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PREVENTING FLASHOVER NEAR A SUBSTATION BY INSTALLING LINE SURGE ARRESTERS

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Abstract - The paper describes a simulation procedure which can be applied in order to analyse the prevention of flashover near a substation by installing line surge arresters (LSAs). The demonstrated procedure includes the application of a three-dimensional electro-geometric model, description of modelling process, EMTP simulations and estimating the lightning performance of a high voltage substation. This is shown in the case study on the double-circuit line of 220 kV with one shield wire entering the substation. By locating LSA on a tower near a substation, the risk of backflashovers near the station is significantly reduced and the steepness and amplitude of incoming travelling waves are lowered, thus improving the protection performance of station arresters.

1 INTRODUCTION

Short circuits on transmission lines need to be avoided, not only to ensure continuous electricity supply for consumers but also to prevent stresses and damage they can cause to power system elements. Insulation faults on a transmission line in front of substations can provoke short circuit currents with high magnitudes. The consequence of insulator flashover is the forming of a surge with a very steep front that enters the substation and causes insulation stress especially on winding elements (transformer). Interruptions provoked by lightning are usually the most frequent cause of transmission line outages. While most lightning outages can be successfully eliminated by circuit breaker reclosing, the momentary loss of supply or load is not tolerated well by electronic equipment.

One way for improving the lightning performance of substations is LSA installation on the first towers of the line entering the substation. LSAs are already employed by numerous electrical utilities around the world.

2 IMPROVEMENT OF LIGHTNING PERFORMANCE OF DOUBLE-CIRCUIT TRANSMISSION LINE

The transmission line faults caused by lightning can be classified into backflashover and shielding failure. The backflashovers on the insulator string may involve one or more phases and one or more circuits of a double-circuit line. To avoid backflashover due to a lightning stroke to tower or overhead ground wire, the tower footing resistance should be as low as possible. In some areas where the soil resistance is high, this method is not practical because it may be too costly.

Another solution, especially for suppression of a double-circuit simultaneous fault, is the installation of the unbalanced insulation of the double-circuit line [1]. This means the increase of the insulation level of one circuit, which should be higher than that of the other circuit. This increase is limited on the existing tower configuration due to the lack of space to increase the insulation length. Therefore usually an increase of insulator string length has to be combined with the improvement of the tower footing resistance.

The installation of a new, or an additional overhead ground wire on top of the tower, or at portions of the line where they are missing, has been also applied to suppress the rise of potential that can lead to the flashover. This measure can demand significant modifications of tower construction due to changes of mechanical forces.

The traditional countermeasures are often not effective enough to prevent simultaneous faults and the installation of LSA can be helpful in such cases in order to prevent double-circuit outages. In this way power supply continuity will be secured and the flashover rate of the double-circuit line significantly improved. Experience shows that the use of LSA is more efficient than conventional methods, especially in cases of double-circuit faults of transmission lines, which can be eliminated almost completely [2].

3 SIMULATION OF LIGHTNING STROKE IMPACTING THE TRANSMISSION LINE

The procedure for preventing flashover near a substation includes the application of a three dimensional electro-geometrical model, transient simulation and the evaluation of the lightning performance of HV substation.

Lightning strokes impacting the HV transmission line are observed in order to determine the density of lightning strokes, which quantifies the threat of lightning strokes per unit length of a line during a one year period. The average lighting stroke density for a given area is defined as the number of strokes per area unit during the one year period.

The goal of the simulation is to determine the distribution of lightning current amplitudes which strike high voltage transmission line or the phase conductor directly. Furthermore, characteristic values, such as minimal, maximal and critical current amplitude will be determined. The Monte Carlo method is used for simulation. This method is suitable for a calculation in case when all input parameters are not exactly known, but parameter distribution functions are known. It is supposed in this calculation, that the distribution of lighting current is known, but the current amplitudes are unknown. By a large number of simulations it is possible to calculate relevant values which are statistically arranged and are later used in lightning overvoltage calculation.

