Transient stress in a mixed overhead line - cable network

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Abstract – *This paper presents a transient study in a mixed overhead-cable network configuration. A small and exemplary high voltage network of 110 kV is investigated with the help of numerical methods and programs. Within the network, substation interconnections were traditionally made with overhead lines. Nowadays cable connections are getting more popular. This leads inevitably to new network designs and furthermore to new (transient) network behaviour. Such a mixed network configuration is also typical for urban areas.*
Several different network configurations and switching states within a mixture of overhead lines and cable sections are researched in this paper. Transient lightning overvoltage trends and peak values are studied and the transient stress at various network nodes is investigated.

Keywords*: ATP, mixed network configuration, transient, overvoltage*

1. Introduction

Traditionally, high voltage networks consist to the most part of overhead lines only. This predominance is going to be changed a little nowadays as it is difficult to erect new overhead lines, especially in urban areas. To find a suitable line route in a built-up area is complicated. Therefore, possible alternatives are needed and one can be the design of new lines and substation interconnections respectively as underground cable lines.
Unfortunately, the operational characteristic of a cable line is completely different from the characteristic of overhead lines. Overhead lines are often affected by lightning incidents but the character of such faults is in most cases of a temporary nature. So the best part of failures caused by external overvoltages on overhead lines can be cleared in short time. In contrary to that are cable lines because in a predominate number of cases the failures are of a permanent character here. This leads to long repair times and also high repair costs because the faulty section needs to be found first. Also the repair work itself is not so straightforward as this is the case on overhead lines. But in a modern protection scheme with surge-arresters, a safe operation of cable lines is possible nonetheless. So within a mixed system, lightning incidents on overhead lines may have severe influence to the attached cable lines. In terms of transient behaviour, the variations in characteristic impedance and natural and reactive power respectively are one of the most important differences that are influencing the network operation [1].
A part of a 110 kV high voltage network of an Austrian utility with a mixed network configuration has been studied and some of the results are presented in this paper. A recently built substation interconnection was designed in mixed network configuration, where about 900 m of cable has been inserted in connection to an existing overhead line. The transient behaviour during lightning was of special interest in this studied case. Because of limited

space along the planed route and especially near the transition site between overhead and cable line, it would be interesting to reduce the number of eventually needed surge arresters to a minimum.
Numerical simulation software based on the EMTP/ATP has been used for the study. Several different network configurations have been analysed in regard of peak transient voltages and the voltage time trend. The influence of different lightning impact points and lightning currents has been studied.

2. Description of the situation

2.1. Network Configuration

A representative part of the network operator's 110 kV high voltage network was studied. The network consists mainly of overhead lines, but about 5 percent of the whole network is already cabled. The part of the network that is interesting for this study is shown in the one-phase schematic diagram in Figure 1.
This section of interest is connected to the Austrian grid via substation "A" and substation "B" with overhead lines, which are not included in this study. Furthermore, substation "C" is a dead-end station and currently supplied by a cable connection from substation "A" only.

