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 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]:

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Paper submitted to the International Conference on Power Systems Transients (IPST2009) in Kyoto, Japan June 3-6, 2009

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

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

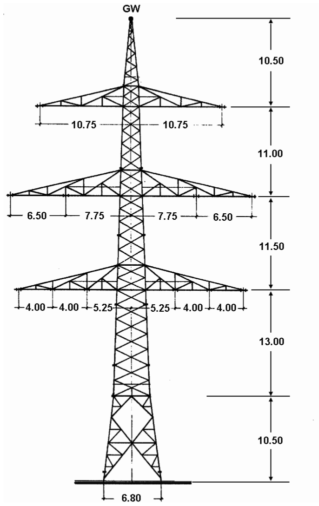

Fig. 1. Layout of a typical multi-circuit suspension tower

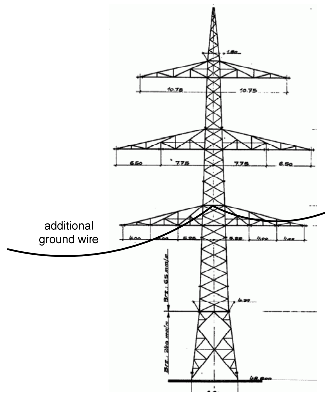

Fig. 2. The location of the additional ground wire at the tower

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

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 $f = 400$ 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).

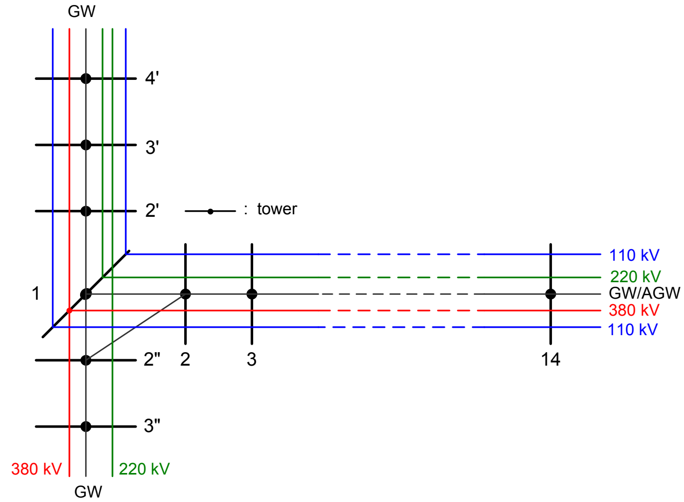

Fig. 3. Modelled part of the transmission line route with a junction at tower #1 (GW: ground wire, AGW: addional ground wire)

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 Ω, which represents the lightning-path impedance [4]. Two different lightning current wave-forms 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.

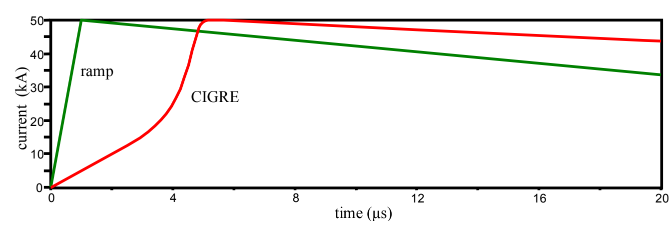

Fig. 4. CIGRE concave waveform and linear ramp function for lightning current representation, *I* = 50 kA

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:

$$\int_0^{t_{flo}} \left[u(t)-U_0\right]dt \geq F \tag{2}$$

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 $t = t_{flo}$ 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]:

$U_0 = 475.42$ kV , $F = 0.304$ 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]

$$u(t) \geq E_{0p} \cdot D \tag{3}$$

where D is the gap length and $E_{0p} = 670\ \mathrm{kV/m}$.

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

$$v_l = 170 \cdot D \cdot \left(\frac{u(t)}{D-l_l} - E_{0p}\right) \cdot \exp\left(0.0015 \cdot u(t)/D\right) \tag{4}$$

where l_l 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:

$$l_l = \int v_l(t)\,dt \tag{5}$$

The breakdown occurs, when the leader length l_l 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:

$$v_{LAVE} = \begin{cases} K_{1A} \cdot \left(\dfrac{u(t)}{D - 2x_{LAVE}(t)} - E_0\right) & \text{for } 0 \leq x_{LAVE} < D/4 \\ K_{1B} \cdot \left(\dfrac{u(t)}{D - 2x_{LAVE}(t)} - E_0\right) & \text{for } D/4 \leq x_{LAVE} < D/2 \end{cases} \quad \text{(m/s)} \tag{7}$$

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

$$x_{LAVE}(t) = \int v_{AVE}(t)\,dt \ \ \text{(m)} \tag{9}$$

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_{1A}, K_{1B} are set to 750 kV/m, 410 µAs/m, 2.5 m²/(Vs) and 0.42 m²/(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.

