Lightning Performance of 275 kV Transmission Lines

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Abstract—This paper presents a comparative lightning performance study conducted on a 275 kV double circuit shielded transmission line using two software programs, TFlash and Sigma-Slp. The line performance was investigated by using both a single stroke and a statistical performance analysis and considering cases of shielding failure and backflashover. A sensitivity analysis was carried out to determine the relationship between the flashover rate and the parameters influencing it. To improve the lightning performance of the line, metal oxide surge arresters were introduced using different phase and line locations. Optimised arrester arrangements are proposed.

Index Terms—Lightning Overvoltages, Statistical Analysis, Electrogeometric modelling, Sensitivity Analysis, Surge Arrester

I. INTRODUCTION

Lightning is a major cause of overhead line faults. Between 5% to 10% of the lightning-caused faults are thought to result in permanent damage to power system equipment [1]. Therefore, the analysis of lightning performance is fundamental when designing new lines and for uprating existing lines to higher voltages. Lightning is a natural phenomenon with random behaviour, and hence a complete study of the lightning performance of an overhead line should also include a statistical approach [2]. Computer software packages have been developed for the evaluation of lightning performance of overhead lines. In this study, two widely-available programs, viz. TFlash and Sigma-Slp have been used in a comparative study of the lightning performance of a generic 275 kV double circuit line.

Both software packages make use of the travelling wave method for the computation of electromagnetic transients along the line [3, 4]. TFlash employs a Stroke Incidence Table (SIT) together with an Electrogeometric Model (EGM) or the EPRI stroke attraction model while Sigma-Slp uses a Monte Carlo statistical method in combination with the EGM to determine strike points on the line. Both programs are capable of modelling the application of line surge arresters.

In this paper, single and statistical stroke analyses were made with different amplitudes of the injected stroke current in order to estimate the flashover performance of the studied transmission line. In this investigation, both shielding failure and backflashover were considered. Detailed sensitivity analysis studies were carried out to determine the relationship between the flashover rate and the parameters influencing it; such as tower footing resistance, ground flash density and front time of the lightning impulse. The overvoltage magnitude and impulse shape on the struck phase conductor is computed for both the shielding failure and backflashover cases.

To improve the lightning performance of the line, the application of metal oxide surge arrester was studied using different arrester configurations and locations. The computed results indicate that arresters installed on the top phase of each circuit give the most significant improvement in lightning performance when combined with low tower footing resistance. Optimised locations of surge arresters were then derived for practical applications.

II. SIMULATED LINE DATA

A 35km long, 275kV double circuit line with 300m span length was selected in this study. The height of the steel-lattice towers of the line is assumed to be 36.88m. The surge impedance of the tower was calculated to be 173.1Ω using (1) [2, 5].

\[
Z_T = 60 \ln \cot \left[ 0.5 \tan^{-1} \left( \frac{r_{\text{avg}}}{h_1 + h_2} \right) \right]
\]

(1)

where, \( r_{\text{avg}} \) is the weighted average tower radius given by (2).

\[
r_{\text{avg}} = \frac{r_1 h_2 + r_2 (h_1 + h_2) + r_3 h_1}{(h_1 + h_2)}
\]

(2)

where, \( r_1, r_2 \) and \( r_3 \) are the radii at the top, midsection and base of the tower respectively, and \( h_1 \) and \( h_2 \) are the tower heights from base to midsection and missection to the tower top respectively.

The line is assumed to be located on flat terrain with a ground flat density of 0.5 flashes per kilometre square per year (fl/km²/yr). It is also assumed that there is no nearby object present to cause an induced voltage flashover on the line.

The phase conductors were twin 175mm² ‘Lynx’ type ACSR conductors with a bundle spacing of 30.48cm and a single Lynx ACSR conductor was used for earthwire. The individual conductors have a 19.53mm diameter. The phase and earth conductors were assumed to have a 7.05m and 6.66m mid-span sag respectively. The Tower structure and conductor geometry are shown in Fig. 1.
The line insulator strings are composed of 16 individual glass insulator discs having 170mm spacing and each disc has a creepage distance of 540mm which is equivalent to a total string length of 3.31m (including the length of the fittings at top and bottom of the string). The calculated critical flashover voltage (CFO) of the insulator string is 1646kV.

To study the lightning performance of the line with surge arresters, metal oxide arresters with a nominal discharge current of 10kA, a Maximum Continuous Operating Voltage (MCOV) of 220kV and an energy capability of 7.8kJ/kV were used. The voltage-current characteristic of the arrester used in this work is shown in Fig. 2.

III. LINE MODELLING TECHNIQUES

The details of the transmission line modelling in the software are as follows:

The line consists of 116 spans with each span represented as a multiphase untransposed distributed parameter line section. To avoid reflections on the line, a sufficiently long section is added to each side of the studied line. At line ends, Sigma-Slp connects coupling matrices while TFlash adds matching impedances in order to avoid reflections. Each simulated span section is further divided into shorter sections to enable stroke simulation at a number of points along the span.

