INVESTIGATION OF LOSSY GROUND IN LIGHTNING INDUCED OVERVOLTAGE AT PRESENCE OF SURGE ARRESTER IN CST SOFTWARE

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ABSTRACT

The lightning overvoltage causes flashovers along the overhead lines and insulation failures in power system equipment. It is important to evaluate the lightning to mitigate its effects and improve the reliability of system. This paper focuses on evaluating the effects of the indirect lightning strikes on medium voltage (MV) lines. A 5 km line has been chosen in Electrical Company of Iran to study the lightning induced overvoltage in different conditions. The amplitude and waveforms of the lightning induced voltage are affected by many factors, such as distance between the lightning strike point and the line, soil resistivity, surge arrester spacing, earth resistance and etc. The back-flow strikes are analyzed in this paper. Effects of the earth resistivity and location of the strike on back-flow strikes and wave shape of lightning-induced voltages are studied in CST software. After fitting the induced waveform, the distribution line has been modeled in EMTP-RV software. Overvoltage protection can be basically achieved by limiting the overvoltage at the equipment location such as one nonlinear element (MO surge arrester). The influence of line and lightning parameters on the effectiveness of surge arresters in terms of the reduction of the induced voltage magnitude is analyzed.

1. INTRODUCTION

Lightning over-voltages in distribution networks caused by direct and indirect strikes can damage the system medium- and low-voltage equipment. When lightning strikes the ground (indirect strike) electromagnetic fields caused by lightning may induce over-voltages on system lines and damage the lines' insulations [1].

The lightning strikes' back-flow surges can be generally modeled using one of the following approaches [2]-[4].

1. Physical or gas dynamics' model, these models rely on radius assessment of a small part of the lightning channel and its properties are similar to the surge pulses.
2. Distributed circuit models, that can be consider as an approximation of electromagnetic circuits, consider the lightning discharge as a transient process.
3. Engineering models which describe the spatio-temporal distribution of channel current (or channel charge density) based on the characteristics of the lightning back-flow surge such as base channel current, upward velocity and the channel shape.
4. The most accurate model presented is electromagnetic model, in which the lightning channel is usually approximated by a high-loss thin wire antenna. The model relies on numerical solution of Maxwell's equations to find the current distribution along the channel.

This paper focuses on assessing the effects of the earth resistivity and location of the strike on the induced overvoltage caused by lightning. The ground resistance has a significant influence on the amplitude and polarity of the induced voltage. Initial part of the total line voltage at the far end is strongly influenced by the lossy ground and the polarity is reversed. In perfect conducting ground, the induced voltage at a given point along the line can be approximately assumed to decrease inversely proportional to the distance. The ground resistivity has a major effect on the wave shape and magnitudes of the induced voltages. It affects both the lightning electromagnetic fields and surge propagation along the line. However, its effect depends strongly on the line configuration and the strike location. It causes an increase, a decrease or inversion of polarity of the lightning induced voltages.

The wire is at a height of 11m above a ground. The simulations are conducted for two values of the ground conductivity of 0.001 S/m and 0.01 S/m and a relative permittivity of $\varepsilon_r= 10$. The return strike current has a peak value of 12 kA and a maximum time derivative of 40 kA/μs (typical of subsequent return strike). Strike location is 50 m from the line. The surge arresters are modeled using a V-I non-linear characteristics.

2. PROBLEM MODEL IN CST SOFTWARE

In the electromagnetic model, in order to find the current distribution along the lightning channel, Maxwell's equations are solved numerically. For this purpose, usually the Method of Moments (MoM) and Finite-Difference Time-Domain (FDTD) approach are used. To achieve the desired velocity of back-flow surge which is usually less than the speed of light in free space, the conductor which represents the lightning channel is surrounded by an insulation or loaded by an additional distributed series inductance. The insulation is used only for the lightning current distribution along the channel and the resistance loading is used only to control the attenuation of the back-flow as the altitude increases[2].

