CALCULATION OF LIGHTNING OVERVOLTAGES USING EMTP

Thor Henriksen

Norwegian Electric Power Research Institute (EFI)

N-7034 TRONDHEIM, NORWAY

ABSTRACT

Overvoltages due to a direct stroke can be analysed more or less directly by EMTP, (although the preparation of input data can be quite time consuming unless a suitable preprocessor is used).

Induced lightning overvoltages represent a greater challenge due to the induced field which varies along the line. The paper demonstrates that the horizontal component of the induced field can be taken into account by adding a contribution to the incoming wave at each end of the line exposed to the induced field. A special technique is then presented which makes it possible to include induced overvoltages in an EMTP calculation without modifying the source code.

Calculated examples show that the network connected to the line exposed to the induced field may have a very great influence on the induced overvoltages.

INTRODUCTION

EMTP was originally designed for calculating switching overvoltages but has later been developed into a general program for transient analyses.

No special attention seems to have been made in this development regarding lightning overvoltages, at least not in the program versions which are in the public domain. EMTP can in spite of this be used for calculating overvoltages due to a direct stroke (i.e. a stroke hitting a tower or one of the conductors of an overhead line). Each span is then represented as a distributed parameter line model. Insulator flashovers are of great importance and must be included. This can be done by using TACS controlled switches. The preparation and debugging of the EMTP input file may be quite time consuming, but this job can be substantially reduced by establishing a suitable preprocessor.

Induced overvoltages due to a stroke in the vicinity of a line cannot be analysed directly by EMTP, and the purpose of this paper is to present a method for calculating such overvoltages using EMTP. Induced overvoltages do not effect the performance of lines with high system voltage (above 100 kV). They are however very important when the system voltage is below 40 kV.

MODEL FOR CALCULATING INDUCED OVERVOLTAGES

This problem has been investigated by several authors. Different approaches give different results, but a recent study by Nucci et al [1] has shown that the work done by Agrawal et al [2] gives in general the most accurate results, and the other approaches are more or less equivalent to simplified versions of the model developed by Agrawal et al.

The first step is to calculate the induced electric field caused by the lightning ignoring the transmission line. The voltage along the line is given as the sum of the scattered voltage u^s and the incident voltage u^i.

The following equations are valid for a lossless line [3]:

$$u^i(x,t) = -\int_0^h E_z^i(x,z,t) \cdot dz \qquad (1)$$

$$\frac{\partial u^s(x,t)}{\partial x} + L\frac{\partial i(x,t)}{\partial t} = E_x^i(x,h,t) \qquad (2)$$

$$\frac{\partial i(x,t)}{\partial x} + C\frac{\partial u^s(x,t)}{\partial t} = 0 \qquad (3)$$

where E_z^i is the vertical component of the induced field and E_x^i is the horizontal component along the line.
i is the current along the line, while
L and C are the per unit length inductance and capacitance, respectively.

The induced field can be considered as a known voltage source in eqs. (1) and (2).

Eqs. (2) and (3) correspond to an ordinarily transmission line except for the term E_x^i. E_x^i is often taken into account by concentrating the voltage at discrete points along the line and using "normal" transmission line segments between these points [3]. It will next be shown that this discretization can be avoided:

Figure 1 shows a line which is divided into two parts in order to take the serial source $E_x \cdot \Delta x$ into account.

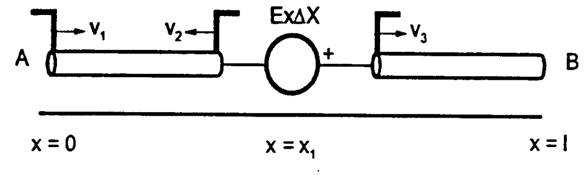


Figure 1: Line with serial voltage source

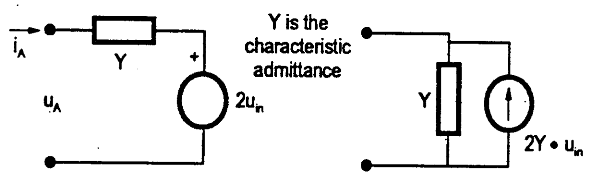
Analyzing the line in Figure 1 shows that a voltage wave transmitted from one end of the line (e.q.V_1) is not influenced by the voltage source as no reflection occurs at $x = x_1$. The voltage source $E_x \cdot \Delta x$ generates two voltage waves v_2 and v_3 as shown in Figure 1. The value of these waves at $x = x_1$ is:

$$-v_2 = v_3 = E_x \cdot \Delta x/2$$

This means that the serial voltage source causes an additional contribution to the incoming voltage wave at each end of the line. A distributed serial voltage source can therefore be taken into account by using an ordinary transmission line model and adding a contribution to the incoming voltage wave at each end of the line.
A mathematical expression for this contribution is given in appendix A.

