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Mitigation of common mode failures at multi-circuit line configurations by application of line arresters against back-flashovers

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SUMMARY

Due to the limited number of corridors multi circuit line configurations are often applied. These overhead lines frequently consist of high towers that are subject to lightning strokes. In case of higher current amplitudes and higher footing resistances due to bad earthing conditions back-flashovers are caused leading to common mode failures and to severe outages.

The paper describes investigations performed by means of computer simulations to identify the towers of a multi-circuit line consisting of voltage levels 380 kV, 220 kV and 110 kV that are endangered by back-flashovers of the 110-kV double-circuit lines. The footing resistance of towers of the targeted line section has been measured by an instrument at high-frequency. Influence of various factors on the back-flashover over 110 kV insulator strings has been studied by means of EMTP-ATP simulations. Different current waveforms of the lightning stroke have been used to represent the first stroke and subsequent strokes. The towers are represented by the models described in [3], [8]. Available flashover analysis methods [7], [8], [12], [13] like leader development method by Pigini et al and by Motoyama, and voltage-time integration method by Kind have been applied.

The towers at which back-flashover is more likely to occur than at other towers are identified by the time integral of voltage according to Kind. Various factors like tower footing impedance, tower surge impedance and tower height are considered. Application of line a surge arrester is shown to be a successful mitigation technique to reduce the back-flashover rate of those 110 kV lines. The lightning overvoltage performance of surge arresters has been analyzed by means of digital simulations. Based on the results of investigations line arresters were installed on the towers in question. Since the installation no further common mode failure has been observed.

KEYWORDS

Lightning – Overvoltage – Backflashover – Tower – Multi-circuit – Overhead line – Surge Arrester

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1. INTRODUCTION

Three-phase tripping of a 110 kV double-circuit overhead line has been increased in a certain region, where relatively tall multi-circuit transmission towers were installed. The lightning strokes registered in this region showed a maximum stroke current of 90 kA. The high-frequency measurement of the tower footing resistance with a 26 kHz measuring current has revealed that the resistance value is relatively high at the some towers.

A back-flashover analysis should indicate which towers of that 5.2 km line route are rather prone to back-flashovers of the 110 kV insulator strings depending on different factors like tower footing resistance, tower surge impedance, tower height, etc. There are various methods published before to model lines, towers, lightning strokes and flashover mechanism over the insulators. Since measurements on real towers [1] are costly, various simulation models should be compared with each other to validate the simulation results.

The transients program EMTP-ATP [2] with the integrated simulation language MODELS is well suited to analyze lightning surge phenomenon on overhead lines as reported in numerous publications [3], [4]. Nearly all system components can be represented by built-in elements in EMTP-ATP like overhead lines with phase and ground wires and towers [5]. The flashover criteria or sophisticated representation of tower footing resistance and lightning stroke current can be modelled preferably using MODELS or TACS.

A measure to prevent back-flashovers is to apply line surge arresters. The protective level of the surge arrester for lightning strokes should be selected such that the limiting voltage of the surge arrester is smaller than the flashover voltageof the insulator. Furthermore, it is important to equip a series of towers with surge arresters without leaving out a tower in-between. Otherwise back-flashover at that tower without surge arresters may be expected due to discharging of surge arresters at the adjacent tower.

2. MODELING METHOD

The modelling method for the back-flashover analysis used in this paper is based upon various publications on this field [3], [6 – 9].

1.1. *Towers*

The height of multi-circuit towers varies in the range of 55 … 88 m. The tower structure also varies from tower to tower along the 5.2 km route. The layout of a typical suspension tower is shown in Fig. 1. The distances are given in meters. The upper two cross-arms carry at left and right side a 220 kV and 380 kV single-circuit line, respectively. A 110-kV double-circuit line is suspended from the lowest cross-arm.

The tower is represented by loss-less *Constant-Parameter Distributed Line* (CPDL) model [2]. The propagation velocity of a travelling wave along a tower is taken to be equal to the light velocity, $c = 300\ \mathrm{m/\mu s}$ [3], [8]. The tower travelling time is $\tau_t = \dfrac{h}{c}$. h is the tower height.