The basic parameter needed for simulation is lightning current amplitude, for which the statistical distribution is known. The log-normal distribution, which is mostly used [3], can be approximated as following:

$$P = \frac{1}{1 + \left(\frac{I}{31}\right)^{2.8}} \qquad (1)$$

Where:

P - probability of occurrence of lightning current amplitude higher than *I*,

I - lightning current amplitude,

The general expression for the striking distance is represented by the equation:

$$R = a \cdot I^b \qquad (2)$$

Where:

R - striking distance,

I - lightning current amplitude,

a - constant [3.3 – 10.6],

b - constant [0.5 – 0.85].

The striking distance can vary significantly and therefore different values of constants and modifications of the above equation are proposed by various investigators [3]. Expression for the striking distance with constants a=7.2, b=0.65 is used in simulations.

The tower of a double-circuit 220 kV line and part of a transmission line is depicted in Fig. 1. Shield wire at six spans; portal and six towers with their arms are modelled as straight lines. All three phase conductors of both circuits are modelled although all phase conductors are not exposed equally to lightning strikes.

In order to collect enough data for statistical calculation, the simulation is conducted for a large number of generated lightning current amplitudes. The random nature of lightning phenomena can be quantified with a large number of samples that make more credible results of statistical calculation. Hence, simulations with large number of strikes are made first in order to get a better view of the numerical relations between ground strikes, strikes on shielding wires and towers and phase conductor strikes.

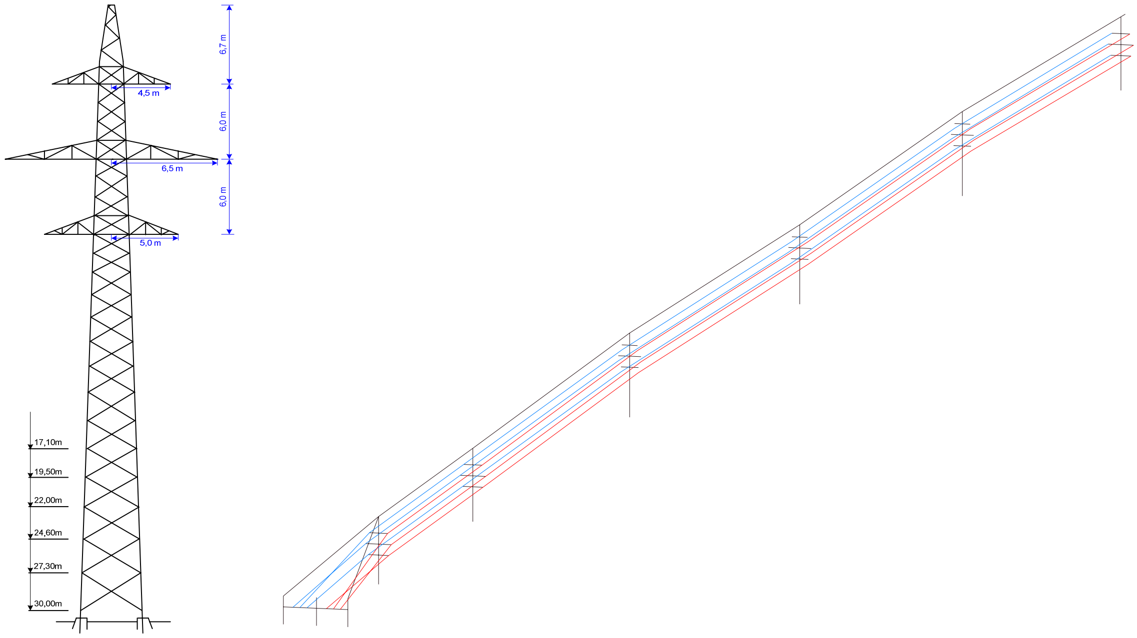

Fig. 1 - 220 kV tower and 3D scheme of the modelled system's six spans

Simulations were carried out until 500 simulations finished with phase conductor strike. There were a total of 24811 simulations made, of which 17014 finished with ground strikes, 7297 with shielding wire and tower strike. According to statistical calculation, the following phase conductor strike currents values are calculated:

- average value: 12.99 kA,
- variance: 63.50 kA,
- standard deviation: 7.97 kA,
- maximal phase conductor strike current: 33.10 kA,
- critical current: 34,94 kA.

Critical current is calculated for the highest tower of the observed part of a transmission line. According to the simulation results 6.85 % of total lightning strokes finished as shielding failure - distribution is shown in Fig. 2.