Figure 2a) shows one end (A) of the equivalent circuit which is normally used in time domain transmission line analyses.

a) Using b) Using



voltage source current source

Figure 2: Equivalent for one end of a transmission line.

u_{in} is the incoming voltage wave transmitted from the other end of the line.

The circuit in Figure 2b) is equivalent, but is more suitable when performing the calculation as in EMTP.

The induced field along the line gives an additional contribution Δu_{in} to u_{in} and can be accounted for by introducing an additional current source at node A equal to $2Y \cdot \Delta u_{in}$. Adding this source gives the correct scattered voltage at node A but an error occurs in the reflected voltage wave which is equal to

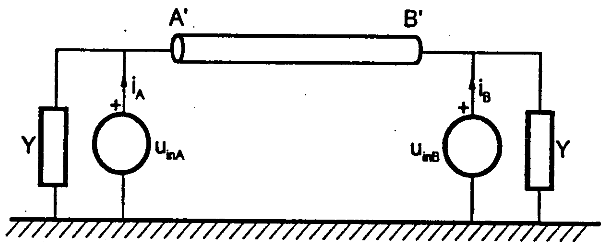
$$u_{refl} = u_A - u_{in}$$

Since Δu_{in} is missing in u_{in} a term $-\Delta u_{in}$ is missing in the reflected wave.

The best solution to this problem is to make a correction of u_{in} before calculating the nodal voltage u_A. Such a correction can in EMTP be done only by modifying the source code. As the source code of updated versions of EMTP/ATP is no more in the public domain an alternative approach is used here:

The missing term in the reflected wave can be compensated for by a current source connected to the other line end, This may give the correct nodal scattered voltage there, but the reflected wave from that node will not be correct and new. correction must be made at the first node. This correction requires a additional correction at the other node and so on. The correction procedure is thus rather complex, but the final result can fortunately be obtained by using the circuit equivalent shown in Figure 3 where i_A' and i_B' equal the current sources to be connected to the original line. The voltage sources in Figure 3 equal the contribution to the incoming voltage wave from the induced electric field without any correction due to reflections.

Figure 3: Circuit used to calculate current sources



representing the induced field along the line.

The line between A' and B' must be identical to the original line.

The transmission line model discussed so far applies to the scattered voltage u^s and the incident voltage must be added in order to get the total voltage at the two ends of the line. This can be done by adding a serial voltage source at each end of the line model.

EMTP IMPLEMENTATION

Figure 4 shows an equivalent which can be used for a line between nodes A and B where one wants to take the induced field into account. The transmission line model between nodes A' and B' is the model which is used when the induced field is ignored.

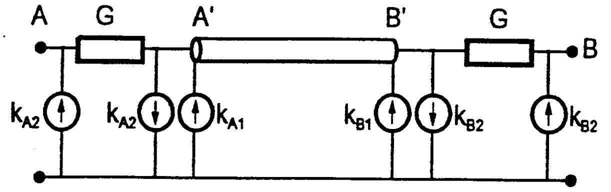


Figure 4: Modification of the line exposed to induced field.

EMTP does not accept serial voltage sources and the sources K_{A2} and K_{B2} and the conductance G are therefore introduced in order to take the incident voltage into account. The conductance G must be large compared to the characteristic admittance of the line. A value equal 10^3 ℧ is suggested since the characteristic admittance is less than 10^{-2} ℧.

The value of G should not be too large since this could result in a near singular system admittance matrix.

The sources K_{A1} and K_{B1} equal the current i_A' and the current i_B' in Figure 3 respectively. The line in Figure 3 must be included in the EMTP time domain network, but without any direct connection to the rest of the network (i.e. no common nodes except ground).

Transferring data from Figur 3 to the sources K_{A1} and K_{B1} causes a delay equal one time step but this can easily be compensated for when assigning values to the voltage sources in Figure 3.

EMTP MODEL VERIFICATION

The proposed method for calculating induced lightning overvoltages has been implemented in EMTP and results have been compared with the ones obtained by an alternative calculation model. The alternative model was developed specially for a lossless line with open ends and the contribution from the induced field along the line was included in the incoming waves before calculating the nodal voltages. Figure 5 shows the line and the stroke location used in the comparison between the two methods.