There are several formulas to calculate the surge impedance of the tower [3], [8]-[10]. As a basis, the formula

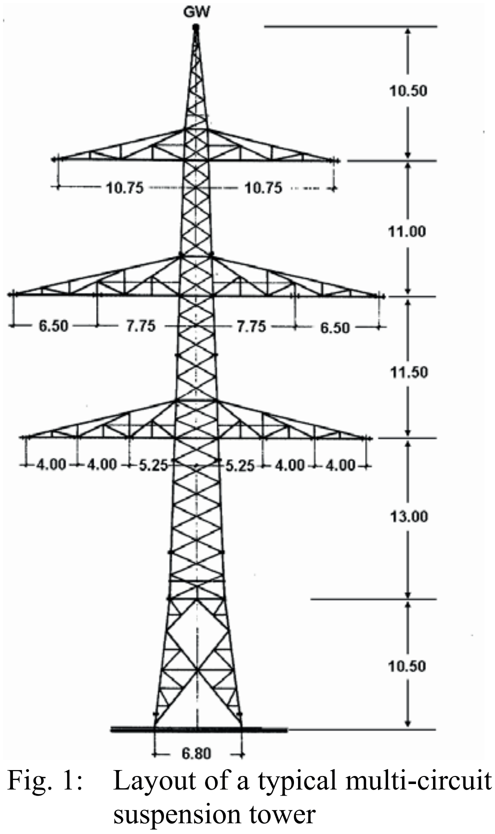


Fig. 1: Layout of a typical multi-circuit suspension tower

given in [10] for “waisted tower shape” (Fig. 2) and recommended by IEEE and CIGRE [8] is used:

$$Z_{t-waist} = 60 \cdot \ln\left[\cot\left\{0.5 \cdot \tan^{-1}\left(\frac{R}{h}\right)\right\}\right] \qquad (1)$$

where $R = \frac{r_1 h_2 + r_2 h + r_3 h_1}{h}$ and $h = h_1 + h_2$

For a tower of 76.5-m height the equation (1) delivers following value:

$$Z_{t-waist} = 233.3\,\Omega\,.$$

It is recommended in Japan [3] to consider frequency-dependent effects for wave propagation along towers, when the tower footing impedance is represented by a linear resistance, which is the case in this study, because the influence of the surge impedance and the frequency-dependent effect of a travelling wave along the tower becomes rather noticeable. As an alternative, the tower model consisting of CPDL model sections is added by *RL* parallel circuits at each section to represent travelling wave attenuation and distortion as shown in Fig. 3.

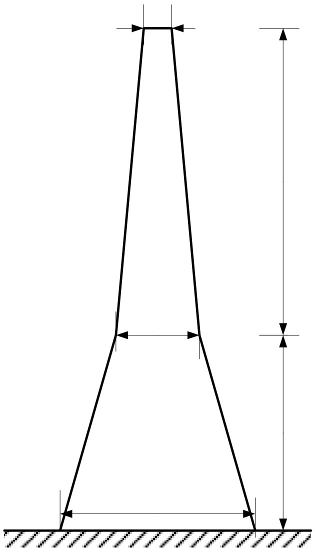


Fig. 2: Waisted tower shape as approximation to calculate tower surge impedance

The *RL* values are determined as functions of surge impedance Z_t, travelling time τ_t, distances between cross-arms x_1, x_2, x_3, x_4, and attenuation factor, $\alpha = 0.89$ as recommended in [3] by following equations:

$$R_i = \frac{x_i}{h} \cdot 2Z_t \cdot \ln\left(\frac{1}{\alpha}\right) \qquad (2)$$

$$L_i = 2\tau_t \cdot R_i \qquad (3)$$

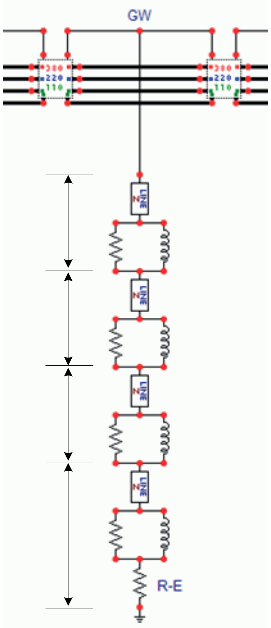


Fig. 3: Tower model with RL-circuits

1.2. Number of Modelled Towers

Total 19 towers of a part of a line route shown in Fig. 4 are represented including all overhead line circuits. Direct lightning strokes to towers between tower #1 and #12 are analyzed.