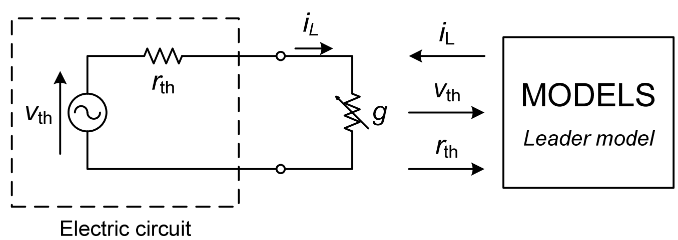

Fig. 5. Interaction between the leader and electric circuit represented by Iterated-type component

The voltage $u(t)$ in (7) is equal to v_{th} (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

$$r_L = \frac{v_{th}}{i_L} \tag{10}$$

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

$$i_L = \frac{v_{th}}{r_{th} + r_L} \tag{11}$$

To show how Motoyama's leader model performs, a lightning stroke to the tower #8 is simulated, where CIGRE wavefom with $I = 75$ 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.

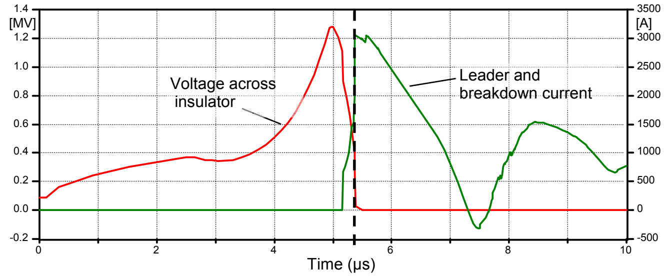

Fig. 6. Flashover across the 110-kV line insulator at tower #8 for a lightning stroke with CIGRE waveform and $I = 75$ kA according to the leader development method by Motoyama

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 0.1Ω in 1 s.

III. Comparison of the Back-flashover 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.

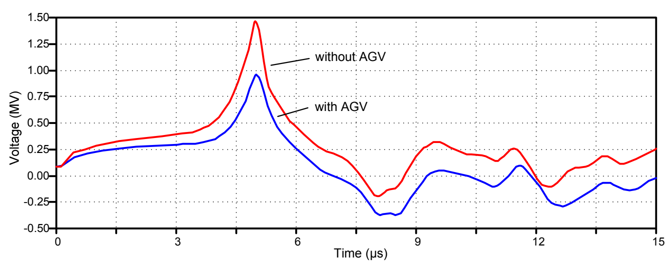

Fig. 7. Comparison of the waveforms of a lightning surge across 110-kV line insulator with and without AGW

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; $3\,\mu s / 77.5\,\mu s$

– Linear ramp function, $I = 20 \cdots 90$ kA; $1\,\mu s / 30.2\,\mu s$.

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.

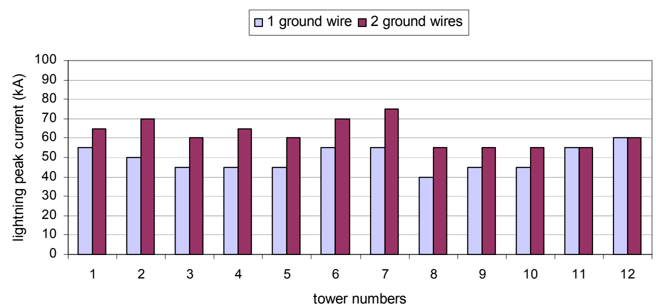

Fig. 8. Comparison of the minimum lightning peak currents of CIGRE waveform (3/77.5 µs) causing back-flashover at the 110-kV insulators for the cases with and without AGW. Flashover model by Kind.

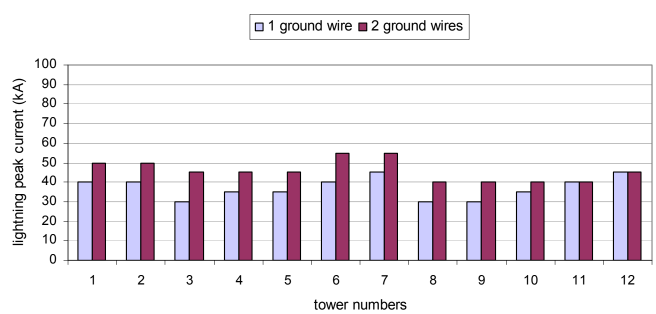

Fig. 9. Comparison of the minimum lightning peak currents of CIGRE waveform (3/77.5 µs) causing back-flashover at the 110-kV insulators for the cases with and without AGW. Flashover model by Pigini.