2.1. Lightning channel model

Electromagnetic models of lightning channel are divided into four categories shown in Fig. 1 [2]. A resistance wire, a fully conductive wire surrounded by an insulating environment, a wire in the air loaded by the additional series inductance and a fully conductive wire placed in a fully insulated environment. In all four models introduced, the conductor should be stimulated by a current source at the near earth end. This current source models the base flow of lightning channel. The model shown in Fig. 1(c) is adopted in this paper. This model uses a fully conductive metal cylinder that is surrounded by insulation.

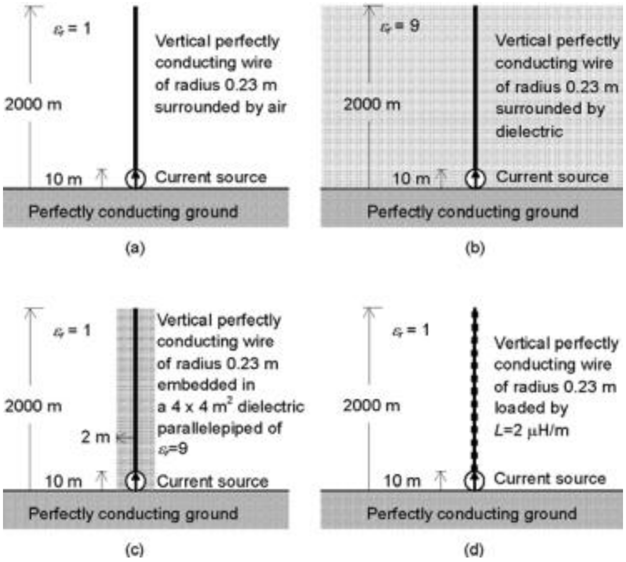

Fig. 1. Electromagnetic models of lightning channel

2.2. Earth model

To find the exact solution, the earth model defined in the software should consider a depth equal to the Earth's skin depth.

2.3. Line model

In this study, the distribution network feeders are three-wire overhead lines. For accurate results, both ends of the line should be connected to a pure ohmic load equal to the characteristic impedance of the network. In the simulations, the pure copper conductors' with radius of 1 cm have been considered.

2.4. Excitation source model

To model the base channel flow in CST software, the equation of the back-flow surge of the basic channels is considered as the sum of two exponential functions. Maximum flow range of the current is 12 kA and the rate of rise of this current is equal to 40 kA/μs [5]. Equation (1) gives the channel current, where n, I_0, τ_1 and τ_2 are considered to be 2, 10.7 kA, 0.25 μs and 2.5 μs, respectively

$$i(0,t) = \left[\frac{I_0}{\eta_1} \frac{\left(t/\tau_{11} \right)^{n_1}}{1 + \left(t/\tau_{11} \right)^{n_1}} \exp\left(-t/\tau_{12} \right) + \frac{I_{02}}{\eta_2} \frac{\left(t/\tau_{21} \right)^{n_2}}{1 + \left(t/\tau_{21} \right)^{n_2}} \exp\left(-t/\tau_{22} \right) \right] u(t) \qquad (1)$$

3. SOIL RESISTANCE MEASUREMENT

The soil resistance changes considering the amount of salt, humidity and temperature. Considering different behaviors of the soil resistance in different frequencies, it is necessary to find the variation of soil resistance with respect to frequency along with the resistance itself in different depths. Standard IEEE81 recommends the Wenner method for determining soil resistance changes with depth.

Given the dependence of induced voltage caused by lightning to the ground conductivity, the soil resistance has been measured by the experts in different areas of Hormozgan regional electricity distribution company. Table 2 shows the results in some areas.