1.3. Transmission Lines

All overhead lines at the same tower are represented by the CPDL model at $f = 400$ kHz. The ground wire is represented like a phase wire, which is connected to the top of the towers (see Fig. 1). Data of the conductors are:

- *380 kV*: 4 conductors/phase, ACSR 265/35 Al/St
- *220 kV*: 4 conductors/phase, ACSR 265/35 Al/St
- *110 kV*: 1 conductor/phase, ACSR 265/35 Al/St
- *ground wire*: AY/AW 216/33 (aerial cable)

In order to take into account the effect of the AC steady-state voltage of the lines on a lightning surge, the transmission lines are connected to AC voltage sources via multiphase matching impedance (surge impedance matrix).

1.4. Lightning Current and Impedance

The lightning stroke is modeled by a current source and a parallel resistance, which represents the lightning-path impedance (Fig. 5). Lightning-path impedance is selected as 400 Ω according to [3].

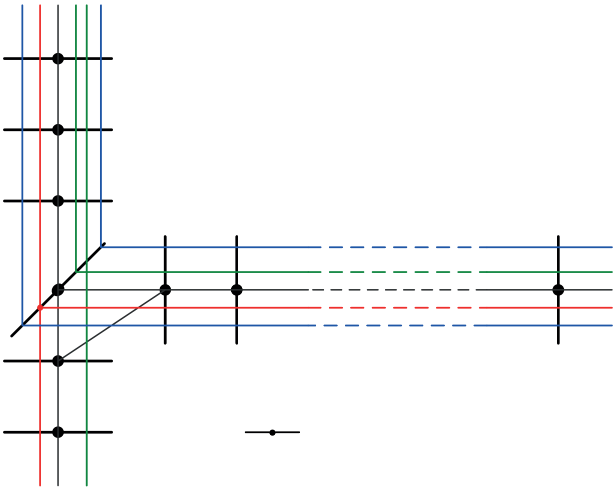


Fig. 4: Modelled part of the transmission line route

Two different lightning current waveforms are used to represent a) first stroke and b) the subsequent strokes:

a) CIGRE waveform of concave shape with front time, $T_f = 3\,\mu\text{s}$ and time to half value, $T_h = 77.5\,\mu\text{s}$.

b) Linear ramp waveform with $T_f = 1\,\mu\text{s}$ and $T_h = 30.2\,\mu\text{s}$

In fact, according to [8] the front time of the first stroke depends on the peak value of the lightning current. In this study T_f and T_h are assumed to be constant. Fig. 6 shows both current waveforms with a magnitude of 50 kA.

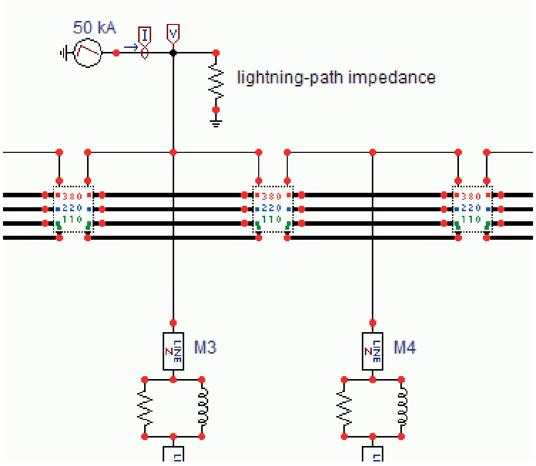


Fig. 5: Lightning stroke model consisting of current source and parallel lightning-path resistance

1.5. Flashover Models

Flashover or back-flashover models estimate the breakdown of the air between the arcing horns of the line insulators under non-standard wave forms. In the literature mainly two methods are known besides the simple flashover estimation by means of a voltage-time curve of an insulator [7], [8]. There are integration methods and Leader development methods. In this study following three flashover models are applied for comparison purposes.

a. Equal-area criterion by Kind [6], [8], [14];
b. Leader development method by Motoyama [4], [12];
c. Leader development method by Pigini et al. [8], [13].