In TFlash, the tower is modelled as a simple transmission line with constant surge impedance, and terminated with a footing resistance. In Sigma-Slp, the tower is modelled by a propagation element model represented by the tower surge impedance and its propagation length. The propagation length is equal to the height of the tower.

A non-linear footing resistance, as derived by Weck [2] and given in (3), is used in both programs

\[ R_f = \frac{R_0}{1 + \frac{I}{I_g}} \]

(3)

where, \( R_0 \) is the low-current tower footing resistance, \( \rho \) is the soil resistivity, \( I \) is the stroke current through the tower footing and, \( E_0 \) the soil ionisation threshold [400kV/m].

In TFlash, the Disruptive Effect (DE) method [6] is used as the default insulator flashover model whereas Sigma-Slp, uses a leader progression method. The DE method defines the disruptive index by

\[ DE = \int \left[ V(t) - A \right]^{B} dt \]

(5)

where, \( V(t) \) is instantaneous value of the impulse voltage, and \( A \) and \( B \) are constants; \( A \) represents the minimum voltage below which breakdown cannot occur and \( B \) is a coefficient indicating that the breakdown process is not linear. When the disruptive index, DE, reaches a critical value, breakdown would occur.

The leader progression method [2] is represented by

\[ V_l = 170 \left[ \frac{u(t)}{d - l_l} - E_0 \right] e^{0.0015 \frac{u(t)}{d}} \]

(6)

where, \( V_l \) is the leader velocity, \( d \) the gap distance, \( l_l \) the leader length, \( u(t) \) the applied voltage and, \( E_0 \) the voltage gradient (520kV/m).

The power frequency voltage may influence the insulator flashover. This influence is taken into account by calculating the voltage across the insulators through a 360° phase cycle, and the flashover rate is determined using its average.

The effect of corona coupling in the line is considered in TFlash while it is ignored in Sigma-Slp.
The EGM is used to determine the strike point on the line. In this investigation, more than 20000 stokes are used for the electromagnetic simulations. The conductor and earth striking distance used in the software are given by [2, 7]

\[ R_s = 10I^{0.65} \quad (7) \]

\[ R_e = \begin{cases} 3.6 + 1.7 \ln(43 - h) & \text{for } h < 40 \text{ m} \\ 5.5I^{0.65} & \text{for } h > 40 \text{ m} \end{cases} \quad (8) \]

where, \( R_s \) is the striking distance to a line conductor, \( R_e \) is the striking distance to earth, \( I \) is the lightning impulse current magnitude and, \( h \) is the height of the tower.

II. SINGLE STROKE ANALYSIS

For the single stroke studies, the overvoltage magnitude and impulse shape on the phase conductor during shielding failure and backflashover are computed. A 32kA, 2/75 impulse current is applied to phase conductor \( A_1 \) at the tower position to simulate a shielding failure flashover on the line. A low current tower footing resistance of 10Ω and 200 Ωm soil resistivity were assumed. Fig. 3a shows typical impulse voltage on the phase conductor. As can be seen in the figure, similar voltage impulse magnitudes were obtained with the two models. However, close examination of the results reveals that the TFlash model predicts a slightly higher overvoltage magnitude and a faster initial rise time compared with the Sigma-Slp model. For the backflashover studies, a 200kA lightning impulse was injected on to the shield wire at a tower position. A low current tower footing resistance of 80Ω and a soil resistivity of 1600Ωm were adopted, which allow backflashover to be initiated. Fig. 3b shows a typical impulse shape of overvoltage computed on the phase conductor during backflashover. Here again, we can observe that the results obtained with TFlash model indicate slightly higher magnitudes of overvoltage and faster rise times compared with the Sigma-Slp model.

III. STATISTICAL ANALYSIS

Statistical flashover analysis of the studied line is carried out to assess the risk of flashover considering the random behaviour of lightning. The flashover rate (number of flashes per 100km per year) is used as the basic parameter in the sensitivity analysis, and the performance of the line is analysed with different arrester configurations.

The programs used in this investigation (Sigma-Slp and TFlash) use slightly different approaches for simulating random behaviour of lightning. In TFlash, random lightning strokes are generated with magnitudes between 1.2 and 161.1kA and with rise times in the range between 1.2 and 4.38 μs. A fixed half time of 75 μs is assumed. The impulse shape varies randomly, with a sample size of 2000. In TFlash, however, the stroke current range can be selected from 1kA to 300kA, and the range is divided up to 512 current ‘bins’. In order to match the two models, as closely as possible, 32 stroke current beans and a current range from 2.5kA to 160kA were selected.

Fig. 3. Overvoltage magnitude and shape on phase conductor \( A_1 \) computed using TFlash & Sigma-Slp.

