Multi-conductor transmission line model for electrified railways: A method for including responses of lumped devices

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Abstract

For studying the response to transients caused by lightning and other electromagnetic disturbance sources, electrified railway systems can be represented as a system of multiconductor transmission lines (MTL) above a finitely conducting ground. The conductors present in this system would be wires for traction power supply, auxiliary power, return conductors for traction current, the tracks, and finitely conducting ground. In contrast to conventional power systems, where the MTL system is usually only terminated at the line ends, there are lumped devices connected in series and as shunt along the railway network, for example, booster and auto transformers, track circuits, and various interconnections between conductors, influencing surge propagation. In this doctoral thesis a new method for incorporating lumped series and shunt connected devices along MTL systems is presented. Telegrapher’s equations, using the finite difference time domain method, are adopted for finding surge pulse propagations along the MTL systems, simultaneously solving for the lumped devices connected along the lines by means of Kirchhoff’s laws for nodal currents and voltages using a circuit solver.

As part of this work, case studies are carried out to determine voltages appearing across devices connected along MTL systems representative of a typical Swedish single-track electrified railway system, in cases of direct and indirect lightning strikes. The influence of soil ionization at the grounding points and the nonlinear phenomenon of flashovers between overhead wires and the poles are also investigated. The calculations made show that the devices connected along this system, which are needed for normal and
safe operation of the railway system, and nonlinearities are affecting the surge current and voltage distribution and peaks appearing along the MTL system and across devices.
List of Papers

This thesis is based on the following papers; these are referred to in the text by their roman numerals.


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The author has also contributed to the following paper, not included in this thesis.


the IEEE Power and Energy Society 2009 in Calgary, Alberta, Canada.

# Abbreviations

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATP/EMTP</td>
<td>Alternative transients program /Electromagnetic transients program</td>
</tr>
<tr>
<td>AT</td>
<td>Autotransformer</td>
</tr>
<tr>
<td>BT</td>
<td>Booster transformer</td>
</tr>
<tr>
<td>EMC</td>
<td>Electromagnetic compatibility</td>
</tr>
<tr>
<td>EMI</td>
<td>Electromagnetic interference</td>
</tr>
<tr>
<td>FDTD</td>
<td>Finite difference time domain</td>
</tr>
<tr>
<td>MTL</td>
<td>Multiconductor transmission line</td>
</tr>
<tr>
<td>MTLL</td>
<td>Modified transmission line equation with linear decay</td>
</tr>
<tr>
<td>NDX</td>
<td>Number of segments in space discretization of a line in FDTD</td>
</tr>
<tr>
<td>SC</td>
<td>Short circuit</td>
</tr>
<tr>
<td>TL</td>
<td>Transmission line</td>
</tr>
<tr>
<td>a_i</td>
<td>Poles</td>
</tr>
<tr>
<td>c_i</td>
<td>Residues</td>
</tr>
<tr>
<td>CI</td>
<td>Recursive convolution term of transient ground impedance</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Volume charge density</td>
</tr>
<tr>
<td>( \zeta )</td>
<td>Transient ground impedances</td>
</tr>
<tr>
<td>( \Psi )</td>
<td>Internal impedance</td>
</tr>
<tr>
<td>R</td>
<td>Resistance</td>
</tr>
<tr>
<td>L</td>
<td>Inductance</td>
</tr>
<tr>
<td>C</td>
<td>Capacitance</td>
</tr>
<tr>
<td>G</td>
<td>Conductance</td>
</tr>
<tr>
<td>C</td>
<td>Speed of light</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$v$</td>
<td>Lightning channel return stroke current velocity</td>
</tr>
<tr>
<td>$E_z$</td>
<td>Vertical electric field</td>
</tr>
<tr>
<td>$E_r$</td>
<td>Radial electric field</td>
</tr>
<tr>
<td>$H_\phi$</td>
<td>Horizontal magnetic field</td>
</tr>
<tr>
<td>$E_{rg}$</td>
<td>Horizontal component of the electric field at a given height above finitely conducting ground</td>
</tr>
</tbody>
</table>
1. Introduction