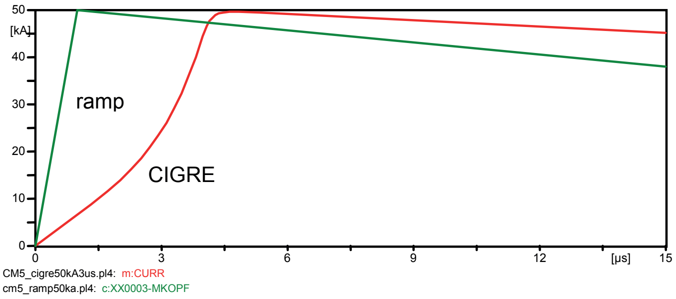


Fig. 6: Lightning current waveforms; CIGRE concave waveform, linear ramp function

The gap length of the 110 kV phase insulators is 0.965 m. Wave deformation due to corona is not considered in the lightning surge simulations [3]. In this paper it is assumed that the lightning stroke terminates at the tower. The surge propagating on the ground wire can normally be deformed by corona. Simulation results neglecting the corona are expected to be higher than considering corona. Consequently, the results will be on the safe side from the insulation viewpoint.

2. BACK-FLASHOVER PERFORMANCE ESTIMATION

In order to estimate roughly which towers on the route from tower #1 to #12 (Fig. 4) are endangered by back-flashovers across 110 kV insulators, the same lightning stroke is applied to each tower. Based on the equal-area criterion by Kind the time integral of the voltage across the 110 kV insulator is evaluated using the following integral on the left-side of equation (4)

$$\int_0^{t_{flo}} \left[u(t)-U_0\right] dt \geq F \qquad (4)$$

where $U_0 = 475.42$ kV and $F = 0.304$ Vs. Following two lightning current waveforms are adopted:

- CIGRE waveform, $I = 50$ kA; $3\,\mu\text{s}/77.5\,\mu\text{s}$
- Linear ramp function, $I = 50$ kA; $1\,\mu\text{s}/30.2\,\mu\text{s}$.

Two different tower models are taken into consideration. The simulation results are summarized in Figures 7 and 8 for the different lightning current waveforms. The horizontal red line indicates the limiting value F according to flashover criterion by Kind. Focusing on Fig. 7, it can be said that a back-flashover can occur more likely at the towers #3, #5, #8, #9 and #10. Similar tendency is shown with a steep ramp lightning current in Fig. 8.

There is a clear correlation between the flashover tendency – higher values of voltage-time integral – and the tower footing resistance, and a rather weak correlation between the flashover tendency and tower surge impedance can be observed as shown in Fig. 9.