In the TFlash model, the selected lightning current impulse shape was used for the entire statistical calculation without any variation. Again, for close matching of the two models, simulations were carried out with a 2/75 lightning impulse.

A. Sensitivity Analysis

Sensitivity analysis studies were carried out to determine the relationship between the flashover rate and the parameters influencing it, such as tower footing resistance, ground flash density (GFD) and front time of the lightning impulse.

(i) Effect of footing resistance

It was found that the shielding failure flashover rate (SFFR) is not affected by footing resistance and a constant SFFR of 0.7 and 0.63 fl/100km/yr was obtained in TFlash and Sigma-Slp respectively. Fig. 4a illustrates the effect of footing resistance on the backflashover rate. As can be seen in the figure, the backflashover rate (BFR) evaluated by Sigma-Slp, for a given value of footing resistance is higher than that computed by TFlash.

(ii) Effect of ground flash density (GFD)

The effect of GFD on SFFR is shown in Fig. 4b. As can be seen, the SFFR calculated using the Sigma-Slp model is lower than the SFFR computed using the TFlash model. The difference may be attributed to the different stroke statistics patterns of the two models. In the TFlash model, 45% to 50% of the current bins are in the low-current range.
which is more likely to result in shielding failures. On the other hand, in the Sigma-Slp model, only 10% to 15% of the total number of strokes are likely to hit the phase conductor as a result of shielding failure. Therefore, the majority of strokes in the Sigma-Slp simulations hit the shield wire or the tower top resulting in higher backflashover rates.

(iii) Effect of impulse shape
The computed effect of lightning impulse shape on the line flashover rate is shown in Fig. 4c. Only results from the TFlash model were shown since it is possible to vary the impulse front time in this case. From Fig. 4c, it can be seen that, for fast front times (< 2µs), the BFR increases as the front time decreases. The simulations show that SFFR is not influenced by variations in the front time; a constant value of 0.7 fl/100km/yr is obtained.

B. Flashover Performance of the Line with Surge Arresters
The objective of this study was to estimate the improvement in flashover rate by implementing surge arresters on the line. Different arrester configurations and locations were analysed and compared to assess improvements in lightning performance of the line. In these studies, low current tower footing resistance value was varied from 10Ω to 80Ω keeping the ratio of soil resistivity to footing resistance constant (ρ/R₀ = 20). An initial study was carried out with arresters positioned at every tower and on every phase conductor. This resulted in a zero flashover rate, but, practically the configuration would be too expensive.

It is well known [8] that, in the low current range, the lightning strikes hit only the top phase conductors of the two circuits during shielding failure. This suggests that the majority of shielding failures for this tower design would occur on the top phases. Table I shows typical results of an electrogeometric model (EGM) study obtained with Sigma-Slp and Fig. 5 shows an example of graphical display of lightning strokes hitting the line for different current magnitudes, which were obtained with TFlash. Based on these studies, four practical different arrester configurations were studied, and are shown in Table II. In the table, the black spots on the phases represent the application of an arrester on that phase.

As can be seen in the table, the Sigma-Slp modelling shows that the application of arresters substantially improves the flashover rate. By placing arresters on the top phases only, a zero SFFR is obtained. However, this arrangement only suppresses backflashover under low footing resistance conditions. On the other hand, with arresters installed on the bottom phases only, a zero backflashover rate is obtained at expense of shielding failure. When arresters are installed on the top and bottom phases, both shielding and backflashover failure can be suppressed. Therefore, to improve the lightning performance, it is recommended to install arresters only in the top phases at towers with low footing resistance and in the top and bottom phases at towers with high footing resistance.

<table>
<thead>
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<th>EGM REPORT IN SIGMA-SLP</th>
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Fig. 4. Sensitivity analysis

Fig. 5. Stroke view at different current magnitude in TFlash
Table III shows the results obtained with the TFlash model, which agree with the previous findings. The SFFR obtained in this case is slightly higher while the BFR lower.

**TABLE II**

<table>
<thead>
<tr>
<th>Footing Resistance (Ω)</th>
<th>Shielding Failure Flashover Rate (fl/100km/yr)</th>
<th>Backflashover Rate (fl/100km/yr)</th>
<th>Total Flashover Rate (fl/100km/yr)</th>
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<tr>
<td>80</td>
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• mark indicates surge arrester in the phase

VI. CONCLUSION

Two similar models of transmission line were studied using Sigma-Slp and TFlash software packages. Satisfactory agreement is given by the two models. It was shown that the lightning performance of overhead transmission lines can be improved by applying surge arresters. Arresters on the top phases improve shielding failure flashover rate, and when applied to the bottom phases they allow improvement of backflashover rate. Adequate selection of the arrester configuration in the line can significantly improve lightning performance and may reduce the financial burden.

REFERENCES