The traction system and devices connected to the electrified railway system were electromechanical at the beginning of the electrified railway industry, more than 150 years ago. With emergence of electrical devices containing integrated circuits and circuit boards, the threshold voltages for the destruction of the electronic circuits used in control and signaling in the railway system have reduced significantly and the sensitivity to electromagnetic interference (EMI) has increased. Thus modern electrified railway networks need more protection. The purpose of the protection system, consisting of several EMI mitigation measures such as filters, surge arrestors and groundings, is to reduce the induced voltages and currents along the system to levels which will not disrupt the normal operation of the devices connected to the railway multiconductor transmission line (MTL) system. As series and shunt components affect the pulse current and voltage distributions, the overall electromagnetic compatibility (EMC) aspect of the system has to be considered as protection systems are designed for electrified railways. For designing and implementing EMI mitigation measures the wave shapes and peak amplitudes of induced voltages and currents, due to the most common and most severe EMI at the device ports along the MTL system have to be known. For this purpose the overhead conductor system and the tracks in electrified railways can be modeled as a MTL system.
To make assessments needed for tailoring a protection system the wave propagation characteristic along MTL systems has to be known. There has been work done on this topic where the EMC aspects have been studied for various power systems, e.g. [1]-[6]. In these studies, it is normal to only include the line end impedances in the calculations and disregard series connected devices and components. Part of the reason is that typical components accounted for in power systems are located at the sending and/or receiving end substations and these consist of transformers, switchgears, generators, etc. However, in many actual MTL systems, such as electrified railways, devices and components are connected in series and as shunts along the system. In the electrified railways these mainly consist of trackside transformers and track circuits.

In the first phase of this project, financed by the Swedish railway administration (Banverket), a common Swedish single-track electric railway system was modeled as nine conductors above finitely conducting ground [7]. As part of this work the effects of ground conductivity on surge current and voltage propagations have been investigated [8]. In this work nonlinear effects, such as pole grounding resistance and insulator flashovers, and some interconnections along the system have been accounted for. However, series and shunt components, such as booster transformers (BT), autotransformers (AT) and track circuits, were not considered in that model.

The aim of this work is to present a method, called here as the interface method, based on transmission line (TL) equations solved by the finite difference time domain (FDTD) method [9]-[11] and Kirchoff’s current and voltage laws [12]-[13], on how to implement lumped series and shunt connected devices along MTL systems. Another method, used for validating the
proposed method, for solving this type of problems is to include the lumped components as differential equations in the FDTD calculations. The second method is seemingly simple for linear components, but as complex devices are regarded the differential equations can become very hard to define and implement. Whereas equivalent frequency dependent circuits can experimentally be obtained and are fairly simple to include along MTL systems using the interface method.

In this thesis the effects of some of the most common devices on the surge current and voltage propagation along a MTL system similar to the Swedish single-track electrified railway system, for direct and indirect lightning strikes, is investigated using the interface method. Prior to this study certain points have to be made clear:

- The layout and physical properties for conductors present in the Swedish single-track electrified railway system.
- Most common series and shunt connected devices along the MTL system.
- How the devices are connected along the MTL system.
- Non-linear effects that will play significant roles in current and voltage distributions along the system, i.e. pole footing resistance and wire to pole insulator flashovers.

Works previously done and the background work of this thesis are presented in Papers I-III and [7].

1.1. The Swedish Electrified Railway System

A normal Swedish single-track electrified railway system can consist of as many as ten above ground
conductors, as seen in Fig. 1.1, and one buried communication cable along the track, not shown in the cross sectional view of the MTL system. The contact and messenger cables, both noted as R3 in the cross-sectional view of Fig. 1.1, are interconnected at every 7-10 m and these conductors can, in accordance with the principle of bundled conductors [14], be combined into a single conductor.

Fig. 1.1. A typical Swedish single-track railway system, adopted from Paper II, and a cross-sectional view of the same, axis in meters. Adopted from [7].

Table 1.1. Conductor nomenclatures and properties in a typical single-track Swedish electrified railway system.