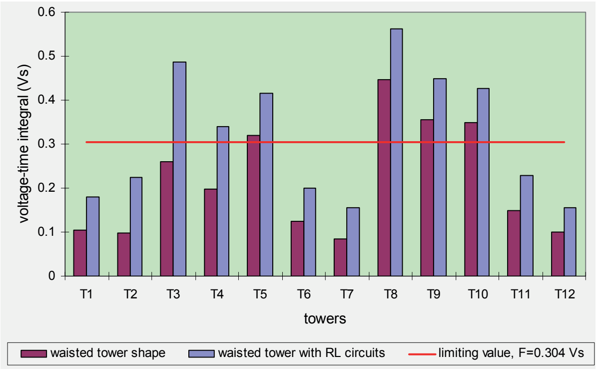


Fig. 7: Voltage-time integral values for the applied CIGRE current waveform

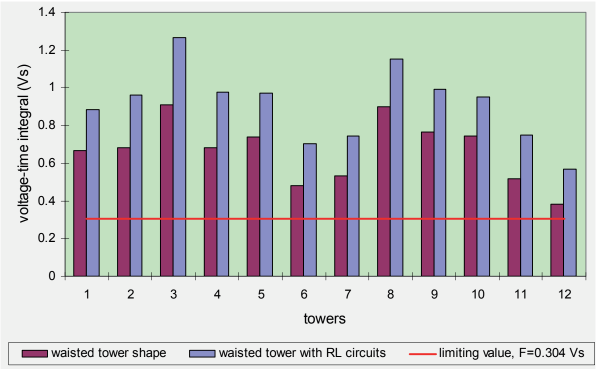


Fig. 8: Voltage-time integral values for the applied current as ramp function

As a simulation example, the computed waveforms of the voltage across the 110 kV insulator at tower #8 with flashover are shown in Fig. 10 and 11 for the three flashover models. With CIGRE lightning current waveform of magnitude 45 kA, a flashover is expected to occur according to Kind and Pigini et al. as shown in Fig. 10. Motoyama's model causes a flashover, when the magnitude of the lightning current is 50 kA (Fig. 11). Note that the voltage waveform before flashover has been deformed in the case of Motoyama, because a pre-discharge current already flows as shown in Fig. 11.

For the selected three towers #3, #7 and #8 the lightning current magnitude is varied in steps of 5 kA and several simulations have been performed. Taking the probability distribution relation for lightning crest current magnitudes according to IEEE [9]

$$p(i > I) = \frac{1}{1+\left(\dfrac{I}{31\,\text{kA}}\right)^{2.6}} \qquad (5)$$

into consideration, it can be said that at the mostly endangered towers #3 and #8 with an average magnitude of $I = 35$ kA, 42 % of lightning strokes would cause a back-flashover across 110 kV insulator. Tower #7 has a relatively low footing resistance. Hence at this tower higher current magnitudes are required for a back-flashover. In case of CIGRE current waveform at least a 60 kA lightning stroke can cause a flashover. The corresponding probability of lightning strokes with $I > 60$ kA is about 15 %.

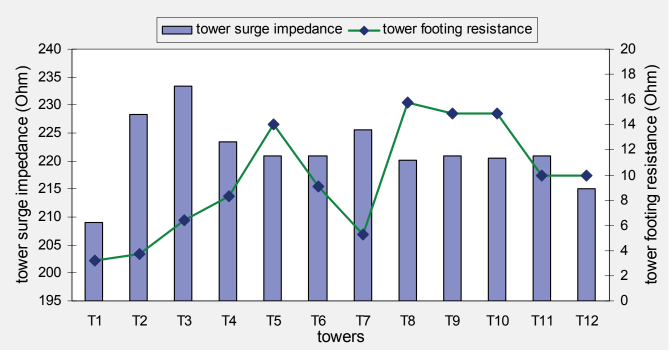


Fig. 9: Tower surge impedances and measured footing resistances

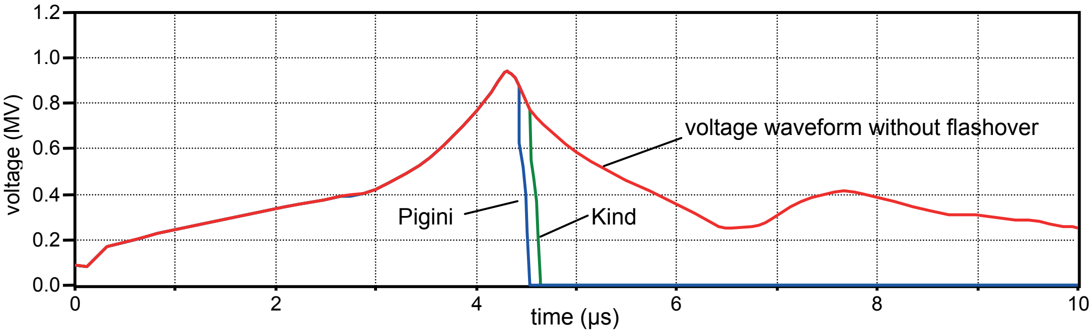


Fig. 10: Flashover across 110 kV insulator at tower #8 according to Kind's and Pigini's model

