Mitigation of Back-Flashovers for 110-kV Lines at Multi-Circuit Overhead Line Towers

Mustafa Kizilcay

Abstract—An increase of back-flashovers in a 110-kV system has been observed along an overhead line route that consists of multi-circuit transmission towers of voltage levels 380-kV, 220-kV and 110-kV at the same tower. The height of multi-circuit towers varies in the range of 55 ... 88 m. The 110-kV double-circuit line is positioned at the lowest cross-arm of the tower as shown in Fig. 1.

In the previous work back-flashover analysis was performed to identify which towers of the 5.2-km line route are rather prone to back-flashovers of the 110-kV insulation. As outcome of that work one insulator string of a duplex line insulator was replaced by a surge arrester at the selected towers of that route to reduce back-flashover rate of the 110-kV line.

In the present paper a different mitigation method for back-flashovers across 110-kV insulation strings is proposed. An additional ground wire is proposed to be installed along that 5.2-km line route in order to reduce the lightning overvoltages across the line insulators.

Keywords: flashover, back-flashover, lightning stroke, lightning surge, transmission tower, EMTP.

I. INTRODUCTION

The tripping of a 110-kV double-circuit overhead line was increased in a certain region at thunderstorms, where relatively tall multi-circuit transmission towers were installed. The multi-circuit transmission route consists of 380-kV, 220-kV and 110-kV overhead lines at the same tower. Lightning strokes registered by lightning flash counters 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 three towers.

A back-flashover analysis was performed which shows that towers of that 5.2-km line route are rather prone to back-flashovers of the 110-kV insulation strings depending on different factors like tower footing resistance, tower surge impedance, tower height, etc [1], [2].

A measure to prevent back-flashovers is to replace one insulator string of a duplex line insulator by a surge arrester. It has been shown in a previous paper [1] line surge arresters can be successfully utilized to prevent back-flashovers across 110-kV phase insulators at endangered towers. For lightning stroke current amplitudes greater than 90 kA, flashover may occur at the adjacent towers due to discharge current of operated surge arresters, when the phase conductors at those towers are not equipped with surge arresters.

Another method for the mitigation of back-flashovers at the 110-kV overhead lines on the same multi-circuit towers would be to install an additional ground wire as close as possible to the phase wires of the two 110-kV systems along that route with high risk of back-flashovers. By the additional ground wire near to the 110-kV phase wires the amplitude of lightning overvoltages appearing between the tower and phase wire can be reduced. A part of the lightning surge travelling along the tower enters into that additional ground wire and will be coupled through the capacitance between the ground wire and phase wires to the phase wires of the 110-kV system. Thus, the surge voltage difference appearing between the 110-kV phase wires and the tower will be reduced resulting in less back-flashover probability.

The transients program EMTP-ATP [3] with the integrated simulation language MODELS is used to model the whole system to analyze lightning surge phenomenon on overhead lines as reported several times in publications [4], [5].

II. MODELING METHOD

The modelling methods for the back-flashover analysis applied in this paper are based upon various publications in this field [3], [6] – [9]. Since the modelling of the transmission system was described in detail in the previous papers [1], [2], here only a brief summary will be given.

A. Multi-Circuit 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-arms. Fig. 2 shows the location of the proposed additional ground wire at the tower.

The tower is represented by loss-less Constant-Parameter Distributed Line (CPDL) model [3]. The propagation velocity of a traveling wave along a tower is taken to be equal to the light velocity [4], [10]. The surge impedance of the tower is calculated according to the formula given in [10] for the "waisted tower shape [1], [12]:

M. Kizilcay is with the Department of Electrical Eng. and Computer Science, University of Siegen, Siegen, Germany (e-mail: kizilcay@uni-siegen.de)

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

(1)

where \( R = \frac{r_1h_2 + r_2h_1 + r_3h_1}{h} \) and \( h = h_1 + h_2 \).

For a tower of 76.5-m height (1) delivers the following value: \( Z_{t\rightarrow \text{wird}} = 233.3 \, \Omega \).