<table>
<thead>
<tr>
<th>Conductor name</th>
<th>Conductor notation</th>
<th>Conductivity (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-rail</td>
<td>R1</td>
<td>4.4×10⁻⁶</td>
</tr>
<tr>
<td>I-Rail</td>
<td>R2</td>
<td>4.4×10⁻⁶</td>
</tr>
<tr>
<td>Contact and Messenger</td>
<td>R3</td>
<td>5.8×10⁻⁷</td>
</tr>
<tr>
<td>Electrical Reinforcement</td>
<td>R4</td>
<td>3.5×10⁻⁷</td>
</tr>
<tr>
<td>Return</td>
<td>R5, R6</td>
<td>3.5×10⁻⁷</td>
</tr>
<tr>
<td>Auxiliary</td>
<td>R7, R8, R9</td>
<td>3.5×10⁻⁷</td>
</tr>
</tbody>
</table>

Names, notations and conductivities of the overhead conductors of Fig 1.1 are presented in Table 1.1. The conductors forming the MTL system consist of the following:

- Two rails; the S-rail, R1, is continuous throughout the entire railway system and used as a return path for the traction current and the I-rail, R2, has
insulated gaps at regular intervals and is used for signaling purposes.

- The bundled $R_3$ conductor, also known as the catenary wire, is used for feeding power to the locomotive through the pantograph located on the locomotive roof with 15 $kV$, 16.67 $Hz$.
- An electrical reinforcement wire, $R_4$, is running in parallel with the catenary and it is connected to it every 200-300 $m$. This wire is present for reducing the catenary system impedance.
- Return conductors, $R_5$ and $R_6$, are used for returning the traction currents to the feeding stations.
- Auxiliary power wires, $R_7$, $R_8$ and $R_9$, operating at 22 $kV$, 50 $Hz$ are used to supply power to trackside equipments after a step down to 400/230 $V$.

The communication cables used in the Swedish railway systems are buried or put in trenches at a depth of 0.5-0.75 $m$ and about 1-2 $m$ away from the tracks on the pole side. There are different kinds of communication cables used on different track sections based on current demand and future planning. A communication cable frequently used by Banverket is the Ericsson made BV ECLALPLE 1S1.2 + 28P 0.9 [15], a cross sectional view of this cable is shown in Fig. 1.2. This multiconductor communication cable consists of 60 copper conductors split in three layers, pair-wise twisted arrangement, enclosed by a stranded aluminum shield and a steel armor [16].
In Swedish double-track railway systems the tracks run in parallel and the overhead conductors are mirrored, with a distance of \(4.4\times10^2\) m between the centers of the lines, with auxiliary wires only present at one side of the track [17].

1.2. Scope of This Thesis

In this thesis a method for determining the effects of passive lumped series and shunt connected devices on transient current and voltage propagations along MTL systems, representative of single track electrified railways, is presented. A methodology for determining equivalent lumped circuits is elaborated upon and the equivalent circuits corresponding to some of the most common devices connected along the Swedish electrified railway system are presented. The nonlinear effects, i.e. soil ionization and flashovers, are also regarded.

In section 2 the most common devices connected along Swedish electrified railway networks are presented.
In Section 3 the proposed method for including lumped components along MTL systems is presented. The lumped component model derivation method and the lumped circuit of common devices along Swedish electrified railway systems are also shown.

In Section 4 the method used for determining induced voltages due to nearby lightning strikes to overhead wires is explained.

In Section 5 the proposed method is verified and simulations corresponding to MTL systems, representative of typical single-track railway systems with series and shunt connected components, are presented and discussed. In the calculations the MTL systems are exposed to direct and indirect lightning strikes and with realistic ground impedance taken into account.

In Section 6 summaries of the papers, which this thesis is based on, are presented.

In Section 7 the conclusions drawn from this work are presented and finally in Section 8 the future scope of this thesis is addressed.