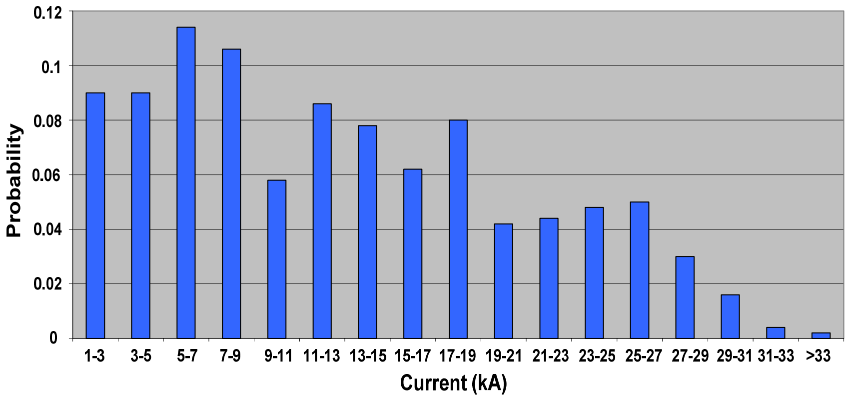

Fig. 2 - Distribution of lightning currents which strike phase conductors

Distribution of lightning strokes per phases (Fig. 3), shows that 66.18 % of strokes, which strike phase conductors finished in the upper phase. About 32.35 % of lightning strokes finished in middle phase and about 1.47 % of lightning currents which strike the lower phase cannot provoke the flashover (e.g. 2.56 kA, 3.06 kA).

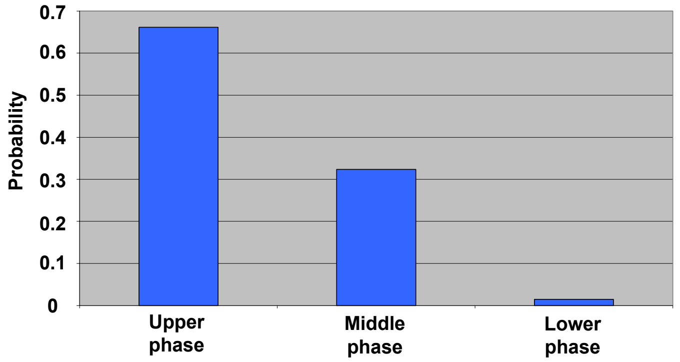

Fig. 3 - Distribution of lightning striking phase conductors per phases

4 MODELING PROCEDURE FOR CALCULATING LIGHTNING OVERVOLTAGES

In the case study 220 kV double-circuit line with one shield wire entering the substation is modelled. For the operating condition (shown by dashed line in figure 4 - LINE 2 and autotransformer AT2 in service) lightning overvoltage calculations were carried out by EMTP-ATP in case when lightning strike the transmission line.