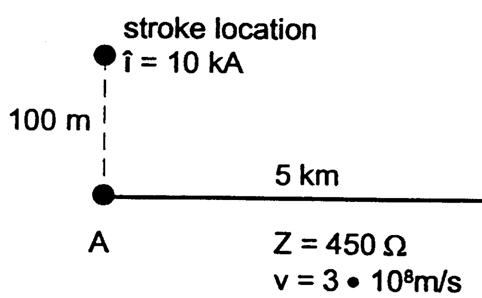


Figure 5: Configuration used for verification calculation.

The induced field was calculated by the formula developed by S. Rusck [4] assuming an infinite length of the lightning channel.

Figure 6 shows the results obtained by EMTP. The results were very close to the ones obtained by the specially developed model. The maximum relative deviation at the peak values in Figure 6 was $3{\cdot}10^{-5}$.

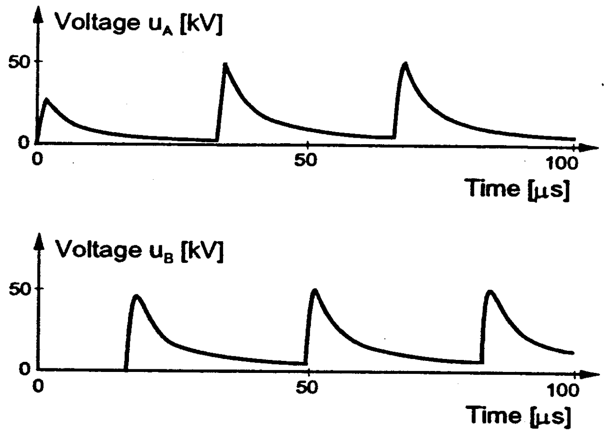


Figure 6: Open end voltage caused by the induced lightning field.

Data from the induced field were transferred to EMTP using type 1-10 sources specified point by point. Five digits were used and this limited accuracy was the main reason for the deviation. An attempt was made where the actual values were replaced by some exponential functions which could be included in EMTP using type 15 sources. The derivation was then reduced to about $3{\cdot}10^{-7}$.

The comparison shows that the EMTP model works satisfactory for an open ended line. This implies that the current sources which compensate for the induced field along the line give correct results. These sources are not influenced by any network connected to the line, and it is therefore reason to believe that the proposed EMTP model works satisfactory even when the line is a part of a greater network.

CALCULATION EXAMPLES

Figure 6 shows the results for a line which is open in both ends. Figure 7 shows how the responses are modified when connecting a cable to node A or B.

Cable data:

Lenght:	1 km
Characteristic impedance:	45 Ω
Velocity:	$1.5 \cdot 10^8$ m/s

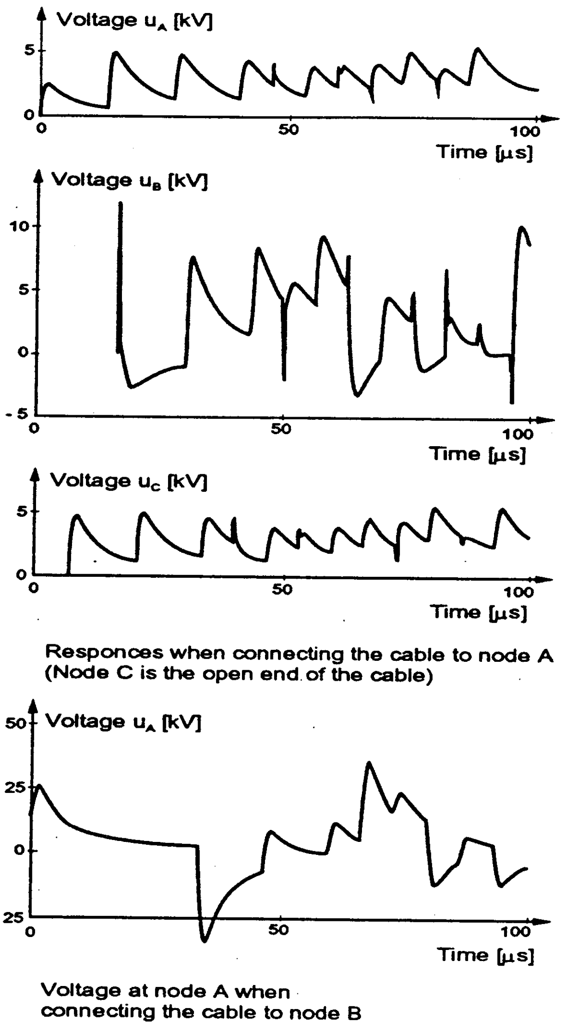


Figure 7: Connecting a cable to the line.

