the simulation of the transient phenomenon caused by a lightning stroke and of the subsequent propagation of lightning overvoltage.

The sources of lightning discharge will be applied at the following five points in the network:

- Points 1, 3 and 5 are in the vicinity of poles placed at the distance of at least one span before the junction pole (where the cable is connected to the overhead line).
- Points 2 and 4 are directly on the junction pole.

The following voltages in all three cable sections K1, K2 and K3 are calculated in the simulations: voltage at the beginning and at the end as well as at four positions placed uniformly along each cable. The pole voltage curves and the currents flowing through surge arresters at the beginning and at the end of each cable are also calculated. The situation is shown in Fig. 1 where the symbols used for the points of the network correspond to those in the model in the EMTP-ATP program.

The network basic insulation level (BIL), i.e. 125 kV according to [1] (in a network with $U_{\text{max}} = 25$ kV), was used as an evaluation criterion for tests and it is supposed that the withstand overvoltage of MV power cables during a lightning pulse must be equal or greater than this value.

![Fig. 1: Description of simulation – points of strokes and measurement](image-url)
A single-phase model was used for the simulation of lightning overvoltages. This approach is considered as sufficient because it is the overvoltage wave caused by a direct stroke of lightning to the phase conductor that is decisive for the analysis of lightning overvoltage. Overvoltages induced in phase conductors are considerably smaller. Since the danger of insulation breakdown due to lightning overvoltage is highest within a distance of two kilometres from the point of stroke for which the differences in the velocity of propagation modes of phase conductors [2] can be neglected, there is either no need to consider the difference in voltage waveforms on phase conductors.

Taking into account the fact that the lightning overvoltage is a very fast transient in an environment containing numerous impedance junctions, it can be expected that high-frequency oscillations will appear. Under such conditions, even relatively short lines of the distribution network should be replaced by a frequency-dependent model [3]. This means that the attenuation and distortion of overvoltage waves in lines respecting the frequency of those oscillations must be considered.

Lines are represented by a single-phase model with distributed frequency-dependent parameters. Both ends of cable sections are protected by MOV surge arresters grounded directly with an earthing resistance of maximum 1 Ω. Conductors connecting the surge arresters are replaced by an inductance of 0.5 μH.

The model of a pole where the back flashover is supposed to appear corresponds to Fig. 2 where the insulator 50% flashover voltage $U_{50}=150$ kV is used in calculations and where the flashovers between the phase conductors – that could distribute the current of lightning discharge to several surge arresters and moderate thus the effects of overvoltage – are not taken into account. The pole earthing resistance is estimated to be $R_z=30$ Ω, the inductance of the conductor connecting the surge arrester is 1μH/m according to [4].

The lightning discharge is represented by a current source generating a current wave whose parameters are the current peak value $I_m$, the wave-front time and the wave-tail time (Tab. 1). During the generating of the current waves of lightning discharges simulating lightning strokes in the model, the current peak value $I_m$ is increased gradually with the constant steepness $S=10$ kA/μs and 30 kA/μs. The wave-front time $T_1$ is then given by the $I_m/S$ ratio.

<table>
<thead>
<tr>
<th>Peak Value</th>
<th>Steepness</th>
<th>Wave-Front Time</th>
<th>Wave-Tail Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_m$[kA]</td>
<td>$S=dI/dt$ [kA/μs]</td>
<td>$T_1$ [μs]</td>
<td>$T_2$ [μs]</td>
</tr>
<tr>
<td>40</td>
<td>10</td>
<td>4</td>
<td>1.33</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
<td>5</td>
<td>1.66</td>
</tr>
<tr>
<td>60</td>
<td>6</td>
<td>6</td>
<td>2</td>
</tr>
</tbody>
</table>

22/0.4 kV distributing transformers are represented by the parallel connection of their input capacitance of 650 μF [4] and the surge arrester as a standard equipment of their input terminals.

RESULTS OF SIMULATIONS

The aim of the simulations was to find critical states where the above-mentioned criterion is exceeded, representing thus an increased risk of a fault in the network. The graphical outputs of the simulations in the EMTP-ATP program is the time behaviour of currents and voltages at the points defined above (see also Fig. 1).