It is recommended in Japan [4] 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. The tower model consisting of CPDL model sections is added by RL parallel circuits at each section to represent traveling wave attenuation and distortion. The calculation of RL values is given in [1] based on [4].

The cross-arms are not represented in the tower model.

B. Number of Towers

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

C. Transmission Lines

All overhead lines at the same tower are represented by the CPDL model at \( f = 400 \, \text{kHz} \). Ground wire is represented like a phase wire. 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 wires: 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).

D. Lightning Current and Impedance

The lightning stroke is modeled by a current source and a parallel resistance of \( 400 \, \Omega \), which represents the lightning-path impedance [4]. 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, \( T_f = 3 \, \mu s \) and time to half value, \( T_h = 77.5 \, \mu s \).

b) Linear ramp waveform with \( T_f = 1 \, \mu s \) and \( T_h = 30.2 \, \mu s \).

Fig. 4 shows both current waveforms with a magnitude of 50 kA.

E. Flashover Models

Flashover models estimate the breakdown of the air between the arcing horns of the line insulators under non-standard wave forms.

In this study three flashover models are applied for comparison purposes [1]:

1) Equal-area criterion by Kind [8], [10], [16];
2) Leader development method by Pigini et al. [10], [15].
3) Leader development method by Motoyama [6], [14].
Wave deformation due to corona is not considered in the lightning surge simulations. The surge propagating on the ground wire can be normally deformed by corona. In this paper it is assumed that the lightning stroke terminates at the tower.

1) Equal-area criterion by Kind

The criterion by Kind requires two parameters, \( U_0 \) and \( F \), and it is tested simply by evaluating the following integral numerically:

\[
\int_0^{T_f} [u(t) - U_0] \, dt \geq F \tag{2}
\]

where \( u(t) \) is the voltage waveform across the insulator.

When the time integral of the voltage difference \( (u - U_0) \) becomes greater than the value of \( F \), then at \( t = T_f \), the flashover occurs. The unknown parameters \( U_0 \) and \( F \) can be obtained from the 50 % sparkover volt-time characteristic of the insulator [1], [16]. The unknown parameters in (2) are determined according to [18]:

\[
U_0 = 475.42 \text{ kV}, \quad F = 0.304 \text{ Vs}.
\]

2) Leader development method by Pigini et al.

The flashover condition is estimated by the imposed voltage across the air gap. The leader onset condition is given as [13]

\[
u(t) \geq E_{op} \cdot D \tag{3}
\]

where \( D \) is the gap length and \( E_{op} = 670 \text{ kV/m} \).

The equivalent leader-developing velocity \( v_L \) (m/s) is computed according to following equation, which was evaluated by several measurements [15]:

\[
v_L = 170 \cdot D \left[ \frac{u(t)}{D - l_t} - E_{op} \right] \cdot \exp(0.0015 \cdot u(t)/D) \tag{4}
\]

where \( l_t \) is the leader length in meter; \( u(t) \) is the voltage imposed to the air gap. The leader length is obtained by the integral of leader-developing velocity:

\[
l_t = \int v_L(t) \, dt \tag{5}
\]

The breakdown occurs, when the leader length \( l_t \) is equal to the gap length \( D \).

3) Leader development method by Motoyama

The flashover model by Motoyama [6], [14] is developed for short tail lightning impulse voltages based on experiments for 1m...3m gap lengths. It is the only model, where the leader development can be modeled as a nonlinear resistance which interacts with the remaining circuit. The leader onset condition for positive polarity is used:

\[
\frac{1}{T_s} \int_0^{T_s} u(t) \, dt = U_{ave} > 400(kV) \cdot D(m) + 50(kV) \tag{6}
\]

where \( u(t) \) is the imposed voltage between archorns and \( D \) is the gap length in meter. \( T_s \) is the streamer developing time (= leader onset time). The leader developing process is defined by following equations:

\[
\begin{align*}
&v_{LAVE} = \begin{cases}
K_{L1} \cdot \frac{u(t)}{D - 2x_{LAVE}(t)} - E_0 & \text{for } 0 \leq x_{LAVE} < D/4 \\
K_{L1B} \cdot \frac{u(t)}{D - 2x_{LAVE}(t)} - E_0 & \text{for } D/4 \leq x_{LAVE} < D/2
\end{cases} \quad (\text{m/s}) \tag{7}
\end{align*}
\]

\[
i_L = 2 \cdot K_0 \cdot v_{LAVE} \tag{8}
\]

\[
x_{LAVE}(t) = \int v_{LAVE}(t) \, dt \quad (\text{m}) \tag{9}
\]

where \( i_L \) is the leader current; \( x_{LAVE} \) is the average value of the leader-developing length; and \( v_{LAVE} \) is the leader-developing velocity. The constants \( E_0, K_0, K_{L1}, K_{L1B} \) are set to 750 kV/m, 410 \( \mu \text{As/m} \), 2.5 \( \text{m}^2/\text{Vs} \) and 0.42 \( \text{m}^2/\text{Vs} \), respectively.

The breakdown occurs when \( x_{LAVE} \) attains \( D/2 \). If the applied voltage \( u(t) \) becomes less than \( E_0 \cdot (D - 2x_{LAVE}) \) during the leader-developing process, the leader is considered to stop its development.

In this paper Motoyama’s leader development method is presented as a nonlinear resistance using Thevenin-type user-defined component in EMTP-ATP [3]. The interface of the leader model with the remaining circuit is shown in Fig. 5.

![Fig. 5. Interaction between the leader and electric circuit represented by Iterated-type component](image)

The voltage \( u(t) \) in (7) is equal to \( v_h \) (Thevenin voltage seen from the leader). Since the leader current, \( i_L \) is determined for a given \( u(t) \), the leader resistance, \( r_L \) is calculated by the equation

\[
r_L = \frac{v_h}{i_L} \tag{10}
\]

The actual leader current, \( i_L \) in Fig. 6 is calculated as follows:

\[
i_L = \frac{v_h}{r_h + r_L} \tag{11}
\]

To show how Motoyama’s leader model performs, a lightning stroke to the tower #8 is simulated, where CIGRE waveform with \( I = 75 \text{ kA} \) is used. The lightning stroke causes a flashover across the 110-kV line insulator as shown in Fig. 7. The leader current starts to grow until breakdown, which is indicated by the vertical dashed line in Fig. 6.
4) Representation of the Air Gap Breakdown

The discharge in the air gap can be represented by a time-dependent arc resistance, decreasing linearly from 10 Ω to 1 Ω in 0.1 µs and to 0.1 Ω in 1 s.

III. COMPARISON OF THE BACK-FRASHOVER PERFORMANCE

The additional ground wire (AGW) as shown in Fig. 2 is considered to exist between towers #1 and #10.

The influence of the AGW regarding the amplitude of the lightning surge voltage appearing across the 110-kV line insulators is for the inner (close to the AGW) phase wires higher than for the outer phase wires (far to the AGW). The effect of the additional ground wire on the lightning surge appearing across the 110-kV insulator compared to the case without additional ground wire is illustrated in Fig. 7 for a lightning stroke to tower #3 with $I = 60$ kA and the waveform. Hereby the outermost phase wire is selected as worst case.

A systematic analysis is performed as explained in [1] in order to determine back-flashover performance of the 110-kV system in the presence of the additional ground wire. Following two lightning current waveforms are injected to each tower in question.

- CIGRE waveform, $I = 20 \cdots 90$ kA; 3 µs/77.5 µs
- Linear ramp function, $I = 20 \cdots 90$ kA; 1 µs/30.2 µs

The current amplitude has been increased in 5 kA steps from 20 kA up to 90 kA and back-flashover across the 110-kV insulators has been examined simultaneously by the three flashover models.

The simulation results are compared in figures 8 and 10 for the lightning current waveform CIGRE. In those diagrams the minimum lightning peak current is shown that causes a back-flashover at the 110-kV insulator. The comparison is made between the cases with and without AGW for the three back-flashover models by Kind, Pigini and Motoyama.