Table 2.Measured values of soil resistivity (Ωm) in different areas

Station No.	1	2	3	4	5	6	7
Soil resistivity	115	593	537	327	103	859	749

4. SINGLE LINE DIAGRAM OF THE SELECTED FEEDER IN HORMOZGAN

Fig. 2 shows the single line diagram of a part of selected feeder. This figure also shows the selected location for lightning strikes. Location 1 is selected here due to relatively tall trees located 50 meters away from the distribution line. Location 2 is selected due to presence of high mountains located 70 meters away perpendicular to the distribution line.

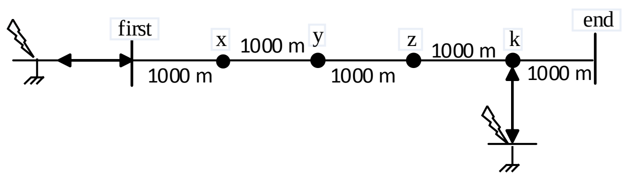

Fig. 2. Single line diagram of a part of the selected feeder

The total length of 5000 m of the selected feeder is studied. Three points X, Y, Z and point k, located in 1000, 2000, 3000 and 4000 m away from the sending end of the feeder, are selected to record the lightning overvoltage induced. The velocity of the back-flow surge of lightning is 1.1×10^{8} m/s [3, 4]. The characteristic impedance of the overhead lines is 450 ohms [7].
Since the selected feeder is relatively long and solving the electromagnetic equations requires a long time and a large memory, in the simulations, the system is shrunk to a smaller system using the scaling technique.

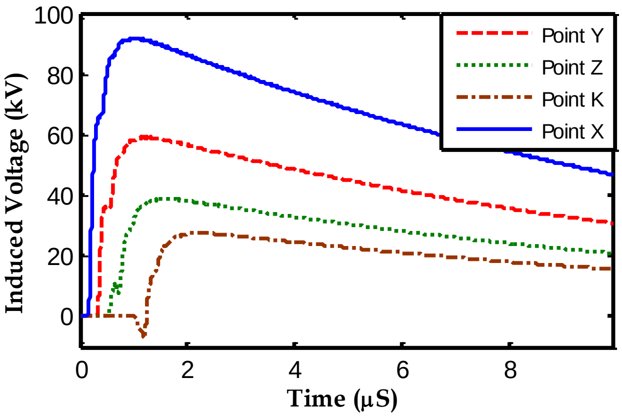

Fig. 3. Induced over-voltage in first lightning strike, with earth conductivity of 0.01 S/m

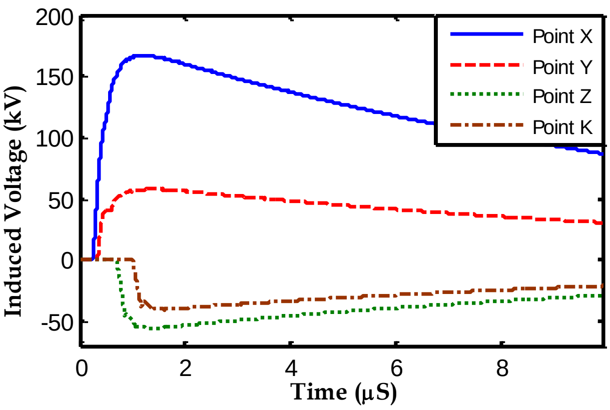

Fig. 4. Induced over-voltage in first lightning strike, with earth conductivity of 0.001 S/m

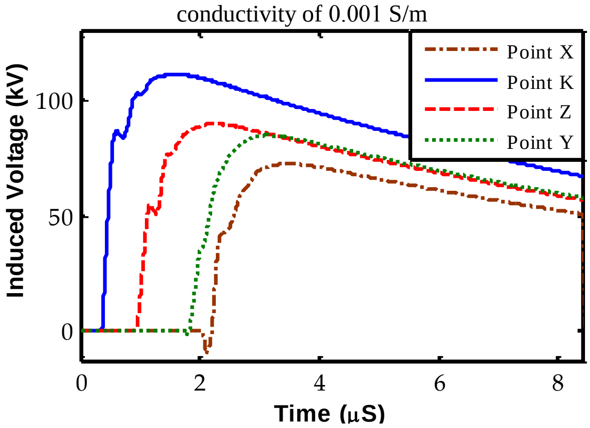

Fig. 5. Induced over-voltage in second lightning strike, with earth conductivity of 0.01 S/m