Lightning Strokes at the Cable-Overhead Line Junction

It can be concluded from the first part of the simulations that the network insulation level (and the cable withstand voltage) were exceeded only for lightning strokes at the cable-overhead line junction, i.e. at points 2 and 4. The current source with a current peak value starting at $I_m=40$ kA applied at those points led to an overvoltage along the inserted cables exceeding the given limit. When the source was applied to the phase conductor on the first pole before this junction, there was an attenuation of transient phenomenon due to the flow of lightning current to the ground and neither the voltage along the cable nor the current through the surge arrester exceeded the critical values.

As an example, let us present the results of the simulation of a lightning stroke with $I_m=40$ kA and $S=10$ kA/μs (i.e. wave shape 4/20) at point 2:

1) The voltage of the phase conductor of the K1 cable – voltage curves at the beginning, at the end and every 200 metres along the cable are calculated. It is clear from Fig.3 that the highest voltage appears in the second fifth of the cable length – at K1P2.

2) The current flowing through the surge arresters of the inserted cables – as it can be seen in Fig. 4, the most loaded surge arrester is the one at the beginning of the cable K1 neighbouring the point of the lightning stroke. The current flowing through the other surge arresters is considerably

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**Fig. 2: Representation of a grounded pole**

The lightning discharge is represented by a current source generating a current wave whose parameters are the current peak value $I_m$, the wave-front time and the wave-tail time.
smaller, with a time delay given by their distance from the point of the lightning stroke.

3) The pole voltages (Fig. 5): the voltage curve for the junction pole stroke by a lightning is identical to the one for the surge arrester at the beginning of the cable K1; as the other surge arresters are concerned, the situation is similar, i.e. the voltage decreases with increasing distance from the point of the stroke.

4) The voltage along the two remaining cables K2 and K3 is below the basic insulation level (Fig. 6, Fig. 7).

From the example shown above, it is obvious that the voltage along the cables changes. This is caused by the fact that the behaviour of waves at the junctions at the beginning and at the end of the inserted cable is – due to surge arresters – not linear. In the beginning, the forward wave arriving at the junction has a zero value. The same applies to the voltage at the end of the line (i.e. voltage of the surge arrester) and the voltage of the reflected wave. The voltage of the surge arrester (i.e. voltage at the end of the cable) increases with the increase of the voltage of the forward wave until it reaches the protecting level of the surge arrester. Then the situation at the junction changes and the impedance of the parallel combination of the surge arrester and the line decreases. The voltage reflected wave also decreases until it reaches a value corresponding to a junction without reflections. The reflected wave at the end of the cable thus reaches its peak before the peak of the forward wave arrives to the end of the cable. It means that the value of the voltage at the end of the cable obtained in the simulation is not the maximum overvoltage of the inserted cable. The maximum voltage can be found at distance \( \Delta x \) before the end of the cable, i.e. at the moment when the peaks of the forward and reflected waves are superimposed. This distance can be found the following way [5]:

\[
\Delta x = v \frac{t_{f_{\text{max}}} - t_{r_{\text{max}}}}{2} = v \frac{\Delta t}{2},
\]
where $t_{p\text{max}}$ time at which the forward wave reaches its peak,
$t_{r\text{max}}$ time at which the reflected wave reaches its peak,
$v$ velocity of propagation of the wave in the cable.

The simulation in the EMTP-ATP program provides only the value of voltage or current at a given moment and point. The values of the forward and reflected wave must be found indirectly by means of mathematical functions incorporated in the model. To compare the maximum voltages for different lightning discharges at the junctions (strokes at points 1, 4), the maximum overvoltage must be found first. The comparison of the resulting maximum overvoltages caused by lightning strokes at the junction pole is shown in Fig. 8 and Fig. 9:

Influence of the Cable Length

There are differences between the values of maximum voltages shown in the curves in Fig. 8 and Fig. 9, with lower overvoltages for longer cables. That is why further simulations were performed to compare the overvoltages in cables of different lengths. Cables of lengths of 1000 m, 500 m and 250 m were inserted in the overhead line and the lightning discharge 40 kA 4/20 in the proximity of the junction was simulated. It was the length of the cable K1 that changed, the current source simulating a lightning discharge was connected to the point 2. The results are shown in Fig. 10:

Lightning Strokes to the First Pole before the Junction

The following step of the analysis was to find the maximum value of the discharge current of a lightning causing an overvoltage along the cable exceeding the withstand voltage of 125 kV while hitting the first pole before the junction. The source of lightning current was applied to the point 3 (with the same distance from the cables K1 and K2). The insulation level was exceeded for the current wave with a peak of 110 kA. The results of the simulation show the following:

1) The voltage along the cable K3, with a length greater than 1500 m, is smaller and its maximum would probably not exceed the network insulation level – Fig. 11.