This thesis will result in a mitigation tool used by engineers at Banverket while planning for new or expanding existing electrified railway systems, as well as estimating the impact of EMI sources on the normal operation of present systems, i.e. as these are subjected for modernization.
2. Devices along Swedish Electrified Railway Systems

The most common devices connected along Swedish electrified railway systems consist of trackside transformers; BT and AT, and track circuits; relay and rectifier units. There are also interconnections between the overhead conductors in the railway system, depending on which feeding system that is used. In the single-track electrified railway system with ten overhead conductors there are not only the contact, messenger and reinforcement wires that are interconnected as explained before. The return conductors are also interconnected, and for BT systems these are also connected to the S-rail at the midpoint between two consecutive transformers, as seen in Fig. 2.1. In double track railway systems the S-rails of the different tracks are interconnected at every 300 m.

![Fig. 2.1. Transformer connections in BT feeding systems.](image-url)
At every pole position the S-rail is shorted to the pole footing. The pole footing is in turn grounded, but due to the phenomenon of soil ionization [18] not to ideal ground. This can be accounted for by connecting series non-linear resistors between every pole footing and the reference ground.

Components and devices connected to the auxiliary wires are not considered in this work.

2.1. Trackside Transformers

There are mainly two types of trackside transformer used in the Swedish electrified railway system, BT and AT. Both these are 1:1 transformers with the same purpose, i.e. to force the traction current to return through the designated return conductors (or negative feeder) to the traction supply to reduce stray currents which may cause EMI with electrical systems in the vicinity of the railway system. There are differences between the transformers, as seen in Figs. 2.1 and 2.2, the primary and secondary coils of a BT are connected in series with the catenary and return conductor, and the coil of an AT is connected as shunt between the catenary and negative feeder and the midpoint of this coil is connected to the S-rail. The distance between two consecutive transformers is also different.

AT systems deliver more effect to the locomotive with the same current magnitude, due to the higher voltage as compared to the BT system. Therefore these transformers are normally installed in railway sections on which high speed trains and heavy cargo trains commute. All feeding systems are not made up of solely BTs or ATs, there also exists system layouts where both transformer types are present and connected in different combinations [19].
2.2. Track Circuit

The track circuits constitute of relay and rectifier units, which are connected as shunts between the S- and I-rails, as seen in Fig. 2.3. The purpose of track circuits is to determine whether a track section is occupied by a train or not, and to accordingly control the signaling systems and devices connected to the railway network.

Fig. 2.3. A typical track circuit configuration used in a Swedish railway system.
The length of a track section can be up to 2.5 km. When the section length is more than 200 m there are signal relays connected at both ends of the track section, as seen in Fig. 2.3. As the section length is less than 200 m there is enough to have only one signal relay connected at one of the ends of the section. The feeding point (rectifier) is connected somewhere in the middle of the track section with maximum distance of up to 1.5 km away from any of the relays [20]. The source of the rectifier is supplying 7 V DC between the S-rail and I-rail [7]. In a non-occupied track section almost the same voltage appears across the relay coils, as very little potential is dropped across the rails. As a train occupies a track section the bogies will short the two rails and the potential across the relay coils will fall to about 0 V. This will trip the relay unit switch and the signaling system is controlled accordingly. Two frequently used relay and rectifier units in Swedish railway systems, JRK 10470 and BML 301053 [21], are shown in Fig. 2.4 and 2.5, respectively.

Fig. 2.4. The JRK 10470, a typical relay unit used in the Swedish railway systems. Adopted from [7].
Fig. 2.5. The BML 301053, a typical rectifier unit used in the Swedish railway systems. Adopted from [7].

2.3. Poles

At every 60 m along the MTL system there are poles. These are not only used for grounding points for the S-rail, but also to hold the overhead wires in the air along the system, as shown in Fig. 2.6. The above ground wires are connected onto this pole by insulators of different materials and impulse withstand overvoltages, as shown in Table 2.1.
Fig. 2.6. Insulators, connections and pole footing resistance in a single track railway system. Adopted from [7].

Table 2.1. Insulator material and withstand voltages.

