Including Surge Arresters in the Lightning Performance Analysis of 132kV Transmission Line

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Abstract—Line arresters are considered as an effective way to improve the lightning performance of transmission lines, especially in parts of line that suffer from high soil resistivity and lightning ground flash density. This paper presents results of the application of line surge arresters on the 132kV double circuit transmission line in EMTP-RV and all the practical scenarios for installation of surge arresters. The study has shown that a significant level of improvement can be reached by installing arresters at all or only some of the line phases. It can increase the strength of the line to withstand lightning currents up to \(-292\text{kA}\). The probability of having this lightning current is practically zero.

Index Terms—Surge Arrester, Backflashover, Lightning Overvoltage, Volt-time model, EMTP-RV

I. INTRODUCTION

Power equipment failure can incur huge financial losses to the transmission companies and it has necessitated the need for paying attention to these widely exposed lines which are subject to vast variety of faults. One of the most frequent issues occurring at the transmission lines are outages caused by the lightning strikes [1]. These outages can be decreased by the proper insulation design and the design of varied devices hinges on lightning overvoltage in the network [2].

To decrease the outage rate due to the lightning, many methods have been proposed such as tower footing resistance reduction, increase of line insulation level, installation of additional ground and guy wires, addition of under-built ground wires, etc. Limited effect or being expensive or difficult to use, are some of the reasons that make some of them impractical [3].

Thanks to the development of polymer-housed metal-Oxide surge arresters, it became practical to use arresters to control line lightning performance, with reasonable price and without tower structure reinforcement [4].

Authors in [5] have investigated the effectiveness of external and internal surge arresters on 500kV DC gas insulated lines. In [6] also it has been shown that the surge arresters are effective in controlling the switching overvoltages. The authors in [7] have investigated the surge arrester application for 750kV transmission lines and have obtained the right size. To assess the effectiveness of surge arresters, a probabilistic approach has been adopted by [8] to estimate the failure risk of such surge arresters.

This paper presents results of the application of transmission line surge arresters on the 132kV double circuit transmission line with using accurate models of line components in EMTP-RV environment.

At first, a brief description of test line has been presented and then, models used for modeling lightning source, tower and transmission line, tower footing resistance, insulator gap and surge arrester in EMTP-RV have been introduced and their parameters have been calculated and finally simulation results and their characterization and conclusion have been presented.

II. BRIEF DESCRIPTION OF TEST LINE

Arvandkenar-Abadan 132kV double circuit is a transmission line located in Iran which has been used as a case study. The complete transmission line information is tabulated in table I. Fig. 1 shows tower structure, phase and shield wire configuration.

III. MODELING

A. Lightning current source model

In order to calculate lightning outage rate, the probability of exceeding stroke of current, \(I\), is needed. This probability distribution function can approximately be computed from (2) [9].
In this paper, double exponential formula which is provided in (3) has been employed to model the current source [10].

\[
P_i = \frac{1}{1 + \left(\frac{1}{31}\right)^{2.6}} \tag{2}
\]

(2)

In this paper, double exponential formula which is provided in (3) has been employed to model the current source [10].

\[
i(t) = 1.04I_m \left( e^{-\frac{t}{T_1}} - e^{-\frac{t}{T_2}} \right) \tag{3}
\]

\[
T_1 = 1.36543T_R \tag{4}
\]

\[
T_2 = \frac{T_1}{2.282835} \tag{5}
\]

Where \(T_1\) is “rise time” and \(T_R\) is “tail time”.

Indeed, as the positive polarity lightning stroke is nearly 5% of all strokes, it is neglected in this work. Moreover, the impedance of the lightning discharge channel is assumed to be 400Ω.

### TABLE I
TRANSMISSION LINE DATA

<table>
<thead>
<tr>
<th>General Data</th>
<th>Shield Wire Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Level</td>
<td>132 kV</td>
</tr>
<tr>
<td>Line Length</td>
<td>53 km</td>
</tr>
<tr>
<td>Location</td>
<td>Mahshahr, Iran</td>
</tr>
<tr>
<td>Number of Thunderstorms</td>
<td>15.2 day in year</td>
</tr>
<tr>
<td>Cross Section Area</td>
<td>39.46mm²</td>
</tr>
<tr>
<td>DC Resistance</td>
<td>2.9 Ω/Km</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Conductor Data</th>
<th>Tower Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Hawk</td>
</tr>
<tr>
<td>Number of Bundles</td>
<td>2</td>
</tr>
<tr>
<td>Bundle Spacing</td>
<td>45.7 cm</td>
</tr>
<tr>
<td>Diameter</td>
<td>21.8 mm</td>
</tr>
<tr>
<td>Total Area</td>
<td>281.03 mm²</td>
</tr>
<tr>
<td>DC Resistance</td>
<td>0.1199 Ω/Km</td>
</tr>
</tbody>
</table>

| Insulator Gap Length | 1350nm
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Resistivity</td>
<td>100-150 Ω.meter</td>
</tr>
<tr>
<td>Lightning Discharge Path Impedance</td>
<td>400Ω</td>
</tr>
</tbody>
</table>