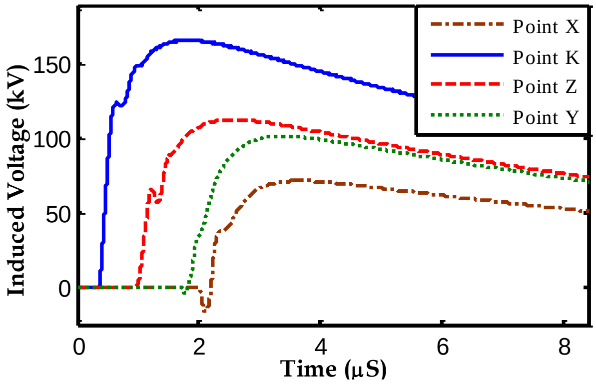

Fig. 6. Induced over-voltage in second lightning strike, with earth conductivity of 0.001 S/m

5. SIMULATION RESULTS OF CST SOFTWARE

Figures (5) to (8) show the induced over-voltages in four points of the line caused by two indirect lightning strikes, one of them in line with the distribution line and the other one perpendicular to the line.
In the simulations of the induced over-voltages caused by the indirect strikes, it was observed that the induced voltage depends on earth conductivity and the distance between lighting strike and line. By reducing the ground conductivity and the distance of a lightning strike to distribution line, the induced over-voltage increases. Though the Earth's skin depth that should be modeled in simulations highly dependents on frequency and conductivity of the earth, here due to the narrow frequency bandwidth, this parameter did not widely affect the results. The earth resistance affects not only the surge polarization but also the induced voltage value. The reflection and refraction coefficients in a non-ideal earth depend on location and frequency and affect the surge polarization. It can be seen that as the strike distance to the line increases the change in the surge polarization is more noticeable.

6. Calculation of the parameters required for simulations using EMTP-RV software

After calculating the induced over-voltages caused by lightning, in order to simulate the behavior of the feeder arresters, EMTP-RV software is used. In order to use Vsurge block in EMTP, the induced over-voltages must be approximated. For this purpose, calculated induced over-voltages are fitted to double exponential functions in form of $V(t)=V_m(\exp(\alpha\cdot t)-\exp(\beta\cdot t))$.
In the case studies, for the over-voltage caused by the first lightning strike at point k, with conductivity of 0.001, the parameters V_m, α, β and shift are calculated and presented in Table (3).

Table (3). Parameters for strike 1 with conductivity 0.001 (S/m)

shift (µs)	β (s^{-1})	α (s^{-1})	V_m (V)
-0.2069e+6	-0.1831e+7	-0.2500e+6	0.2716

6.1. Distribution poles' model

Considering that the distribution poles are usually made of concrete, they are modeled by a series resistor and inductor. The insulators are modeled using the EMTP library models. The poles' model is shown in Fig. 7.