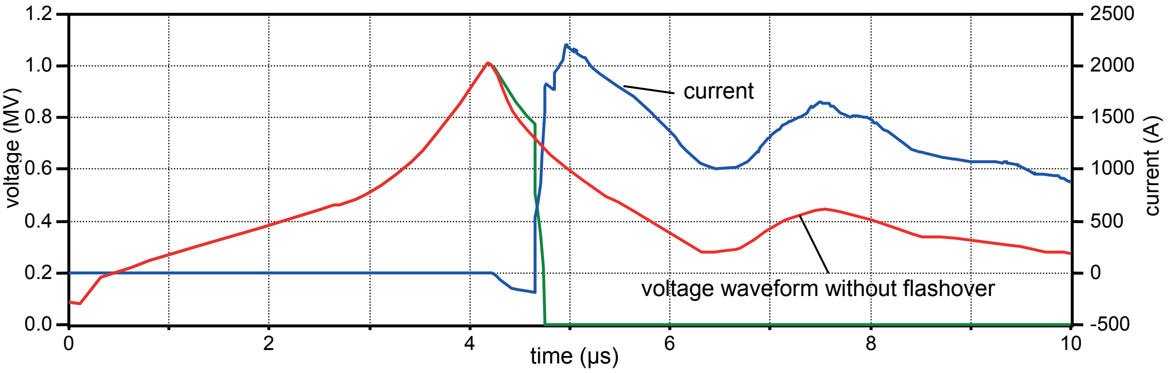
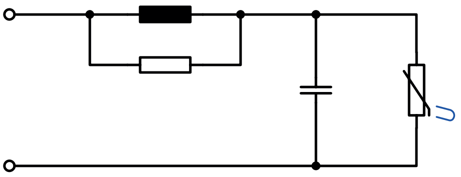


Fig. 11: Flashover across 110 kV insulator at tower #8 according to Motoyama's model

3. MITIGATION OF BACK-FLASHOVERS BY LINE SURGE ARRESTERS

Line surge arresters parallel to the phase insulators of 110 kV circuits can prevent back-flashovers at those towers [16]. Towers #3, #5 and #8 are selected as mostly endangered towers by back-flashovers of the 110-kV lines and are equipped with line surge arresters. The model referring to [15] of the selected surge arrester with rated voltage of 156 kV and its nonlinear voltage-current characteristic are shown in figures 12 and 13, respectively.

It can easily be checked by the Kind equal-area criterion that no flashover can occur across the insulator string parallel to the surge arrester, because the voltage across the insulator will be limited by surge arresters below U_0 in equation (4) as shown in Fig. 14 for a lightning stroke with $I = 100\,\text{kA}; 3\,\mu\text{s}/77.5\,\mu\text{s}$.



$L_0 = 0.307\ \mu\text{H}$; $R_0 = 153.5\ \Omega$;
$C = 65.1\ \text{pF}$

Fig. 12: Surge arrester model

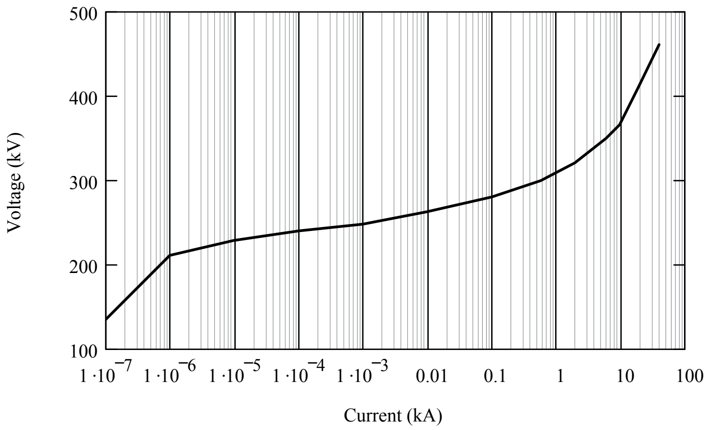


Fig. 13: Voltage-current characteristic of the surge arrester

The simulations of lightning strokes with $I = 200\,\text{kA}; 3\,\mu\text{s}/77.5\,\mu\text{s}$ at the towers #3 and #8 also confirmed that no breakdown can occur across parallel insulators according to the other two flashover models by Pigini et al and Motoyama.

