Investigating Lightning-Induced Overvoltages Transmitted to Customer Side

Nehmdoh Sabiha and Matti Lehtonen

Abstract-- **In Finland, the distribution networks are frequently exposed to lightning. Therefore, it is worthy to study the low voltage network response at the customer terminals when the lightning directly or indirectly hits the primary terminals of distribution transformers. In this paper, an accurate and simplified model for the distribution transformer under lightning strokes is used as it has been presented in [1]. The impact of feeder numbers, lengths, types and loads on the lightning reached at the service entrance point is investigated. The high frequency model representation of distribution transformer and low voltage network are combined in a single arrangement in the environment of ATP/EMTP. This study enhances the lightning protection design.**

Keywords- aerial cables, lightning strokes, high frequency model of distribution transformer, ATP/EMTP

I. Introduction

A distribution network is frequently subjected to lightning strokes which hit the primary terminal of the distribution transformer. To investigate the effect of these strokes on the low voltage networks, an accurate model of the transformer is necessary as well as a model of low voltage network to obtain real response in this situation.

There are many high frequency transformer models which aim to study the effect of the lightning strokes on the voltage transferred to the transformer secondary side. However some of these models [2-4] need sophistications to find their parameters, or aren't tested for transferred voltage to the secondary side [5], or need the module of the measured impedance with certain behavior which is not available for all transformers [6], or need more calculations for the parameters evaluation [7], or have large nodal admittance matrix [8]. So, a simple way to model the high frequency transformer with simple circuit is used in this paper.

The transference of surges from medium voltage to low voltage networks is the most frequent among all possible mechanisms of overvoltage generation on consumer loads which also threaten insulation of power distribution lines. So, many studies have been done to investigate the induced overvoltages on the distribution line caused by lightning stroke [9-16]. However, the impact of feeder numbers, lengths, types and loads in low voltage networks have not been considered. Other studies have been done through the observations of lightning induced voltage on distribution lines [17-19].

The transference of surges from medium voltage to low voltage networks may take place according to three main mechanisms: (i) coupling of both circuits through distribution transformers and their connections, (ii) electromagnetic coupling between medium voltage to low voltage conductors if they are installed one above the other, (iii) indirect current injection into the low voltage circuit due to flashovers across medium voltage to low voltage insulators [13].

In this paper an accurate model with a simple circuit for high frequency transformer is used to study the response of the low voltage network due to lightning strokes at the primary terminal of the distribution transformer. The effect of the low voltage network configuration, number of overhead cables, lengths, load and types is investigated through the peak voltage profile along the feeder.

II. High Frequency Transformer Model

A simple high frequency transformer model for unloaded as well as loaded conditions was proposed by the authors to study the response of the low voltage network under lightning strokes hit the primary terminals of the distribution transformer [1]. In this model the transformer frequency response using experimental measurements was investigated in order to find the model parameters. The experimental setup was accomplished to measure the transient features due to impulse signals. Then it was verified concerning two practical distribution transformers with different types and ratings. In this paper, the analysis was carried out on the bigger one is rated 100 kVA.

The transformer model has been presented using a port-type network. There are four types of the port-type networks: impedance parameters, admittance parameters, hybrid parameters and transmission parameters networks. The simplest one is the impedance parameters network as the open circuit tests are needed to compute the network parameters. Therefore, the impedance parameters two-port network was considered to model the transformer as shown in Fig. 1. The transformer model parameters are summarized in Table 1. The details for transformer model evaluation are addressed in [1].

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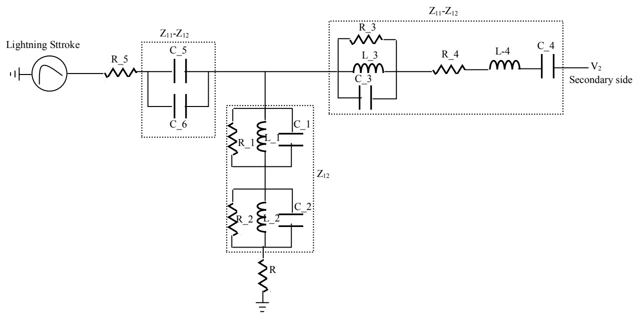


Fig. 1 High Frequency Transformer Model.