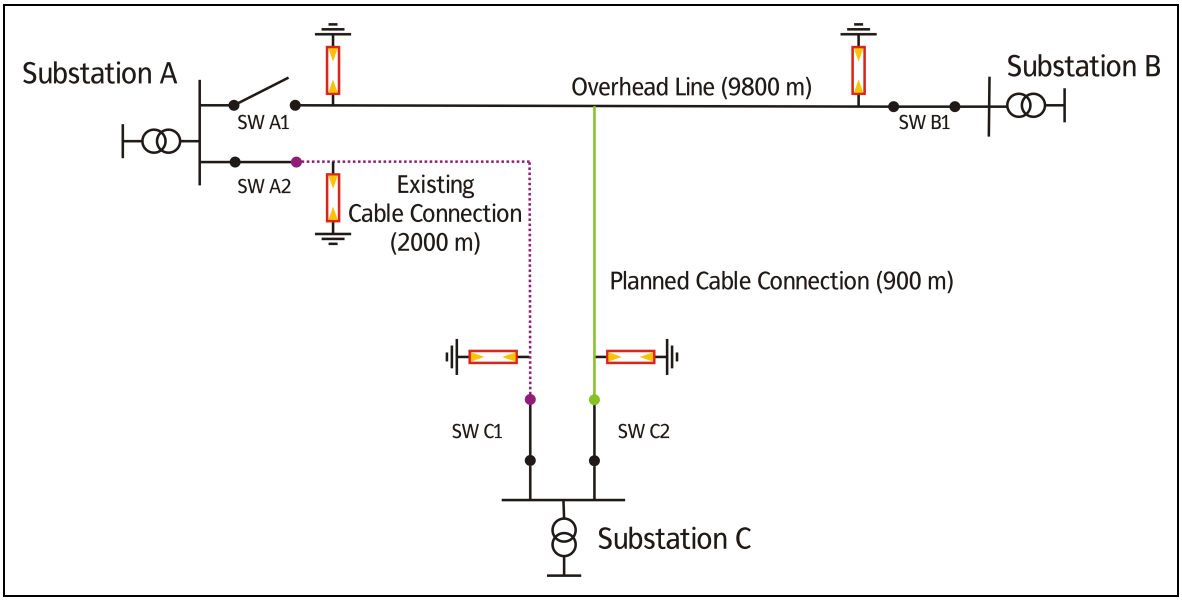

Figure 1 Present network configuration with the planned cable interconnection

A small town and an industrial centre with substantial power demand is fed through substation "C". Now, a notable increase of power demand in that area made an additional connection to the network and some conversion work in the substation necessary. The new connection is designed as cable system based on the local geographic situation..

2.2. Task Description

Due to the fact that the space at the junction point of the planned cable connection and the existing overhead line is quite limited, the network operator wanted to know, if it is possible to install the planned new cable without surge arresters, optionally using higher insulation coordination values. Furthermore, from the viewpoint of tower static and tower geometry it

would be desirable if the installation could be achieved with a low number of surge arresters or if they could be even neglected.
The whole study is done in view of transient overvoltages caused by lightning incidents, as switching transients are not a big issue in this voltage level. This is due to the voltage level where lightning incidents are by far dominating the insulation coordination and on the other hand, both cable lines are rather short so that charging currents during switching processes will have limited effects only.
So for a starting point of the investigations, the cable bushings of the new XLPE connection are protected with surge arresters at the substation "C" only.

In the new network configuration, as it is pictured above, three different network switching states can occur. They are described in the following table:

Table I Possible network configuration states with the planned cable connection

State	Switch A1	Switch A2	Switch B1	Switch C1	Switch C2
I	Open	Closed	Closed	Closed	Closed
II	Closed	Closed	Closed	Closed	Open
III	Closed	Closed	Closed	Open	Closed

State I is shown in Figure 1. Switch A1 is opened, so the connection between substation "A" and "B" is routed over substation "C". Although the three switching states differ only slightly from each other, it is interesting to find out the state with the highest transient voltages and the highest transient stress firstly.

3. System Modelling

For the numerical simulations the EMTP/ATP software tools have been utilised. To simulate the network, several different standard components have been adapted which will be described in the following paragraphs [2].

3.1. Overhead Line

A frequency-dependent model has been used to simulate the overhead line. Based on the geometrical data of the steel towers, the suspension points of the conductor wires have been defined. The overhead line has a total length of approximately 10 km. Actually, the line was divided into two sections. One section is 8700 m long and divided into 29 span fields with a constant span width of 300 m. This is the part from substation "B" to the transition tower with the new cable connection. The remaining route from the tower to substation "A" is simulated with 6 span fields with an average span width. The soil resistivity has been set to 100 Ωm, an average value. As back flashovers have not been considered as critical here, a representative modelling has been done with some simplifications. Protection with arcing horns (according to the insulation coordination respectively) is installed at every tower on the line and so that was also simulated.