<table>
<thead>
<tr>
<th>Conductor</th>
<th>Insulator</th>
<th>Impulse withstand voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R3</td>
<td>Rod/Composite</td>
<td>225</td>
</tr>
<tr>
<td>R4</td>
<td>Line post</td>
<td>170</td>
</tr>
<tr>
<td>R5, R6</td>
<td>Spool</td>
<td>60</td>
</tr>
<tr>
<td>R7, R8, R9</td>
<td>Pin</td>
<td>140</td>
</tr>
</tbody>
</table>
3. Line Voltage and Current Solution

To determine the induced voltage and current waveforms and peak amplitudes due to EMI, along overhead conductors in a MTL system, a line voltage and current solution method is required. The method chosen in this investigation is based on Telegraphers’ equations [22] using the FDTD method [7], [9]-[11], given by (3.1) for a lossy line in time domain. The reasons for this choice is that the results are reasonably accurate, the method is computationally efficient and it is fairly easy to implement the influence of finitely conducting ground and field to wire coupling along a given MTL system.

\[
\begin{align*}
\frac{\partial V(x,t)}{\partial x} + R \cdot I(x,t) + (L_i + L_e) \frac{\partial I(x,t)}{\partial t} &= 0 \tag{3.1a} \\
\frac{\partial I(x,t)}{\partial x} + G \cdot V(x,t) + C_e \frac{\partial V(x,t)}{\partial t} &= 0 \tag{3.1b}
\end{align*}
\]

In (3.1) \( V \) and \( I \) are voltages and currents at any point along the line. Internal line inductance \( L_i \), external line inductance \( L_e \), internal line resistance \( R \), line external capacitance \( C_e \) and line conductance \( G \) are calculated from the line geometry [7], [9]-[11]. The modifications made to the Telegrapher’s equations in (3.1) to take into account the effects of finitely conducting ground can be found in the next section.
3.1. The FDTD Method

In the FDTD method of solving telegraphers’ equations the line is discretized into \( NDX + 1 \) voltage nodes and \( NDX \) current sections separated by the distance \( \Delta x \), as shown in Fig. 3.1. In Fig. 3.1 the line is fed by an ideal current source in parallel with a resistance, \( R_S \), at one end and it is terminated by \( R_L \) at the other end. The Telegraphers’ equations corresponding to the lossless case are given in (3.2).

\[
\begin{align*}
\frac{\partial V(x,t)}{\partial x} + L_e \frac{\partial I(x,t)}{\partial t} &= 0 \\
\frac{\partial I(x,t)}{\partial x} + C_e \frac{\partial V(x,t)}{\partial t} &= 0
\end{align*}
\] (3.2a, 3.2b)

Using (3.1) or (3.2) the voltages and currents propagating along a TL can be solved by leap-frog scheme [7], [9]. In the FDTD method first the equations for the voltages are solved and later the currents for every time step, \( \Delta t \). The recursive relation corresponding to (3.2b), for the voltage at the first node, any node \( k \) along the line and the last node, are given by (3.3a), (3.3b) and (3.3c) respectively.
Using the voltages at the nodes, the currents in each section between the nodes can be calculated by (3.4) for a lossless line, in accordance with (3.2a).

\[
I_{k+1} = \left( \frac{L_e}{\Delta t} \right) \left[ \frac{L_e}{\Delta t} I_k^n - \frac{V_{k+1}^{n+1} + V_k^{n+1}}{\Delta z} \right]
\] (3.4)

As lossy ground is considered the skin effect, volume charge density, internal and ground impedances has to be accounted for. These parameters will affect the currents in each section between the nodes [7]. The Telegraphers’ equations in this case have to be expressed as (3.5).

\[
\frac{\partial V(x,t)}{\partial x} + A \cdot I(x,t) + \frac{B}{\sqrt{\pi}} \left( \int_0^t \frac{\partial I(x,t-\tau)}{\partial \tau} d\tau \right) + L_e \frac{\partial I(x,t)}{\partial t} + \int_0^t \varsigma(t-\tau) \cdot \frac{\partial I(x,t)}{\partial \tau} d\tau = 0
\] (3.5a)

\[
\frac{\partial I(x,t)}{\partial x} + C_e \frac{\partial V(x,t)}{\partial t} = 0
\] (3.5b)

Where \( A \) and \( B \) are constants for taking into account the skin effect [9] and \( \varsigma(t) \) is transient ground...
impedance [2], [7], [23]-[24]. (3.5a) can be solved, as for the lossless case of (3.2b), in terms of voltages at the nodes and expressed as (3.6).