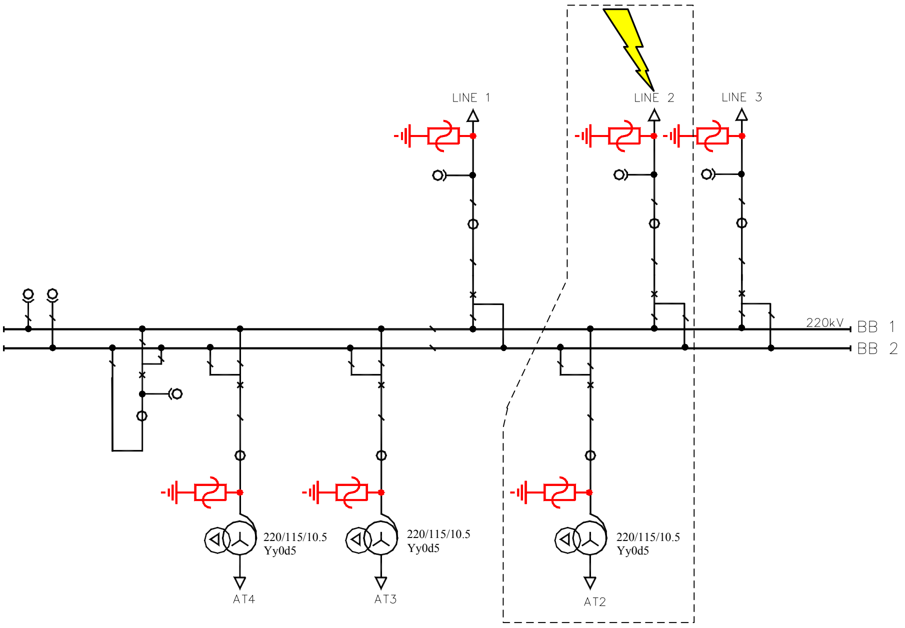

Fig. 4 – Single-line diagram of the 220 kV substation – placement of station surge arresters

The power transformer is modelled as a lumped capacitance of 6000 pF and capacitor voltage instrument transformer with lumped capacitance which has value of 4400 pF. The substation buses are represented by line sections.

The lightning stroke hitting a tower or a phase conductor can be replaced by a surge current generator and a resistor (Norton generator). The peak current magnitude and the tail time are important when observing the line arrester energy stresses, while the influence of the rise time is hardly noticeable in such a case. In contrast the current wave front is an important parameter with regard to insulator flashover. The so-called Heidler model can approximate well the concave form of the lightning current front.

The transmission line, conductors and earth wire is represented by several multi-phase untransposed distributed parameter line spans at both sides of the point of the lightning stroke impact. Two or three line spans at both sides of the point of impact should be modelled when observing the flashovers of the insulators. Many more spans are needed for the evaluation of the line arrester energy stresses when arresters are installed in the neighbouring spans. Figure 5. depicts the model used for simulation of lightning striking a double-circuit 220 kV line.

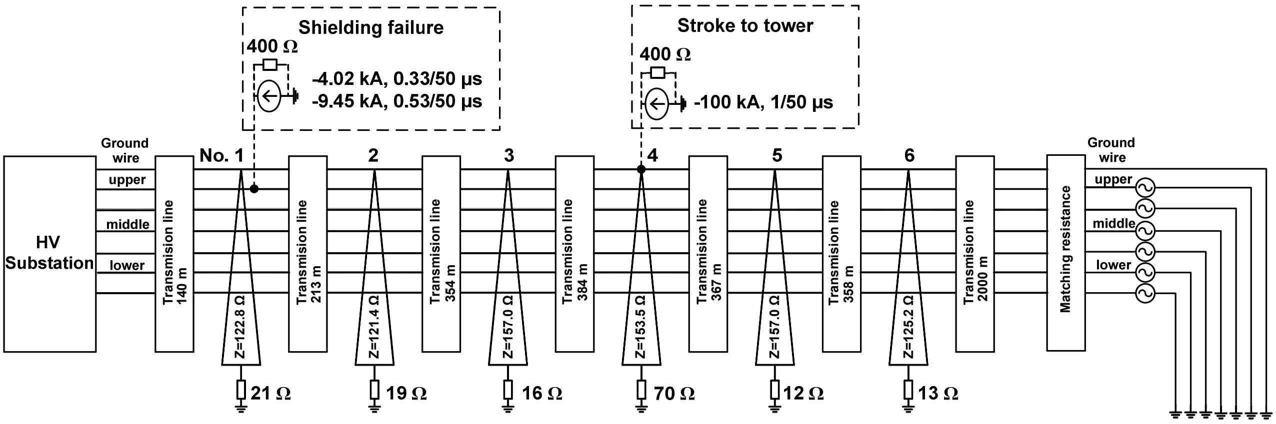

Fig. 5 – Model of 220 kV double-circuit line entering HV substation

Tower surge impedances [4] are calculated using equation (3). Each tower is divided in four parts. First part is from tower top to upper arm, second one from upper arm to middle arm, third part from middle arm to lower arm and the last part from lower arm to ground. On this way it is possible to calculate transient voltages of tower arms.

$$Z = 60 \cdot \left\{ \ln\left(\frac{H}{R}\right) - 1 \right\} \qquad (R << H) \qquad (3)$$

Phase voltages at the instant at which a lightning stroke impacts the line must be included.
The largest voltage difference across insulator/arrester terminals occurs during the peak value of phase voltage, which has the opposite polarity of the lightning surge. For statistical calculations, phase voltages can be deduced by randomly determining the phase voltage reference angle and considering a uniform distribution between 0^0 and 360^0. To avoid reflection of travelling wave, line is terminated with multiphase matching resistance on one end.