Table 1 Transformer model parameters.

Elements	Values	Elements	Values
R_1 (Ω)	500	C_1 (μF)	0.021063
R_2 (Ω)	558.5405	C_2 (μF)	0.00302967
R_3 (Ω)	3822.4695	C_3 (μF)	0.00512
R_4 (Ω)	1E-6	C_4 (μF)	0.00013893
R_5 (Ω)	50 (unloaded)	C_5 (μF)	0.0004221
R (Ω)	3000 (loaded)	C_6 (μF)	0.00019152
L_1 (mH)	0.00856		
L_2 (mH)	0.0046		
L_3 (mH)	0.036897		
L_4 (mH)	0.068493		

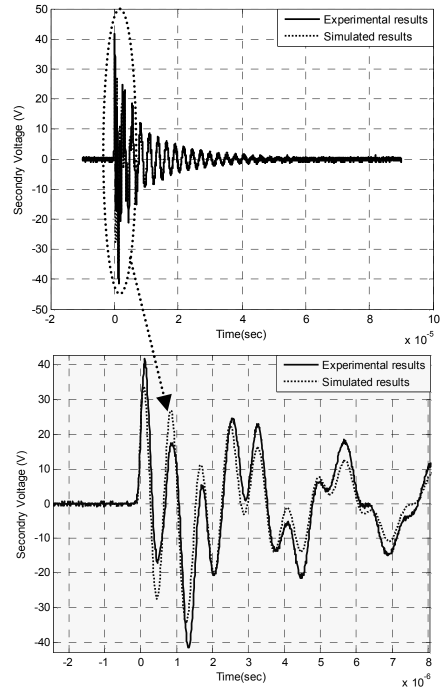
The validation of the proposed high frequency transformer model was achieved by examining of the voltage transferred to the secondary side due to lightning strokes at the primary terminal of the transformer. The comparison between experimental and simulation of the voltage transferred to the secondary side shows a good agreement for unloaded as well as loaded conditions as shown in Fig. 2 for a transformer in our case. During accomplishing experiments, the transformer was directly loaded at the secondary terminals using resistance paralleled with capacitance. The simulations were carried out using ATP/EMTP where the ATPDraw program used as preprocessor [20]. Analysis of the experimental and simulated transferred voltage in frequency domain and extra results can be found in [1].

III. Induced Voltage Profile in Low Voltage Networks

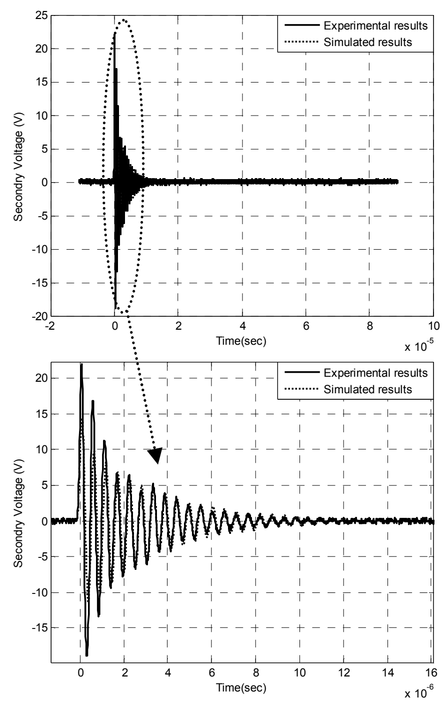
In Finland, the most common low voltage lines are aerial bundled cables where the most common cable types are AMKA 35, AMKA 70, and their multiplies [21]. In this paper, AMKA 3×35+70 cable type is used where its identification is reported in [22]. More details supporting the ATPDraw simulation are illustrated in the Appendix A. The simulation of this cable was carried out using LCC JMarti model.