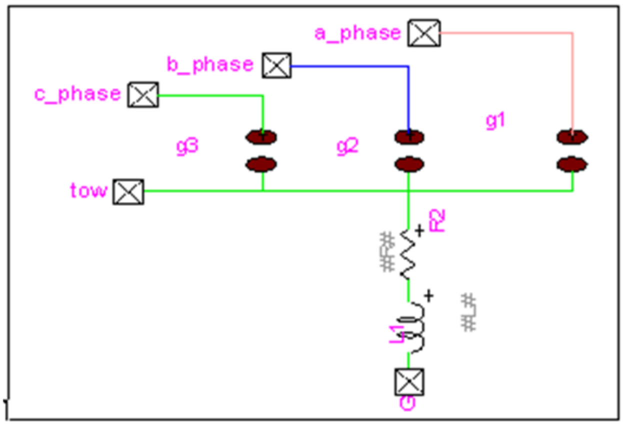

Fig. 7. Distribution poles in EMTP software

6.2. Transient model of the lines

Frequency function model of lines is the most accurate transient model. Combining the distributed model and frequency-dependent model, the transient behavior of the lines can be properly studied. Inductance and resistance of line are estimated as a function of frequency where the skin effect is also considered. Line capacitance is considered to be a fixed in this model.

Lightning covers a wide range of frequencies, so the transformer model that is appropriate for this study is a model in which the effects of resistance, leakage inductance, the nonlinear core and transformer capacitance are included. Fig. 8 shows the schematic of such a model.

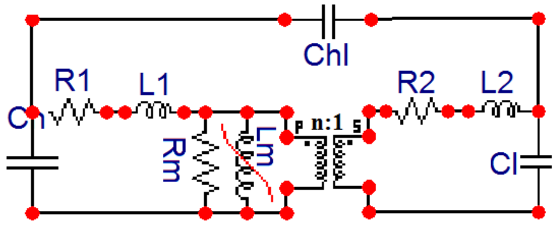

Fig. 8. Transformer model for transient studies

In this model, C_l is the capacitance between the low-voltage coil and the transformer case, C_h is the capacitance between the high-voltage coil and the transformer case and C_{hl} is capacitance between two transformer coils. In general, the transformer capacitances depend on the frequency. Transformer capacitance values can be found using different diagnostic methods such as identification, frequency domain and time domain methods and also using the model order reduction techniques.

The relationship between the oscillation frequency and transformer capacitance is given in (2), where, f is the oscillation frequency, L_T is the leakage inductance of the transformer at the regarding side and C is the capacitance at the regarding side of the transformer.

$$C = \frac{1}{(2\pi f)^2 L_T} \tag{2}$$

The relationship between the capacitances of the transformer equivalent model is provided in (3), where C is the capacitance seen from the transformer low-voltage side. The transformer capacitances usually satisfy (4). Using these relationships and considering the oscillations' frequency, capacitance C_l, C_h and C_{hl} are calculated.

$$C = C_l + C_{hl} \tag{3}$$

$$\frac{C_{hl}}{C_{hl} + C_l} \leq 0.4 \tag{4}$$

6.3. Model of substation surge arrester

Fig. 9 presents the surge arrester model. In this model two nonlinear branches are separated using an RL filter

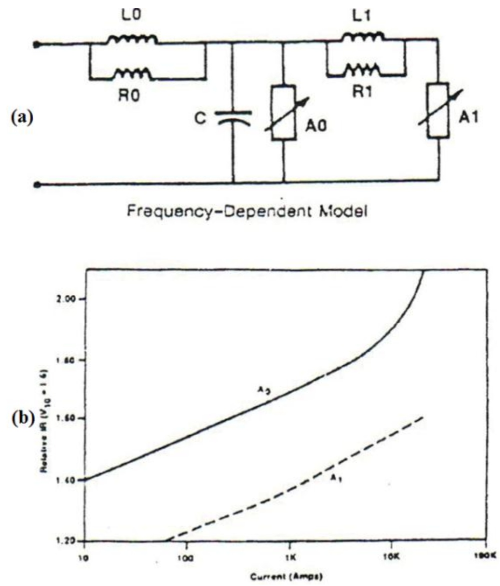

Fig. 9 . (a) IEEE model, (b) the relation between nonlinear branches A0 and A1.