It is evident from Figure 7 that the cable has a very strong influence on the induced overvoltages. It is therefore important to take the complete network into account when analyzing induced lightning overvoltages.

MODEL GENERALIZATION

The description presented in this paper has been limited to a single phase lossless line. There is no principal problem in removing these restrictions. The model used for the coupling between the induced field and the voltage and current along the line is in [2] presented for a multiphase line were losses are taken into account. The calculation of the induced field and its contribution to the incoming voltage wave becomes more complex when losses are considered, but this is more or less in line with problems generally encountered when taking losses into account.

The technique presented here for including the contribution from the induced field in the EMTP model is in principle valid even for a multiphase line where losses are taken into account. The line in Figure 3 is terminated at each end by the characteristic admittance, which in general is frequency dependent. This admittance must be the same as the characteristic admittance used in the model of the line.

CONCLUSION

A method for calculating induced lightning voltages using EMTP has been presented.

The method does not require any modification of the EMTP source code, although this could make the calculation more efficient. Combining the method presented here with the one in [3] would be of great interest in this respect.

A fictitious line is introduced in order to avoid the source code modification and it has been shown that this rather special approach does not cause any numerical problems.

The overvoltages occuring when a line is exposed to an induced field from a lightning stroke is strongly influenced by the network connected to the line. Most software developed for calculating induced lightning overvoltages has serious limitations compared to EMTP when modelling such a network.

REFERENCES

[1] C.A. Nucci, F. Rachidi, M. Ianoz, V. Cooray, C. Mazzetti:
"Coupling models for lightning-induced overvoltage calculations. A comparison and consolidation".
22nd International Conference on Lightning Protection, Budapest, Hungary, September 1994.

[2] A.K. Agrawal, H.J. Price, S.H. Gurbaxani:
"Transient response of a multiconductor transmission line excited by a nonuniform electromagnetic field".
IEEE Trans. on Electromagnetic Compatibility, pp. 119-129, vol. EMC-22. 1980.

[3] C.A. Nucci, R. Iorio, A. Mansoldo, V. Bardazzi, A. Porrino:
"A code for the calculation of lightning-induced overvoltages and its interface with the electromagnetic transient program".
22nd International Conference on Lightning Protection, Budapest, Hungary, September 1994.

[4] S. Rusck:
"Induced lightning overvoltages on power transmission lines with special reference to the overvoltage protection of low voltage networks", Trans. of the Royal Institute of Technology, Stockholm, Sweden, no. 120, 1958.

APPENDIX A

TRANSMISSION LINE WITH DISTRIBUTED SERIAL VOLTAGE SOURCE

The following equation can be obtained in the frequency domain by combining eqs. (1) and (2)

$$\frac{d^2U}{dx^2} + Z \cdot Y \cdot U = \frac{dE_x}{dx} \qquad \text{(A.1)}$$

where Z and Y are the serial impedance and shunt admittance, respectively. (The superscript s of U has been omitted.)

The general solution of (A.1) when $dE_x/dx = 0$ is well known:

$$\begin{aligned} U(x,s) &= A(s) \cdot \exp(-\sqrt{Y \cdot Z} \cdot x) \\ &+ B(s) \cdot \exp(\sqrt{Y \cdot Z} \cdot x) \end{aligned} \qquad \text{(A.2)}$$

It is convenient to use the same solution when $dE_x/dx \neq 0$ except that A and B now are functions of the position x as well. Ref. [A.1] shows how to detemine A(x,s) and B(x,s). The result may be written:

$$\begin{aligned} U(x,s) &= A_1(s) \cdot \exp(-\sqrt{YZ}x) \\ &+ \frac{1}{2} \int_o^x \exp[-\sqrt{YZ}(x-\varsigma)] E_x(\varsigma) \cdot d\varsigma \\ &+ B_1(s) \cdot \exp(-\sqrt{YZ}(l-x)) \\ &- \frac{1}{2} \int_x^l \exp[\sqrt{YZ}(x-\varsigma)] E_x(\varsigma) \cdot d\varsigma \end{aligned} \qquad \text{(A.3)}$$

The solution is written in such a way that $A_1(s)$ equals the reflected wave at x = 0 (i.e. the voltage wave injected into the line). $B_1(s)$ equals the reflected wave at x = l.

Equation (A.3) shows that E_x gives an additional contribution to the incoming voltage wave at each end of the line.

REFERENCE:

[A.1] E. Kreyszig: "Advanced Engineering Mathematics", Section 2.16, Second Edition John Wiley and Sons Inc. New York 1967.