3.2. Cable Lines

Two different cable systems have been simulated, namely the existing oil-filled cable and the new XLPE insulated cable (see Figure 2). The oil-filled cable is about 2 km long and divided

into 3 sections with around 650 m length each. The line was designed with cross-bonding and the cable sheath has been grounded at one end and at all joints.
Furthermore, the XLPE-insulated cable has a length of 900 m and was divided for the simulation into 3 sections with 300 m each to place voltage probes. As this is a relatively short cable, the cable sheath has been grounded at one end only and cross-bonding was not applied

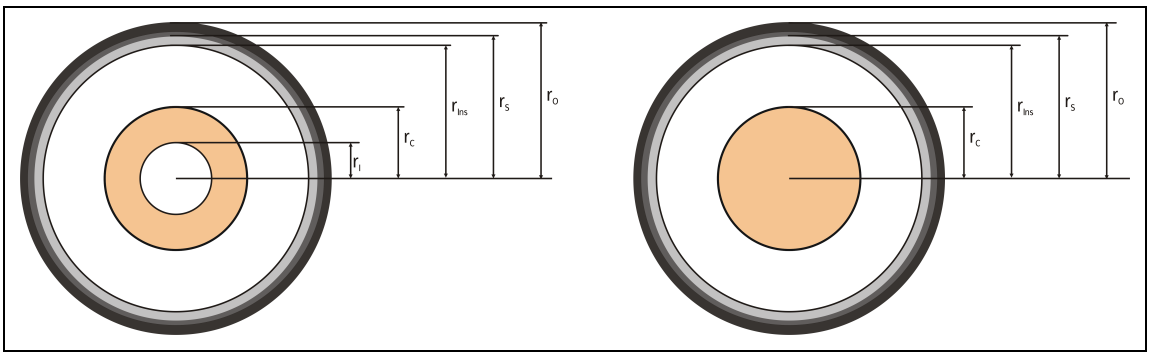

Figure 2 Cables cross sections: Oil-filled cable (left) and new XLPE insulated cable (right), dimensions are not to scale

Similar to the resistivity used at the overhead lines, a standard soil resistivity of 100 Ωm has been simulated. A frequency dependent model was utilized in the software to simulate the cables. Geometric data according to Table II has been used to replicate the cables in the simulation program.

Table II Parameters of the cables

	Oil-Filled	XLPE
Cross-Section [mm²]	500	500
r_i [mm]	6,0	0
r_c [mm]	11,6	13,3
r_{ins} [mm]	23,0	31,3
r_s [mm]	26,2	34,7
r_o [mm]	33,0	37,5

As no specific cable data sheets have been available, some of the values have been estimated. It has to be said here, that the values for the insulation thickness for the XLPE cable in the table below have to be seen as some sort of starting values. This is due to the fact that the customer wanted to overcome the necessity of installing surge arresters by a slight increase in insulation thickness and therefore in the withstand voltage. Furthermore, the cables are buried in a depth of 1,5 m and are laid in a distance of 1 m horizontally to each other.

3.3. Lightning Source

A Heidler-type source (Type 15) has been used as a current source for the lightning studies. The peak value of the current was chosen with 10 kA (positive polarity). This seems to be a reasonable value as studies in connection with the Austrian Lightning Detection and Information System (ALDIS) are showing that the median value of the lightning current is in

the region between 10 to 15 kA [3]. The lightning occurred at +10 µs after simulation start, so in the diagrams the normal operational voltage is seen before.

3.4. Surge Arresters

As the simulated substations have not been erected at the same time, different protection schemes and protection devices are used in each station. Actually, three different types of surge arresters are installed in the studied substations, two with metal-oxide design and one SiC-design with series gap. The arresters have been modelled as nonlinear current-dependent resistor (Type 99) according to the manufacturers' datasheets.