As shown in Fig. 3, a 350 m feeder is divided to seven subsections with seven different loads where each subsection length equals to 50 m. At the end of each subsection, there is a resistive load which is randomly selected in a range of 1 to 2 kW. For example, the load distribution from point A1 to point G1 is 1, 2, 1.5, 1, 1, 2 and 1.5 kW, respectively.

The ATPDraw network of the distribution transformer shown in Fig. 1 and the network of the overhead cable feeder shown in Fig. 3 are combined in a single arrangement in order to investigate impact of some factors on the lightning overvoltage reached to the customer entrances. This is discussed in the following subsections where input impulse signal to the distribution transformer is 100 kV, 0.87/50 μsec.



(a) Unloaded condition



(b) Balanced loaded condition.

Fig. 2 Time response of voltage transferred to the Secondary side (T1).

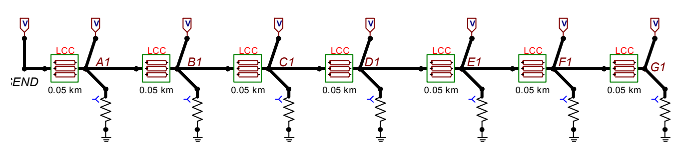
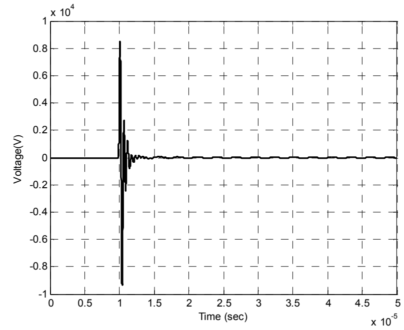
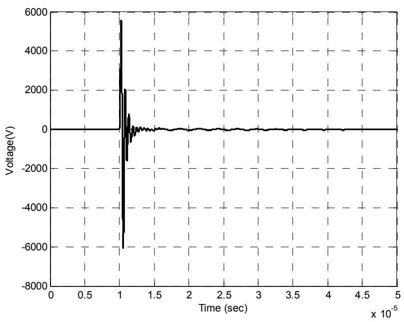


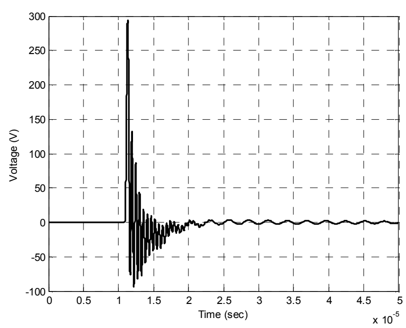
Fig. 3 Overhead cable configuration



a) Voltage at SEND.



b) Voltage at point A1.



c) Voltage at point G1.

Fig. 4 secondary voltage transferred by 350 m feeder.

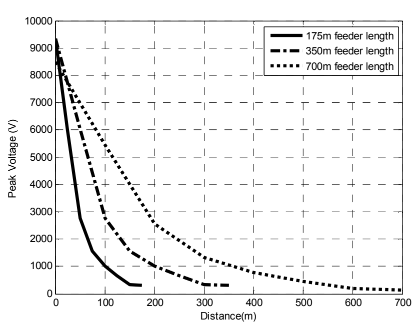


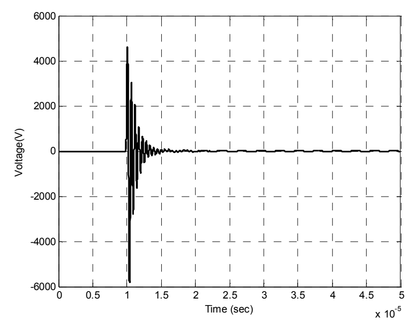
Fig.5 Peak voltage profile along the LV line.