\[
I_k^{n+1} = \left( \frac{L}{\Delta t} + \frac{A}{2} + \frac{B \rho(0)}{\sqrt{\pi \Delta t}} + \zeta(0) \right) \left( \begin{array}{c} \frac{L - A + 2 \cdot B \rho(0)}{\Delta t} \frac{2}{\sqrt{\pi \Delta t}} + \zeta(0) - \zeta(1) \\ \frac{1}{2} \sum_{i=1}^{10} \Psi_i + \frac{\zeta(1)}{2} \end{array} \right) I_k^n - \frac{B}{\sqrt{\pi \Delta t}} \sum_{i=1}^{10} \Psi_i + \frac{\zeta(1)}{2} \cdot I_k^{n-1} - \frac{V_{n+1}^k + V_{n+1}^{k+1}}{2 \Delta x} - C_{I_k}^n
\]

(3.6)

With \( \rho(0) \) as volume charge density and \( \zeta(0) \) and \( \zeta(1) \) as transient ground impedances at times 0 and \( \Delta t \), respectively. \( \Psi \) is the internal impedance and \( CI \) is the recursive convolution term of the transient ground impedance derived by (3.7) and (3.8), respectively.

\[
\Psi_i^a = a a_i \cdot e^{a_i} \cdot \left[ I_k^{n+1} - I_k^{n-1} \right] + e^{a_i} \cdot \Psi_i^{n-1}
\]

(3.7)

\[
C_{I_m} = \sum_{j=1}^{N_c} \sum_{r=1}^{N} C_{I_{mj,r}}
\]

(3.8)

\( N_c \) and \( N \) are number of conductors in the MTL system and number of terms in the fitted transient ground impedance and \( C_{I{mj,r}} \) is as expressed in (3.9). \( a a_i \) and \( a_i \) in (3.7), and \( AA_i \) and \( \chi_i \) in (3.9) are the constants and exponential terms in the Prony approximation [9].
\[
CI_{mj,rt} = e^{\chi_{mj,rt} \Delta t} \left( \frac{1}{2} AA_{mj,r} \cdot \left[ I_{k}^{n+\frac{1}{2}} - I_{k}^{n-\frac{1}{2}} \right] + \frac{1}{2} AA_{mj,r} \cdot e^{\chi_{mj,rt} \Delta t} \cdot \left[ I_{k}^{n-\frac{3}{2}} - I_{k}^{n-\frac{1}{2}} \right] \right)
\] (3.9)

3.2. Inclusion of Lumped Series and Shunt Components

In the interface method the lumped components exists either between a given voltage node on the line to ground, between voltage nodes of different lines or between two voltage nodes of the same line along the MTL in the FDTD line representation, as applicable. As the lines are evaluated using the FDTD method all the node voltages along the MTL, except the voltage nodes on which the lumped components are connected at are solved for at a given time step. The section currents entering those nodes at the previous time step are modeled as current sources connected to the lumped device as seen in Figs. 3.2 and 3.3, for components connected as line termination and along a line, respectively. The voltages at the nodes, to which the lumped components are connected, are solved by a circuit solver software; here the Alternative transients program/Electromagnetic transients program (ATP/EMTP) software is used [25]-[27]. The node voltages calculated by the circuit solver are returned to the FDTD routine as node voltages and the currents along the line are solved by the FDTD method. This procedure is repeated for all time steps. This method is presented in Papers IV-V.
In Figs. 3.2 and 3.3 the right and middle sections, respectively, are solved by the circuit solver and the rest of the system is solved by the FDTD method. The lumped components are represented by $Z$ components and $C'$, having the value $\frac{1}{2}C_e \Delta x$ (line to ground per unit length capacitance of the line). $C_e$ is the same line external capacitance as in (3.2) and (3.3). $I_L$ and $I_R$ are the currents at the boundary of the lumped component and $V_L$ and $V_R$ are the nodal voltages at the lumped component boundaries. It is worth noting that for lumped components connected as line terminations only one section current is used and one node voltage is returned. Whereas in series connected components, currents and voltages at both sides of the components
are exchanged between the FDTD routine and the circuit solver.