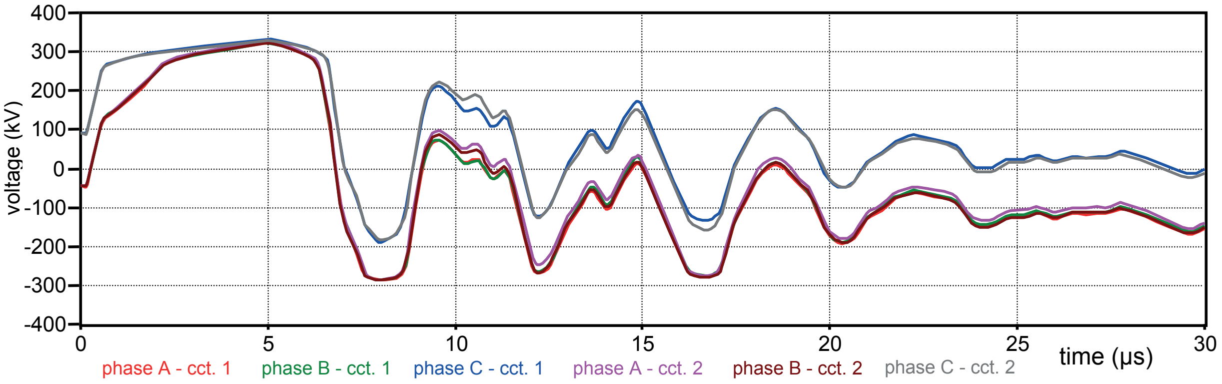


Fig. 14: Voltages across six 110 kV phase insulators at tower #3 which are limited by line surge arresters (no flashover at adjacent towers is assumed)

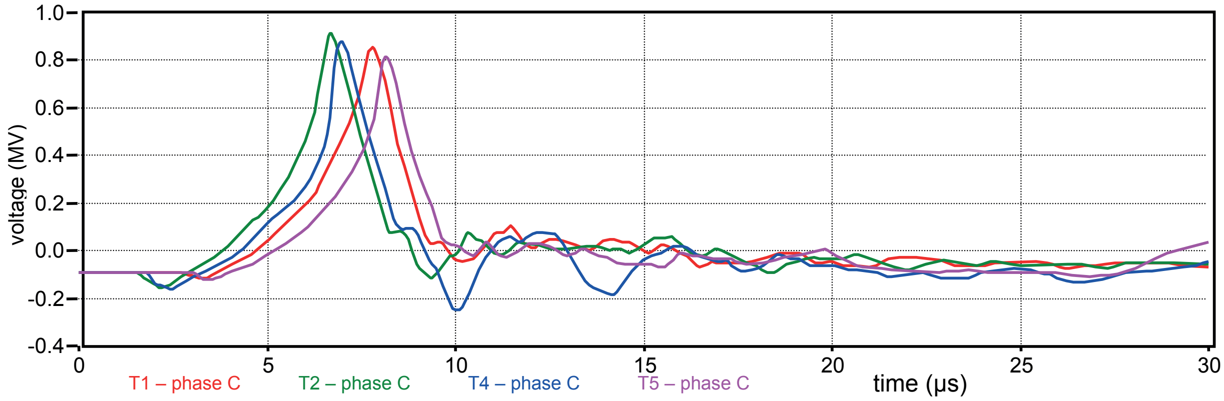


Fig. 15: Voltages between phase *c* and the tower at towers #1, #2, #4 and #5 of the 110 kV line due to discharging of line surge arresters at tower #3. No flashover at adjacent towers is assumed.

Due to discharging of the surge arresters the voltage of the 110 kV phase conductors temporarily increases significantly. Fig. 15 shows voltages between phase *c* and tower at the towers #1, #2, #4 and #5, when a lightning stroke with $I = 100\,\text{kA}; 3\,\mu\text{s}/77.5\,\mu\text{s}$ hits the top of the tower #3. The operating

50-Hz voltage of phase *c* is at moment of the lightning stroke equal to the negative peak value (–90 kV). Depending on the amplitude of the discharge current of surge arresters, a flashover may take place at other towers, which are not equipped with surge arresters. In this respect two cases have been studied: lightning stroke to towers #3 and #8, which are equipped with line surge arresters for 110 kV. Adjacent towers do not contain any line surge arresters.