A. *Impact of the Feeder Length*

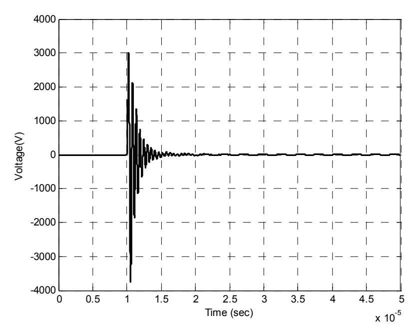
Fig. 4 shows the measured voltages at the beginning of feeder (SEND), at the first load (point A1) and at the last load (point G1). The highest peak is at SEND where its value is 9.3 kV and reduced at A1 to 6 kV. Then the signal peak is more reduced until the feeder end which is 293 V at G1. The corresponding voltage profile is the dot-dash curve shown in Fig. 5. The peak of propagated voltage is reduced when it is measured at longer distance because the attenuating impact is increased for longer distance. To study the feeder length impact, two examples of 700 m (through doubled the subsection length) and 175 m (through halved the subsection length) feeder lengths are considered as shown by dot and solid curves respectively in Fig. 5. The same load is considered. As the feeder total length is increased, as the propagated voltage peak curve is moved up which means that the peak voltage is increased when the feeder length behind the measuring point is increased.

B. *Impact of the Feeder Number*

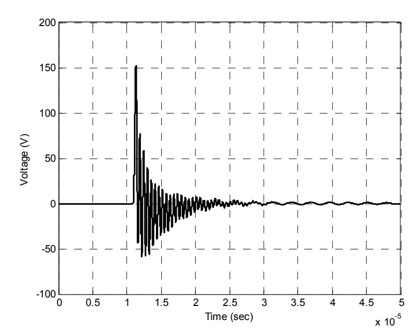
The feeder number is doubled to study the effect of the parallel feeder impact on the consumer side when the lightning strokes hit the primary terminals of the distribution transformer. The corresponding time domain measurements at Points SEND, A1 and G1 are shown in Fig. 6 which is summarized by dash-dot line curve depicted in Fig. 7. By comparing with the voltage profile of a network with a single feeder, the voltage peaks are reduced to their half values. They are further decreased where the number of feeders is increased. The case when the feeder number is seven as depicted by dotted curve shown in Fig. 7 where a number of consumers are forty nine consumers.



a) Voltage at SEND.



b) Voltage at point A1.



c) Voltage at point G1.

Fig. 6 secondary voltage transferred by two 350 m feeders.

C. Impact of Load reduction

When the loads are reduced to their half values concerning networks of one, two and seven identical feeders, the corresponding peak voltage profile along the feeder length are shown in Fig. 8. The peak voltage profile is increased when the loads are reduced that is because the network damping is reduced.

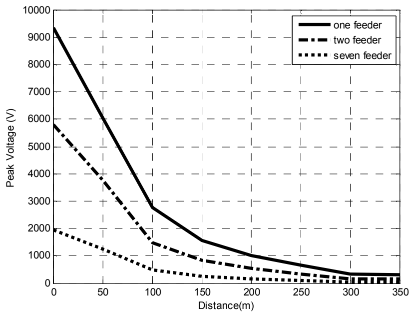
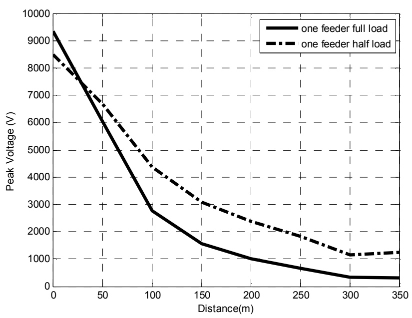
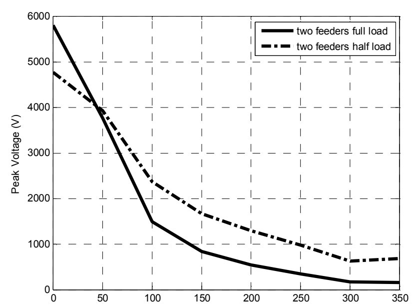


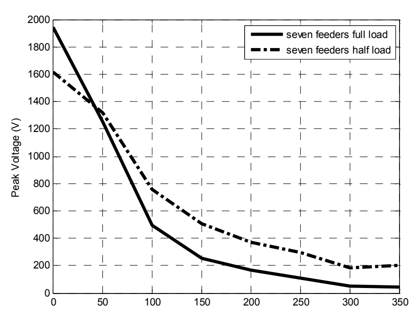
Fig. 7 Number of Feeders Impact.



a) One feeder.



b) Two feeders.