2) The voltage along the cable K1, with a length smaller than 1000 m, exceeds the network insulation level (125 kV) – Fig. 12.

In this case, there is a positive influence of the neighbouring poles of the branches S101 and S121. As it can be seen from the pole voltage curves (Fig. 13), a part of the lightning discharge current flows through them. Currents flowing through the surge arresters at the beginning of the cable K3 and at the end of the cable K1 are almost identical (Fig. 14).
If two consecutive cable sections were placed in a direct line without a branch, the situation would be certainly worse and the overvoltages along the cables as well as the currents flowing through the surge arresters of the cables would be higher. The only way to eliminate such a case is to decrease the earthing resistance of poles at least to the order of ones of ohms so that a part of the current flowing through the surge arresters could pass to the ground through the pole. To illustrate this, the results of three simulations are compared in Fig. 15, Fig. 16 and Fig. 17:

- The situation described above – 110 kA 4/20 lightning discharge at the pole S31 (point 3).
- The same situation, but in a direct line – the branch is disconnected before the pole S101.
- The earthing resistance of the pole S31 in the direct section of the overhead line is 15 Ω instead of the original value of 30 Ω, at the same lightning discharge 110 kA 4/20.
- The earthing resistance of the pole S31 in the direct section of the overhead line is 5 Ω instead of the original value of 30 Ω, at the same lightning discharge 110 kA 4/20.

Fig. 12 Voltage along the cable K1 for the lightning stroke 110 kA 4/20 to the pole S31 (point 3)

Fig. 13 Voltage on the poles S31, S101 and S121 for the lightning stroke 110 kA 4/20 to the pole S31 (point 3)

Fig. 14 Currents flowing through the surge arresters of the cables K1 and K3 for the lightning stroke 110 kA 4/20 to the pole S31 (point 3)

Fig. 15 Current flowing through the surge arrester at the end of the cable K1, lightning stroke 110 kA 4/20 at the point 3

Fig. 16 Current flowing through the surge arrester at the beginning of K3 cable, lightning stroke 110 kA 4/20 at the point 3

Fig. 17 Voltage on the pole S31, lightning stroke 110 kA 4/20 at the point 3
CONCLUSIONS

It can be concluded from the results of the simulation of lightning strokes in a 22 kV distribution network with inserted cable sections that the principal cause of the cable insulation breakdown are the lightning strokes hitting junction poles, i.e. poles where the cables are connected to the overhead line. The lightning discharges with an amplitude of 40 kA applied at those points cause an overvoltage along the cable exceeding its withstand voltage at lightning discharge corresponding to the network insulation level. The values of overvoltage along the cable showed an important dependence on the amplitude of lightning discharge while its steepness did not have a considerable influence on the overvoltage. A lighting hitting the junction poles led to the overloading of the surge arresters protecting the overhead line-cable junction. This phenomenon can be partially attributed to a relatively high value of the pole earthing resistance ($R_z = 30\,\Omega$) used in the model in comparison to a low resistance of the surge arrester ($R_z = 1\,\Omega$). Still, it can be concluded from high values of the currents flowing through the surge arresters (more than triple the discharge nominal current of 10 kA) for a lightning discharge in the proximity of the junction pole that the surge arresters will be destroyed by the current thermal effects. In case of short sections of cable lines inserted in an overhead line (less than 1 km), the increase of the overvoltage level must be taken into account.

Lightnings hitting poles separated by at least one span can be dangerous only if the discharge current exceeds 100 kA and the negative effects of such discharges depend strongly on the earthing resistance of the affected pole. Its value should be equal to or greater than the earthing resistance of the junction pole. If this condition is not respected, an important part of the discharge current passes through the junction pole with a lower earthing resistance equipped with a surge arrester, which might deteriorate the situation.

REFERENCES


Acknowledgments

This paper contains the results of research works funded from project No. 2A-2TP1/051 of the state budget of Ministry of Trade and Industry of the Czech Republic.