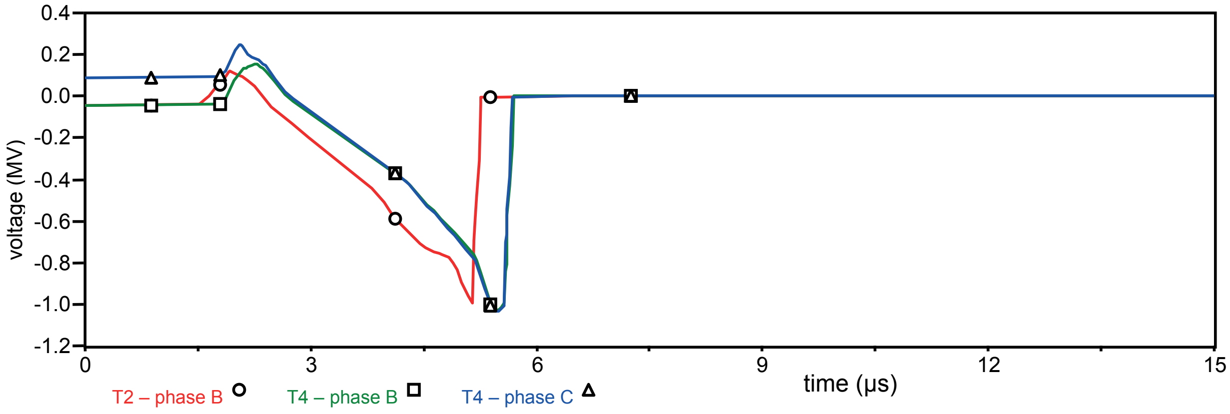


Fig. 16: Waveforms of voltages across 110-kV phase insulators with flashovers at towers #2 and #4 (It is assumed that no line surge arresters are installed at those towers)

The CIGRE current waveform with 3/77.5 µs as lightning stroke is used by increasing the amplitude in 5 kA steps. The flashover condition is checked by the Kind equal-area criterion. At tower #3, when $I > 95$ kA and at tower #8, when $I > 90$ kA, a flashover is expected at the adjacent towers across the 110 kV phase insulators. Waveforms of the voltage across flashed-over insulators are shown in Fig. 16 for the case of lightning stroke to tower #3 with 110 kA. At tower #2 the phase *b* and at tower #4 the phases *b* and *c* attain flashover. Therefore the installation of line surge arresters at the towers #1 - #5 and #8 - #10 is recommended to avoid flashovers when adjacent towers are hit by strokes in the range of 90 kA.

An important question is, how well the surge arresters will perform in terms of energy absorption. A lightning stroke with $I = 200\,\mathrm{kA};\, 3\,\mu\mathrm{s}/77.5\,\mu\mathrm{s}$ is applied as worst-case to the top of towers #3 and #8. It is assumed that no line arresters are installed at adjacent towers. Consequently, flashover takes place in all phases of the 110-kV double-circuit line at adjacent towers. Maximum energy absorption computed is 34 kJ, which is uncritical.

4. CONCLUSION

A flashover analysis has been performed for a 110 kV double-circuit overhead line, which is a part of a multi-circuit transmission route. The towers at which back-flashover is more likely than at others are identified in order to take countermeasures like installation of line surge arresters at those towers.

Multi-circuit tower system is modeled with the graphical preprocessor *ATPDraw* and the simulations are performed using *EMTP-ATP*. Three back-flashover models are used to test the performance of line surge arresters, which can be successfully used to prevent back-flashovers at endangered towers. It is shown that for lightning stroke current amplitude from 90 kA upwards flashover occurs at the adjacent towers, when the phase conductors at those towers are not equipped with surge arresters due to discharge current of stressed surge arresters. Energy absorption of the selected 110 kV line arresters remains uncritical.

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