Insulators themselves represent capacitances with only very moderate influence on the occurrence of overvoltage. The decisive parameter for the behaviour of overhead line insulation subjected to the lightning overvoltages is its corresponding flashover voltage, which depends on the voltage level due to different insulation clearances. The flashover volt-time characteristic of an 220 kV insulator string [5] is given by the following equation:

$$U(t) = K_1 + \frac{K_2}{T_{front}^{0.75}} \qquad (4)$$

Where:

$K_1 = 0.4\,L$ [m];
$K_2 = 0.7\,L$ [m];
L - flashover distance [m];
T_{front} - front duration in [μs].

Flashover characteristic it is modelled using Model and TACS-controlled switch in an EMTP calculation.

Tower footing resistances are modelled taking into account ionization [5]. The ionization model according to equation (5) takes into account the soil ionization that is caused by the lightning currents. In the EMTP calculation the tower grounding is represented as non-linear resistors using Model and TACS-controlled time-dependent resistor:

$$R_i = \frac{R_o}{\sqrt{1 + \left(\frac{I}{I_g}\right)}} \qquad (5)$$

Where:

R_o - footing resistance at low current and low frequency, i.e. 50 or 60 Hz [Ω],
I - stroke current through the resistance [kA],
I_g - limiting current to initiate sufficient soil ionization [kA].

The tower footing resistance remains $R_i = R_o$ if $I < I_g$ and varies according to the given equation if $I > I_g$. The limiting current is given by:

$$I_g = \frac{\rho \cdot E_0}{2 \cdot \pi \cdot R_o^2} \qquad (6)$$

Where:

ρ - soil resistivity [Ωm];
E_0 soil ionization gradient, recommended value: 400 [kV/m].

The model of gapless type line arrester includes non-linear and dynamic behaviour of the arrester. The non-linear behaviour is represented by the U-I characteristic depicted in Fig. 6. while the frequency-dependent arrester model takes into account its dynamic behaviour.

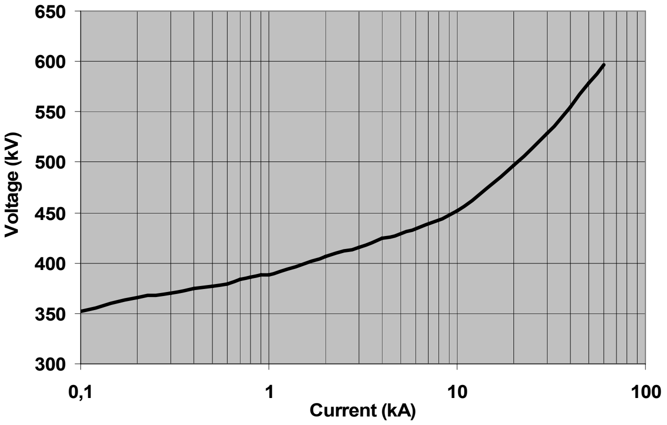

Fig. 6 - U-I characteristic of surge arrester for 220 kV line (U_r=192 kV)

A frequency-dependent arrester model is depicted in Fig. 7. Model parameters are identified using a formula that does not require any iterative correction and that makes use only of the data reported on manufacturers' datasheets [6].

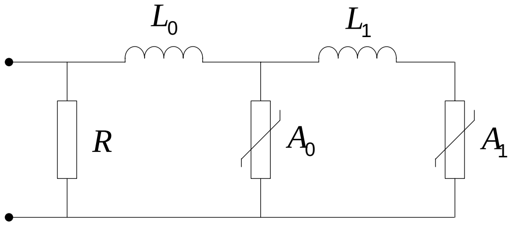

Fig. 7. Frequency-dependent arrester model

5 OVERVOLTAGE PROTECTION OF 220 KV SUBSTATION – SIMULATION RESULTS

Simulations of lightning overvoltages are conducted for direct strokes to the phase conductor near the substation, because that is one of the most severe cases for substation equipment. Lightning overvoltages are calculated for the operational condition shown in Fig. 8. (one transmission line and transformer in service) in case of lightning impacting the line.