B. Tower and Transmission line model

Double circuit transmission line is modeled with frequency-dependent model in EMTP-RV. Phase coupling is considered in this model. Multistory model [11] is used for tower model. It is multistoried as shown in Fig. 2. Tower surge impedance is calculated from CIGRE recommended equation (6) and then because of similar structure of HS2-10” vertical tower and [11], the same ratio has been chosen for dividing surge impedance between upper and lower halves.

\[
Z_{surge} = 60\ln[\cot(0.5\tan^{-1}\left(\frac{R}{h}\right))] \tag{6}
\]

Where

\[
R = r_1 h_2 + r_2 h + r_3 h_1 \tag{7}
\]

\[
h = h_1 + h_2
\]

Height and radius has been shown in Fig. 3. Calculated tower model parameters and their formulas have been listed in Table II.

C. Tower footing resistance model

Several methods have been proposed to calculate the tower footing resistance while there are fast transient surges which can ionize the soil and change the resistance. However, one of the most simple and practical approaches which takes the surges considerations into account is provided by CIGRE [9].
TABLE II.
MULTISTORY TOWER MODEL PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_{s\text{urge}}$</td>
<td>179.2</td>
</tr>
<tr>
<td>$Z_{1}$</td>
<td>$Z_{2}$</td>
</tr>
<tr>
<td>$Z_{21}$</td>
<td>$Z_{22}$</td>
</tr>
<tr>
<td>$v_{21}$</td>
<td>$v_{22}$</td>
</tr>
<tr>
<td>$v = 300$</td>
<td>[Ω]</td>
</tr>
<tr>
<td>$\gamma = 0.8944$</td>
<td>[μs]</td>
</tr>
<tr>
<td>$\tau = 2H/v = 0.28$</td>
<td>[μs]</td>
</tr>
<tr>
<td>$r_{1} = -(2 \times Z_{1} \times \ln \gamma)/(h_{1} + h_{2} + h_{3})$</td>
<td>[Ω/m]</td>
</tr>
<tr>
<td>$r_{2} = -(2 \times Z_{24} \times \ln \gamma)/h_{4}$</td>
<td>[Ω/m]</td>
</tr>
<tr>
<td>$R_{1} = r_{1} \times h_{1}$</td>
<td>[Ω]</td>
</tr>
<tr>
<td>$R_{2} = r_{2} \times h_{2}$</td>
<td>[Ω]</td>
</tr>
<tr>
<td>$R_{3} = r_{2} \times h_{3}$</td>
<td>[Ω]</td>
</tr>
<tr>
<td>$R_{4} = R_{4} \times \tau$</td>
<td>[μH]</td>
</tr>
<tr>
<td>$L_{1} = R_{1} \times \tau$</td>
<td>[μH]</td>
</tr>
<tr>
<td>$L_{2} = R_{2} \times \tau$</td>
<td>[μH]</td>
</tr>
<tr>
<td>$L_{3} = R_{3} \times \tau$</td>
<td>[μH]</td>
</tr>
<tr>
<td>$L_{4} = R_{4} \times \tau$</td>
<td>[μH]</td>
</tr>
</tbody>
</table>

According to this method the tower footing resistance could be calculated from (8).

$$R_{F} = \frac{R_{0}}{\sqrt{1 + \frac{I}{I_{g}}}}$$

(8)

Where: $R_{0}$: Tower footing resistance at low current and low frequency (ohm), $I_{g}$: Limiting current initiating soil ionization (kA) which can be calculated by (9):

$$I_{g} = \frac{1}{2\pi} \times \frac{E_{0} \times \rho}{R_{0}^{2}}$$

(9)

Where $\rho$ is soil resistivity (ohm-meter), and $E_{0}$ is soil ionization gradient (about 400 kV/m).

D. Backflashover model

In volt-time model [9], it is assumed that Backflashover occurs when tower voltage is higher than lightning impulse withstand voltage or Basic insulation level (BIL) of the insulator strings. The lightning impulse withstand voltage of the insulator string, is not a unique number. The insulator string may withstand a high magnitude impulse voltage with short duration while it fails to withstand a lower magnitude impulse voltage with longer duration. A simplified expression of withstand voltage capability for an insulator string can be calculated as in (10):

$$V_{f0} = K_{1} + K_{2} \frac{t^{0.75}}{L}$$

(10)

Where $V_{f0}$ = flashover voltage (kV),

$K_{1} = 400*L$

$K_{2} = 710*L$

$L = \text{insulator length (m)}$

$t = \text{elapsed time after lightning stroke, \mu s.}$

Fig. 4 shows the V-t relationship of a sample insulator.