For the waves that it takes a long time that they achieve their maximum, the impedance of the RL filter is too small and then the two branches are paralleled. For the waves that it takes a little time for them to reach the maximum, the RL filter shows a large impedance, branch A1 is omitted and according to the model the arrester voltage increases. The model parameters can be found using (5).

$$R_1 = 65\frac{d}{n}\Omega,\quad R_0 = 100\frac{d}{n}\Omega,\quad c = 100\frac{n}{d}\mu F \tag{5}$$

$$L_1 = 15\frac{d}{n}\mu H,\quad L_0 = 0.2\frac{d}{n}\mu H$$

where d is the height of the surge arrester in meter, n is the number of parallel arrester columns, inductance L_1 is in fact the inductance used to model the surge arresters, L_0 is the inductance regarding the magnetic field near the surge arrester, R_0 is used for stabilizing the solutions and c is the capacitance between the terminals of the arrester. V-I curve of a 20 kV arrester in is shown Fig. 10 .

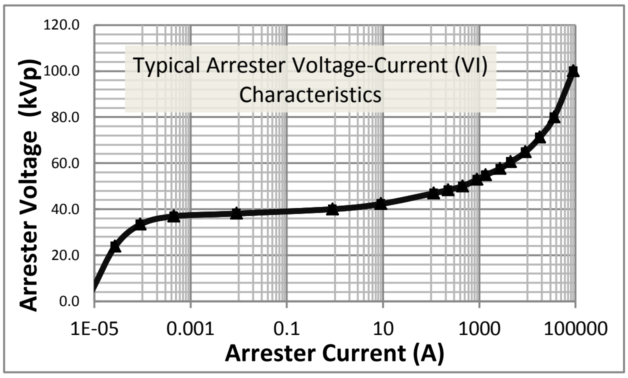

Fig. 10. Voltage-current curve of the system 20 kV arrester

Using the parameters presented in table (3) in EMTP-RV software, it is concluded that if earth wire of surge arrester installed at the input side of distribution station is disconnected or arrester is faulty, the exact same voltage induced in the overhead lines will be applied to transformers' windings. But if an arrester is installed at the primary side of the transformer, it restricts the overvoltage to its residual voltage.

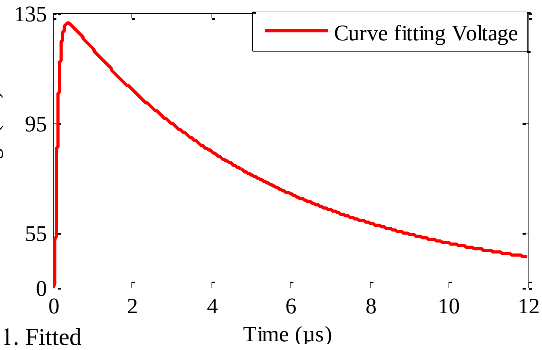

Fig. 11. Fitted induced over-voltage

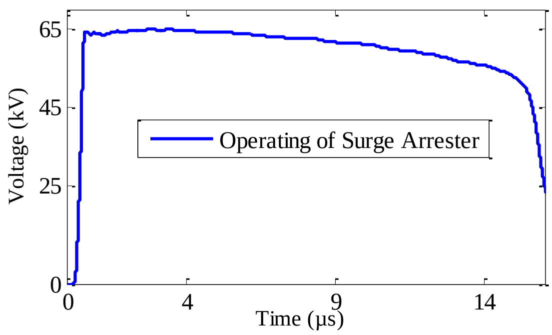

Fig. 12. Residual voltage across the arrester

7. Conclusion

According to field measurements of soil resistivity in different parts of the feeder, simulation within the measured conductivity of the earth in the values of 0.01 and 0.001 were performed using CST software. The results showed that increasing the earth resistance, significantly increases the induced over-voltages which may lead to irreparable damages to the system equipment if the system was left unprotected. By reducing the conductivity of the ground, the induced voltage is substantially increased due to horizontal electric fields. By reducing the distance of a lightning strike from the line has the same effect on the induced voltage.

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