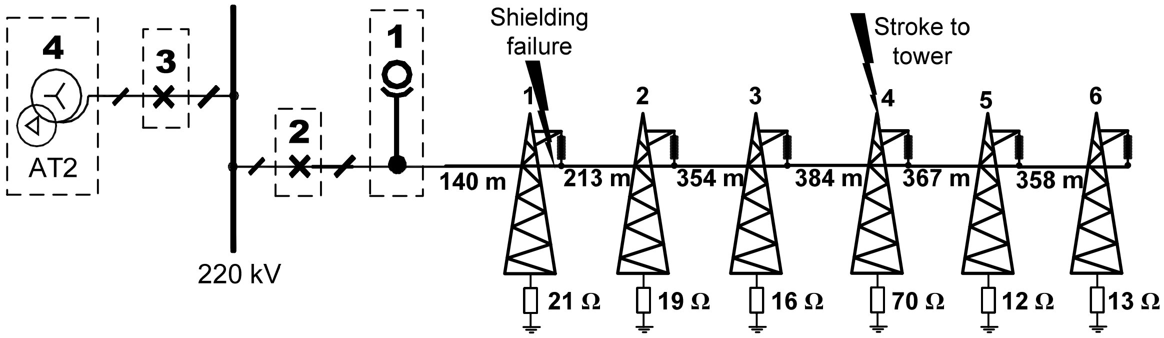

Figure 8. Substation elements analyzed in overvoltage calculation

Table 1 gives peak values of overvoltages on the following substation elements: (Fig. 8): 1 – voltage instrument transformer in line bay; 2 – circuit breaker in line bay; 3 – circuit breaker in autotransformer AT2 bay; 4 - autotransformer AT2.

For different lightning current parameters the stroke to the upper phase conductor at first tower is simulated. Surge arresters in the autotransformer bay are included in all simulations. Calculation results are shown in table 1.

Table 1: Overvoltage calculation results on substation elements for different lightning current parameters

Lightning current parameters	Insulator flashover in upper phase	Surge arrester in line bay	LSA in upper phase at first tower	Voltage on voltage instrument transformer in line bay (1)	Voltage on circuit breaker in line bay (2)	Voltage on circuit breaker in autotransformer bay (3)	Voltage on autotransformer AT2 (4)
4.02 kA, 0.33/50 µs	No	No	No	727 kV	693 kV	523 kV	512 kV
9.45 kA, 0.53/50 µs	Yes	No	No	993 kV	975 kV	689 kV	538 kV
9.45 kA, 0.53/50 µs	Yes	Yes	No	705 kV	687 kV	612 kV	438 kV
9.45 kA, 0.53/50 µs	No	Yes	Yes	449 kV	472 kV	461 kV	459 kV

Calculation results show that surge arresters in the line bay protect substation elements (voltage instrument transformer and circuit breaker) that are not effectively protected with surge arresters in the autotransformer bay. Surge arresters in the line bay also reduce overvoltage values on the autotransformer (Table 1.) and takes a part of the overvoltage energy. Furthermore, in operating conditions when the circuit breaker or disconnector in the line bay is opened, all substation equipment from the circuit breaker (disconnector) towards the transmission line remains completely unprotected from overvoltages. The modern concept of overvoltage protection is the placement of surge arresters close to power transformers and in the line bay in front of voltage instrument transformers.

Lightning currents of smaller amplitudes often originate from multiple strokes with higher steepness. Almost all lightning currents hitting the phase conductor (except the smallest) can cause insulator flashover, although insulator flashover voltage is high. For maximum operating voltage of 245 kV circuit breaker and voltage instrument transformer have standard lightning insulation level of 1050 kV / 460 kV. Coordination lightning impulse withstand voltage of 913 kV was determined for safety factor K_s=1.15. Although insulator flashover results in voltage unloading, if no surge arresters are installed in the line bay, the voltages on the circuit breaker and voltage instrument transformer exceed a value of 913 kV. Power transformer has a nonstandard reduced insulation level of 900 kV / 395 kV. Coordination lightning impulse withstand voltage of 720 kV was determined as 80% of transformer's standard lightning impulse withstand voltage (900 kV). Overvoltages on power transformer AT2 in all simulations were below the coordination lightning impulse withstand impulse voltage of 720 kV. Lightning activity can cause momentary outages of certain transmission lines when the circuit breaker switches off the line. In that case substation elements behind the circuit breaker remain completely unprotected and exposed to lightning overvoltages.