E. surge arrester model

Metal Oxide surge arresters protect power equipment insulation from system overvoltage. These arresters have high resistance at the normal system operation but when facing system overvoltage, they will show low resistance. There are several models proposed in literature to describe this nonlinear behavior but in this study IEEE frequency dependent model [13] has been chosen because of its enough accuracy for lightning studies.

Fig. 5 IEEE frequency dependent model

The inductance $L_{0}$ in the model represents the inductance associated with magnetic fields near the arrester. The resistor $R_{0}$ is used to stabilize the numerical integration in the software. The capacitance $C$ represents the terminal-to-terminal capacitance of the arrester.

The inductance $L_{1}$ and the resistance $R_{1}$ make a filter between the two nonlinear resistances.

For slow-front surges, this R-L filter has very little impedance and the two non-linear sections of the model are in parallel. For fast-front surges the impedance of the R-L filter becomes more significant. This results in more current in the non-linear section named $A_{0}$ than in the section named $A_{1}$.

$$L_{i} = 15 \left( \frac{d}{n} \right) \mu H$$

(11)

$$R_{i} = 65 \left( \frac{d}{n} \right) \Omega$$

(12)
\[ L_0 = 0.2 \left( \frac{d}{n} \right) \mu \text{H} \]  
\[ R_0 = 100 \left( \frac{d}{n} \right) \Omega \]  
\[ C = 100 \left( \frac{n}{d} \right) p\text{F} \]

Where \( d \) is the estimated height of the arrester in meters (from catalog data) and \( n \) is the number of parallel columns of metal oxide in the arrester.

The non-linear V-I characteristics \( A_0 \) and \( A_1 \) can be estimated from per unitized curves given in Figure 6.
For $A_b$ in Fig. 6,
\[ \text{Discharge,} \, KV = \left[ \text{Relative IR in p. u. for} \, A_b(t) \right] \times \frac{V_{10}}{1.6} \]
Likewise for $A_1$, the
\[ \text{Discharge,} \, KV = \left[ \text{Relative IR in p. u. for} \, A_1(t) \right] \times \frac{V_{10}}{1.6} \]
Where $V_{10}$ is discharge voltage for 10kA current with 8/20 μs waveshape per kV. Table III shows line arrester specification used for this simulation.

<table>
<thead>
<tr>
<th>TABLE III SIEMENS 3EL5 108-0LK23 SPECIFICATION [12]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height(d)</td>
</tr>
<tr>
<td>Parallel column(n)</td>
</tr>
<tr>
<td>Maximum value of Residual voltage at discharge current 8/20 μs and 10 kA(V_{10})</td>
</tr>
<tr>
<td>Maximum value of Residual voltage at discharge current 30/60 μs and 2kA</td>
</tr>
<tr>
<td>Maximum Continuous Operation Voltage</td>
</tr>
</tbody>
</table>

IV. SIMULATION AND RESULTS

Simulation has been done with accurate modeling of components in EMTP-RV software. Fig. 7 shows the schematic of test line. Fig. 8 shows the induced voltage on insulator without surge arrester for standard lightning current of -100 kA that as it can be observed, flashover occurs across insulator. Fig. 9 shows the same situation for insulator but with surge arrester installed at the upper phase. For installation of surge arresters a comprehensive plan must be studied to consider all scenarios. Fig. 10 illustrates all the different practical scenarios for installation of insulators. Scenarios with the same number of surge arrester per tower have been compared in Figs. 11-15. Finally, in Fig. 16 lightning current causing flashover in all scenarios, have been shown graphically.

V. CONCLUSION

According to the simulation results, the standard lightning current of -77kA can cause flashover across insulators of the line without surge arrester. This current results 3.7 line outage per 100km per year, but with installing surge arrester, this line can withstand lightning currents up to -292kA. The probability of having this lightning current, is practically zero.

As shown in Fig. 16, scenarios 1, 4 and 10 are the most efficient among other installation scenarios; as it is shown in Figs. 11-16, inefficient strategies for installing surge arresters can waste a lot of money even with more arresters per tower.

The study has shown that, as expected, a significant level of improvement can be reached by installing arresters at all or only some of the line phases. The improvement of lightning performance can be very significant when arresters are installed at two phases, but even with the installation of a single arrester per tower at the upper phase, a significant reduction of the total flashover rate can be achieved.

REFERENCES