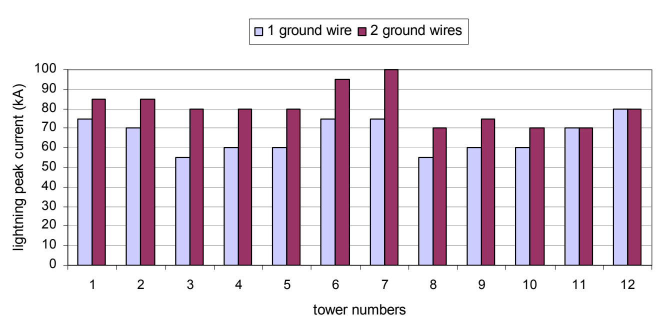

Fig. 10. Comparison of the minimum lightning peak currents of CIGRE waveform (3/77.5 µs) causing back-flashover at the 110-kV insulators for the cases with and without AGW. Flashover model by Motoyama.

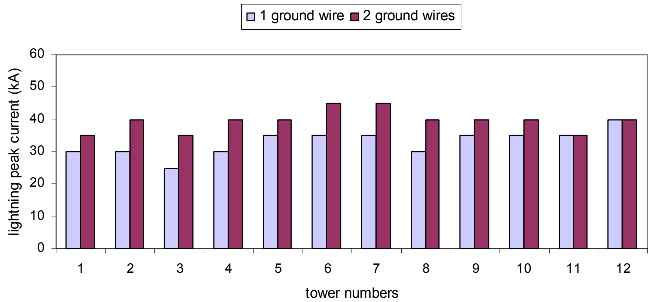

Fig. 11. Comparison of the minimum lightning peak currents of linear ramp type (1/30.2 μs) causing back-flashover at the 110-kV insulators for the cases with and without AGW. Flashover model by Kind.

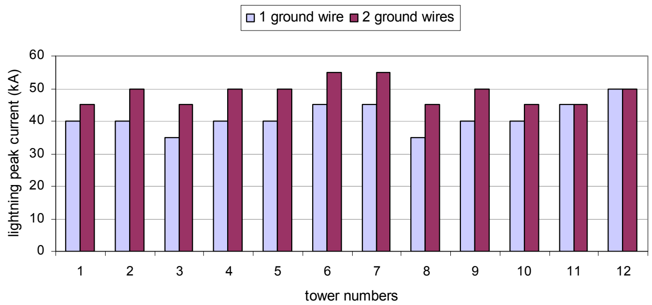

Fig. 12. Comparison of the minimum lightning peak currents of linear ramp type (1/30.2 μs) causing back-flashover at the 110-kV insulators for the cases with and without AGW. Flashover model by Pigini.

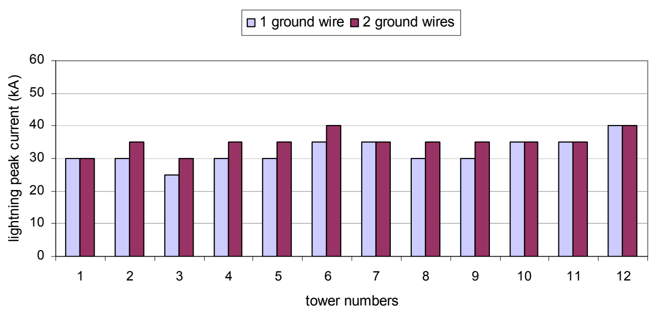

Fig. 13. Comparison of the minimum lightning peak currents of linear ramp type (1/30.2 μs) causing back-flashover at the 110-kV insulators for the cases with and without AGW. Flashover model by Motoyama.

Taking the probability distribution relation for lightning crest current magnitudes according to IEEE [11]

$$p(i > I) = \frac{1}{1 + \left(\frac{I}{31\,\mathrm{kA}} \right)^{2.6}} \tag{12}$$

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: $p(i > 45\,kA) = 27.5\,\%$
– with additional GW: $p(i > 60\,kA) = 15.2\,\%$

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.

TABLE 1
COMPARISON OF MEAN BACK-FLASHOVER PROBABILITIES FOR THE CASES WITH ONE AND TWO GROUND WIRES

current waveform	Kind		Pigini		Motoyama	
	1-GW	2-GW	1-GW	2-GW	1-GW	2-GW
CIGRE	24.9 %	14.2 %	41.2 %	26.6 %	13.6 %	7.7 %
Ramp	48.3 %	34.3 %	34.3 %	23.6 %	50.3 %	43.4%

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

[1] M. Kizilcay and C. Neumann, "Backflashover Analysis for 110-kV Lines at Multi-Circuit Overhead Line Towers," *Proc. International Conference on Power Systems Transients (IPST'07)*, June 4-7, 2007, in Lyon, France.