Examples of overvoltages on the voltage instrument transformer and circuit breaker in the line bay are shown in Fig 9. for three cases of surge arrester placement:

a) surge arrester installed in autotransformer bay
b) surge arrester installed in autotransformer bay and line bay
c) surge arrester installed in autotransformer bay and line bay + LSA at first tower (in the upper phase)

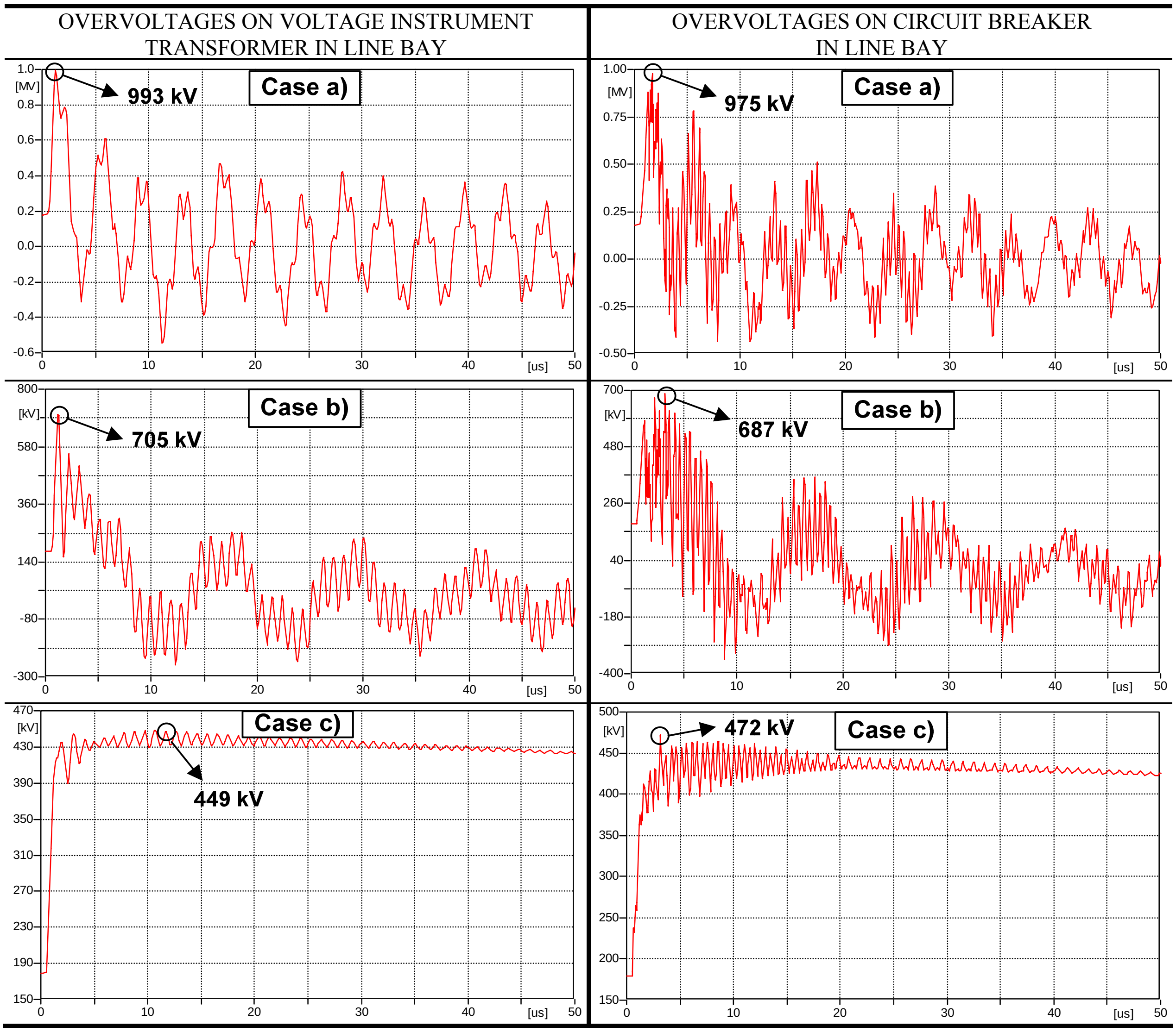

Figure 9. Overvoltages on voltage transformer and circuit breaker

Overvoltage protection is improved by installing additional surge arresters in the line bay. Calculation results show that complete protection is achieved by installing surge arresters close to the voltage instrument transformer in the line bay and in front of the power transformer. Thereby all substation elements are completely protected from overvoltages Overvoltage protection decreases the dielectric stresses of the power transformer insulation and all substation elements. When an additional LSA is installed, overvoltage protection of the substation is improved and "the first line" of protection is displaced to the transmission line entering the substation.

Besides direct lightning strokes to phase conductors, another dangerous event for substation elements is the occurrence of backflashover near a substation, which results in short circuit currents of high magnitudes. A lightning stroke (100 kA, 1/50 μs) to a fourth tower with the highest footing resistance (70 Ω) is analyzed.

The appearance of backflashover strongly depends on the tower footing resistance and the voltage phase angle. In order to prevent backflashover occurrence the LSA was installed in the upper phase of one system.