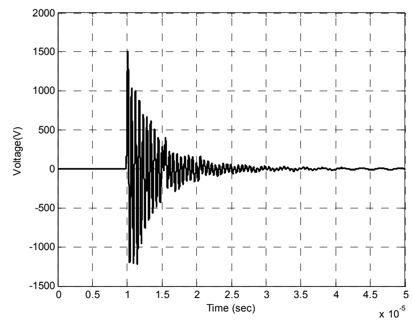


c) Seven feeders.

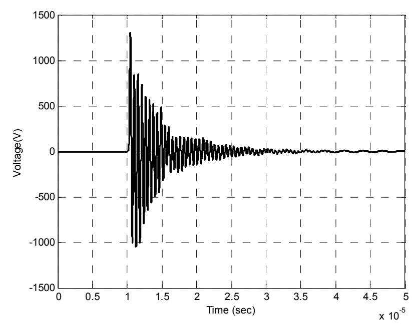
Fig. 8 Load size Impact.

D. Impact of Underground cable

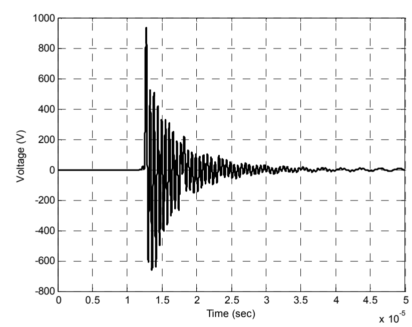
When the overhead cable feeder is totally replaced by underground cable, the corresponding time domain simulation results are shown in Fig. 9 where the network has only one feeder. The considered underground cable is four-core, XLPE/PVC cable and its data are reported in [23] and summarized in the Appendix B. The effect of this configuration can be investigated through the peak voltage profile as shown in Fig. 10 which is compared with the profile when the network is of overhead cable. The voltage peaks at loads close to the transformer are reduced when the network is of underground cables; however, the voltages at loads behind 250 m are higher when the network is underground cables.



a) Voltage at SEND.



b) Voltage at point A1.



c) Voltage at point G1.

Fig. 9 secondary voltage transferred by underground cable.

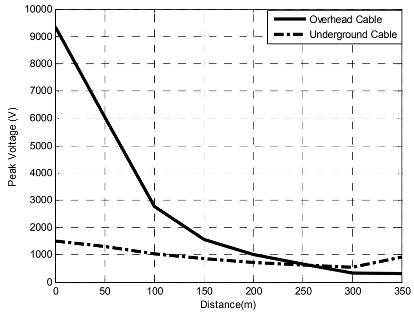
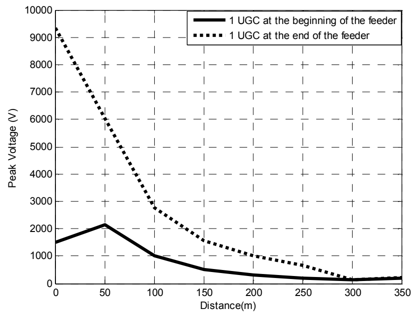
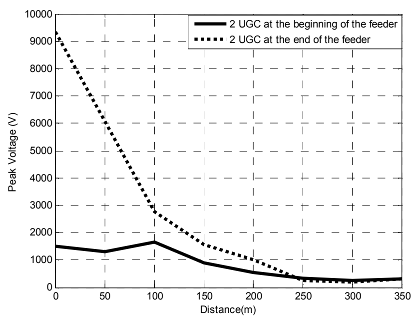


Fig. 10 Comparing overhead cable and underground cable networks.



a) Only one section underground cable.