4. Lightning Studies

The transient network behaviour of the mixed system during lightning was investigated during different conditions. Firstly, it was necessary to find out, if there are large differences between the network switching states. Next, lightning impact location and lightning current have been varied. The peak voltages and the voltage time trend at the XLPE cable have been examined in detail.

4.1. Network switching states

All three network switching states have been stressed with the same configuration first: A direct phase hit into the top phase wire, one tower away from the transition tower to the new cable line. The results showed that, although the time trend of the transient voltages differs, the peak values are very similar. Flashovers occurred on the overhead line in the vicinity of the lightning impact but the interesting outcome was that the nominal insulation level in the XLPE cable was not exceed. On the other hand, the security margin of the cable is low but tolerable, as the following figures reveal. Figure 3 and Figure 4 show the transient voltages in Configuration III at the transition tower. It can be clearly seen that there is a flashover on the affected phase at the tower but within the cable line the voltage is below the insulation level.

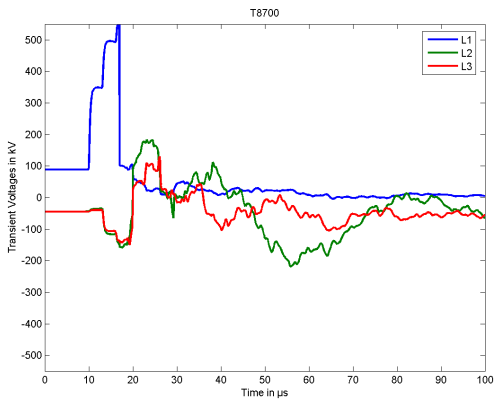

Figure 3 Tower hit by lightning strike

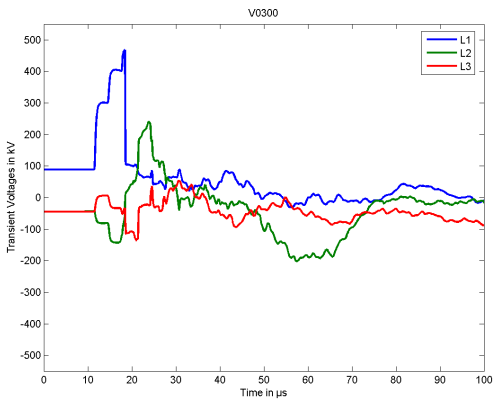

Figure 4 Inside the cable (300 m away)

4.2. Variation of impact location

Because of the similar results of the transient studies for the three network switching states, Configuration III was chosen as an exemplary state for further presentation here in this paper.

This was actually done with no special reason but allows the comparison with the graphs above. Expectedly, lightning impacts near the transition tower are considered as the most dangerous ones, whereas impacts further away from the cable do not have these high overvoltages as this is demonstrated in Figure 5 and Figure 6.