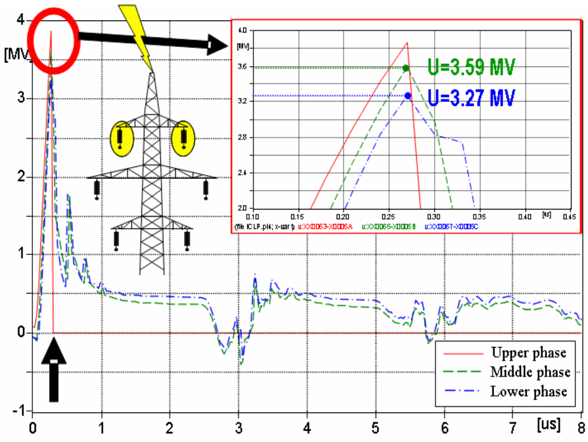

Figure 10. Voltages in phases of one circuit (without LSA)

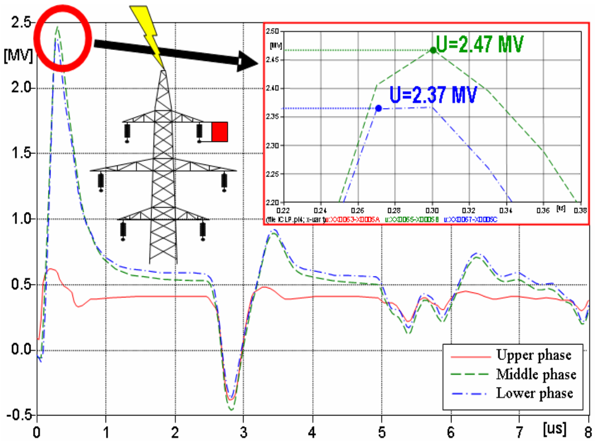

Figure 11. Voltages in phases of one circuit (LSA installed in the upper phase)

Backflashover occurs in the upper phases of both circuits if surge arresters are not installed (Fig. 10). If a surge arrester is installed in the upper phase of one circuit, the backflashover is in this case prevented in both circuits (Fig. 11). The arrester in the upper phase also reduces voltages in the other phases (better coupling factor, tower voltage reduction).

6 CONCLUSIONS

In cases when insulator flashover occurs near a substation, short circuit currents can have high magnitudes and a very steep front of wave is formed that enters the substation and causes insulation stresses, especially on winding elements such as the transformer.

Backflashover near a substation can be avoided by installing LSAs and the overvoltage protection of the substation can be improved. The installation of LSAs can also minimize operation of the circuit breakers with a possible system outage resulting from backflashover on the transmission line. This eliminates interruption of power supply and results in better power quality.

The analysis performed are conducted with the application of a three-dimensional electro-geometric model and EMTP simulations. Results show that the installation of LSA in front of the HV substation significantly prevents backflashover and improves the overvoltage protection of the entire substation.

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