In figures 11 to 13 the minimum lightning peak currents of linear ramp type (1/30.2 µs) are compared between the cases with and without AGW for the three flashover models by Kind, Pigini and Motoyama.

The results presented in the figures 8 to 13 show the amplitudes of the minimum lightning peak currents causing back-flashover for the case with AGW are at least 10 kA higher than the case with only one ground wire. At the last two towers #11 and #12 there is no difference because the additional ground wire is considered to exist between towers #1 and #10.
Taking the probability distribution relation for lightning crest current magnitudes according to IEEE [11]

\[
p(i > I) = \frac{1}{1 + \left( \frac{I}{31 \text{ kA}} \right)^{2.6}}
\]  

(12)

into consideration, the reduction in the probability of lightning strokes causing back-flashover can be estimated. For example, for the mostly endangered tower #3 according to Fig. 8 (CIGRE waveform; flashover method Kind) the probability of back-flashovers is as follows:

- with only one GW: \( p(i > 45 \text{ kA}) = 27.5\% \)
- with additional GW: \( p(i > 60 \text{ kA}) = 15.2\% \)

Table 1 compares mean back-flashover probabilities over 10 towers for the cases with one (1-GW) and two (2-GW) ground wires regarding flashover models and current waveforms.

For the lightning current waveform CIGRE approximately the probability of back-flashovers will be halved, if an additional ground wire can be installed. A reduction of back-flashover probability of approximately 25% is expected for the steep ramp current waveform.

### IV. Conclusion

A different method for the mitigation of back-flashovers at the 110-kV overhead lines on the same multi-circuit towers has been presented in this paper compared to previous work [1], [2]. An additional ground wire as close as possible to the phase wires of the two 110-kV systems along the line route with high risk of back-flashovers can reduce the amplitude of the lightning surge across the 110-kV line insulator.

A systematic flashover analysis has been performed for a 110-kV double-circuit overhead line, which is a part of a multi-circuit transmission route. Two different lightning stroke current waveforms have been applied. The back-flashover performance is estimated by means of three different flashover models. The effectiveness of the additional ground wire as a mitigation method has been shown by comparison of the back-flashover performance with and without additional ground wire. The probability of the back-flashovers can be reduced significantly by this mitigation method. When the mitigation techniques 1) replacement of one insulator string by surge arresters and 2) additional ground wire, are compared with each other, following pros and cons can be stated as a summary for both techniques:

- At each tower 6 surge arresters are required for the double-circuit 110-kV overhead line. In order to prevent flashovers at the adjacent towers due to discharge current of operated surge arresters, surge arresters should be installed successively at each tower in the endangered area with high lightning activities. Consequently the resulting investment cost of this method is high. On the other hand, the probability of back-flashovers will be reduced substantially.

- The installation of an additional ground wire along the endangered overhead line route requires less investment, but the protection degree against back-flashovers is not so high compared to the solution with surge arresters, although the probability of flashovers can be reduced significantly by an additional ground wire as proposed in this paper.
V. REFERENCES


VI. BIOGRAPHIES

Mustafa Kizilcay was born in Bursa, Turkey in 1955. He received the B.Sc. degree from Middle East Technical University of Ankara in 1979, Dipl.-Ing. degree and Ph.D. degree from University of Hanover, Germany in 1985 and 1991. From 1991 until 1994, he was as System Analyst with Lahmeyer International in Frankfurt, Germany. 1994-2004 he has been professor for Power Systems at Osnabrück University of Applied Sciences, Germany. Since 2004 he is with the University of Siegen, Germany, holding the chair for electrical power systems as full professor. Dr. Kizilcay is winner of the publication prize of Power Engineering Society of German Electrical Engineers Association (ETG-VDE) in 1994. His research fields are power system analysis, digital simulation of power system transients and dynamics, insulation-coordination and protection. He is a member of IEEE, CIGRE, VDE and VDI in Germany.