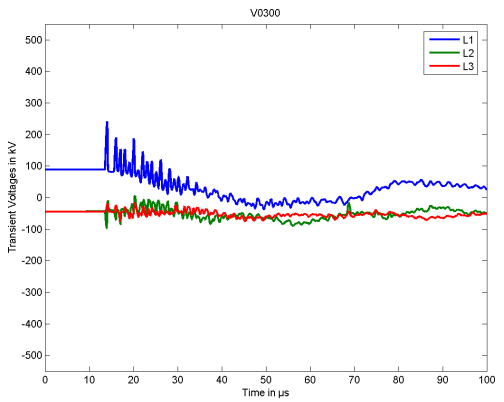

Figure 5 Voltage time trend in the cable (300 m), impact in 600 m distance

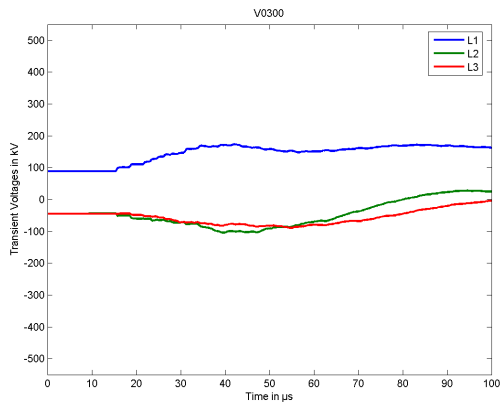

Figure 6 Voltage time trend in the cable (300 m), impact in 3 km distance

The influence of the phase wire which is hit is not so easy to determine. First, the effects are depending of the value of the operational voltage during the lightning impact. Variations are possible in both sides of the maximum operating voltage, but also a zero-crossing of the voltage could be possible for example. Furthermore, the voltage stress is also determined by the tower and the earthing conditions. In this case, impacts in all phase wires have been investigated. There are differences of course, but such details might be interesting for other studies like backflashover-investigations for example.

4.3. Variation of lightning current

For the variation of the lightning current a model in configuration III was used. The lightning impact location was directly at the transition tower into the top phase wire, as this is the same as in the other simulations.

As the figures below are revealing, the safety margin at the first cable joint is considerable low at a lightning strike of 20 kA. In the case of a 100 kA strike, which is actually quite unlike to happen, there is even a double fault with phases 1 and 2 affected. But the question of survivability of the surge arresters in terms of energy absorption capability needs to be carefully evaluated as well.

So this is actually a tough question what to do here. Finally, a solution with a cable that had a slightly increased insulation level has been tried out. In connection with the statistic analysis based on the data of ALDIS [3] this could be a feasible solution. Actually, this is then turning more into an economic decision about risk assessment and total costs. Technically, several solutions might be possible to overcome this specific situation.

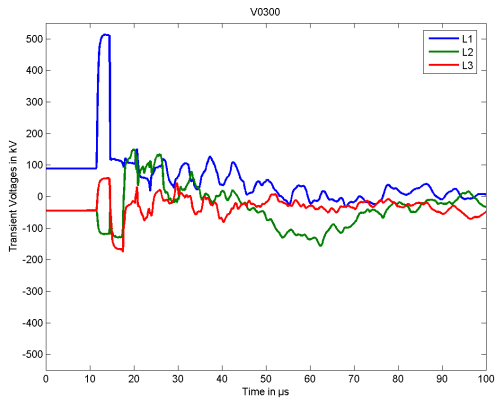

Figure 7 Voltage time trend in the cable (300 m), 20 kA lightning strike

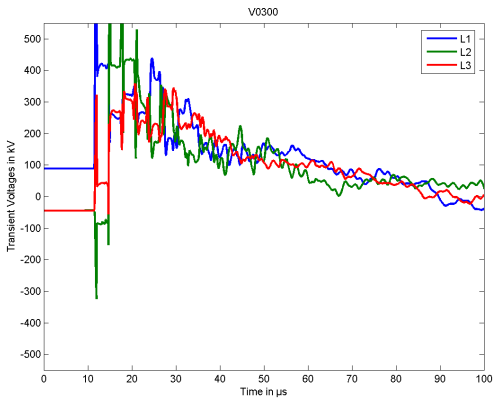

Figure 8 Voltage time trend in the cable (300 m), 100 kA lightning strike

5. Conclusion

Within the investigations of this mixed system configuration, some interesting outcomes could be observed. A reduced availability of space and limited tower static led to the question if it is possible to protect a cable in some sort of a “siphon connection” with surge arresters at one side only. The surge arresters are located in a substation where it is comparable easy to install them.

Different variations in terms of lightning impact location, lightning current and network switching states have been investigated. The basic outcome was that it is possible to operate the cable with surge arresters on one side only in general. There is still a safety margin during normal operation but there are certain extreme conditions where severe overvoltages and equipment damage might occur. For example, this would be the case for lightning currents of about 100 kA. Fortunately, such extreme conditions happen rather seldom. To improve the safety margin, the cable bushing and (parts of) the cable can be designed with an higher insulation level. It is in discussion to apply such a measure instead of the installation of surge arresters at the tower with changing the tower geometry.

References

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