[2] M. Kizilcay and C. Neumann, "Mitigation of common mode failures at multi circuit line configurations by application of line arresters against back-flashovers," presented at the CIGRE-Symposium on Transient Phenomena in Large Electric Power Systems, April 18-21, 2007, Zagreb, Croatia.

[3] Canadian/American EMTP User Group: *ATP Rule Book*, distributed by the European EMTP-ATP Users Group Association, 2008.

[4] Ametani, A.; Kawamura, T.: "A Method of a Lightning Surge Analysis Recommended in Japan Using EMTP", IEEE Trans. on Power Delivery, Vol. 20, No. 2, pp. 867-875, April 2005.

[5] Yamada, T.; Mochizuki, A.; Sawada, J.; Zaima, E.; Kawamura, T.; Ametani, A.; Ishii, M.; Kato, S.: "Experimental Evaluation of a UHV Tower Model for Lightning Surge Analysis", IEEE Trans. on Power Delivery, Vol. 10, No. 1, pp. 393-402, Jan 1995.

[6] H. Motoyama, K. Shinjo, Y. Matsumoto, N. Itamoto: "Observation and analysis of multiphase back flashover on the Okushishiku test transmission line caused by Winter lightning", *IEEE Trans. On Power Delivery*, Vol. 13, No. 4, pp. 1391-1398, October 1998.

[7] Dommel, H. W.: *EMTP Theory Book*, Bonneville Power Administration, conversion into electronic format by Can/Am EMTP User Group in 1995.

[8] Schmitt, H.; Winter, W.: "Simulation of Lightning Overvoltages in Electrical Power Systems", Proceedings IPST 2001 (International Conference on Power System Transients), Rio de Janerio, June 24-28, 2001.

[9] IEEE Fast Front Transients Task Force, Modeling and Analysis of System Transients Working Group: "Modeling Guidelines for Fast Front Transients", IEEE Trans. on Power Delivery, Vol. 11, No. 1, pp. 493-506, Jan. 1996.

[10] CIGRE WG 33-01: "Guide to Procedures for Estimating the Lightning Performance of Transmission Lines", Technical Brochure, October 1991.

[11] IEEE Working Group on Lightning Performance of Transmission Lines: "A Simplified Method for Estimating Lightning Performance of Transmission Lines", IEEE Trans. on Power App. & Systems, Vol. PAS-104, No. 4, pp. 919-927, April 1985.

[12] Chisholm, W. A.; Chow, Y. L.; Srivastava, K. D.: "Travel Time of Transmission Towers", IEEE Trans. on Power App. and Systems, Vol. PAS-104, No. 10, S. 2922-2928, Oktober 1985.

[13] IEEE Working Group on Estimating the Lightning Performance of Transmission Lines: "IEEE Working Group Report – Estimating Lightning Performance of Transmission Lines II – Updates to Analytical Models", IEEE Trans. on Power Delivery, Vol. 8, No. 3, pp. 1254-1267, July 1993.

[14] Motoyama, H.: "Experimental study and analysis of breakdown characteristics of long air gaps with short tail lightning impulse", IEEE Trans. on Power Delivery, Vol. 11, No. 2, pp. 972-979, April 1996.

[15] Pigini, A.; Rizzi, G.; Garbagnati, E.; Porrino, A.; Baldo, G.; Pesavento, G.: "Performance of large air gaps under lightning overvoltages: Experimental study and analysis of accuracy of predetermination methods", IEEE Trans. on Power Delivery, Vol. 4, No. 2, pp. 1379-1392, April 1989.

[16] Fernandes, M.; Correia de Barros, M. T.; Ameida, M.E.: "Statistical Study of the Lightning Overvoltages at a Gas Insulated Station Transformer", Proceedings IPST 1995 (International Conference on Power System Transients), Lisbon, 3-7 September 1995.

[17] Koettniz, H.; Winkler, G.; Weßnigk, K.-D.: Fundamentals of Electrical Operational Phenomena in Electrical Power Systems, (original title in German: Grundlagen elektrischer Betriebsvorgänge in Elektroenergie-systemen), Deutscher Verlag für Grundstoffindustrie, Leipzig, 1986.

[18] CIGRE WG 33.02: "Guidelines for representation of network elements when calculating transients", CIGRE Technical Brochure, No. 39, 1990.

VI. Biographies

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