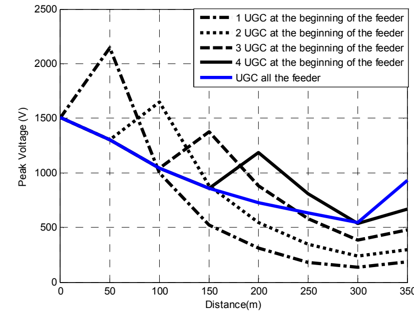


b) Two sections are underground cable.

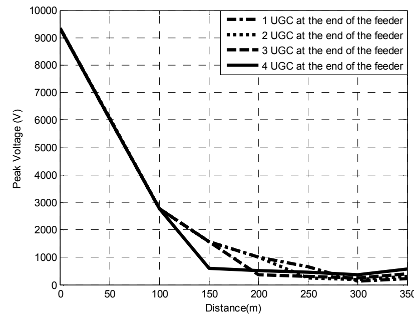
Fig. 11 Impact of underground cable position.

Fig. 11.a illustrates the voltage profile when the network feeder is overhead cable; however, when the first section is underground cable (UGC) and when the last section is underground cable. Then, when two subsections are underground cable at the beginning of the feeder and when two subsections are underground cable at the beginning of the feeder, the corresponding results are shown in Fig. 11.b. The impact of underground cables at the beginning is bigger than their impact when they are at the feeder end.

Finally, the peak voltage profile for one, two, three and four sections of underground cable is shown in Fig.12. This is considered when the cable sections are at the feeder beginning and its end. It is also confirms the underground cable impact is higher when the cable is installed at the feeder beginning.



a. Cable sections at the feeder beginning.



b. Cable sections at the feeder end.

Fig. 12 Underground cable share impact.

IV. CONCLUSIONS

An accurate high frequency transformer model suitable for lightning study has been presented to investigate the effect of lightning induced overvoltage on the customer side. Also, the impact of feeder numbers, lengths, types and loads on the lightning reached at the service entrance point has been investigated through the peak voltage profile along the feeder length. These voltage profiles for different conditions show reasonable results.

V. APPENDIX

The feeders are represented using LCC JMarti model. The configuration of the overhead cable and the corresponding dimensions and parameters are shown in Figure A. However, the underground cable sections are considered four core cables buried 0.7 m deep under earth and arranged as shown in Figure B.

In Overhead cable, the messenger conductor has two dual functions, it is earthed in addition to it is uncovered for the protection purpose. The dimensions and parameters are:

- Conductor cross-section = 35 mm^2,
- Outer insulation thickness = 1.6 mm,
- Over messenger area =70mm^2,
- Conductor resistivity = 2.84×10^{-9} Ω.m,
- Relative permeability of the conductor material = 1,
- Relative permeability of the insulator material outside the conductor = 1,
- Relative permittivity of the insulator material outside the conductor = 2.3.

Underground cable dimensions and parameters are:

- Conductor cross-section = 35 mm^2,

- Outer insulation thickness = 0.9 mm,
- Overall diameter =25.4 mm,
- Conductor resistivity = 2.84×10^{-9} Ω.m,
- Relative permeability of the conductor material = 1,
- Relative permeability of the insulator material outside the conductor = 1,
- Relative permittivity of the insulator material outside the conductor = 5.1.

Pipe data are :

- Depth= 0.7 m,
- Inner radius= 0.0105 m,
- Outer radius= 0.0109 m,
- Insulator radius= 0.0127 m,
- Conductor resistivity = 2.84×10^{-9} Ω.m,
- Relative permeability of the conductor material = 1,
- Relative permittivity of the insulator material = 5.1.

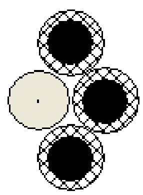


Fig. A Three phase conductors + one messenger overhead cable.

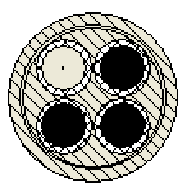


Fig. B Four cores, XLPE/PVC underground cable.

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