If a purely resistive component, \( Z=R \), would be connected as line termination in accordance with Fig. 3.2, the current entering the last voltage node of the line can be expressed as (3.10), in time domain, and expanded in central difference approximation as (3.11). It is seen that the later equation is, after rearranging, identical to (3.3a). This shows that the interface method will, analytically, give same result as it would if the FDTD method was to be applied with a resistive line termination.

\[
I_{NDX}(t) = \frac{V_{NDX+1}(t)}{R_L} + \frac{C \Delta x}{2} \frac{\partial V_{NDX+1}(t)}{\partial t} \tag{3.10}
\]

\[
\frac{I^n_{NDX} + I^{n-1}_{NDX}}{2} = \left[ \frac{V_{NDX+1}^{n+1} + V_{NDX+1}^{n}}{2R_L} + \frac{C \Delta x}{2} \frac{V_{NDX}^{n+1} - V_{NDX}^{n}}{\Delta t} \right] \approx I^n_{NDX} \tag{3.11}
\]

As a purely resistive series connected lumped component is regarded, i.e. \( Z_1=R_1 \), \( Z_2=R_2 \) and \( Z_3=R_3 \), as per Fig. 3.3, the currents entering the nodes can be expressed as (3.12), or as (3.13) expanded in central difference approximation.

\[
I_L(t) = \frac{C \Delta x}{2} \frac{\partial V_L(t)}{\partial t} + \frac{V_L(t)}{R_2} + \frac{V_L(t) - V_R(t)}{R_1} \tag{3.12a}
\]

\[
-I_R(t) = \frac{V_R(t)}{R_3} + \frac{V_R(t) - V_L(t)}{R_1} + \frac{C \Delta x}{2} \frac{\partial V_R(t)}{\partial t} \tag{3.12b}
\]

\[
\frac{I_L^n + I_L^{n-1}}{2} = \left[ \frac{C \Delta x}{2} \frac{V_L^{n+1} - V_L^{n}}{\Delta t} - \frac{V_R^{n+1} + V_R^{n}}{2R_1} \right] \approx I_L^n \tag{3.13a}
\]
For the special case of $R_1 \to 0$ and $R_2 = R_3 \to \infty$ it is seen that adding (3.13a) and (3.13b), and rewriting the nodal voltages as $V_L = V_R = V_k$ and the currents as $I_L = I_{k-1}$ and $I_R = I_k$, (3.3b) is obtained.

The above analogies can be extended to MTL systems and much more complex circuitry consisting of linear and non-linear elements, where the number of current sources and voltage nodes used for information exchange will increase depending on the number of lines in the MTL system.

3.3. Lumped Circuits

Lumped frequency dependent models of components are needed to determine the influence of these along MTL systems at transient conditions. Some of the component models needed for analysis of transient response of railway systems are lumped models of the most common trackside transformers (BT and AT) and track circuits (relays and rectifiers).

Lumped models can be determined by considering the connected devices to be linear networks; one or two ports depending on how it is connected along the system under study. Model parameters are determined from experimental tests as described in [7] and Paper V, or from data sheets.
3.3.1. Transformer Models

The driving point admittances for the transformers, as shown in Fig. 3.4, and their equivalent π model were obtained by assuming the units to be two port linear networks. Each component in the π model is realized as circuit component consisting of resistance, inductance, capacitance and conductance (RLCG model) as discussed in [28]-[30].

Fig. 3.4. π admittance model used to derive the transformer models.

The voltages and currents at the input and output ports of the terminal model in Fig. 3.4 are related as (3.14).

\[
\begin{pmatrix}
I_1 \\
I_2
\end{pmatrix} =
\begin{pmatrix}
y_{11} & y_{12} \\
y_{21} & y_{22}
\end{pmatrix}
\begin{pmatrix}
V_1 \\
V_2
\end{pmatrix}
\] (3.14)

The admittance values, \(y_{11}, y_{12}, y_{21}\) and \(y_{22}\), can be obtained by performing short circuit (SC) tests as the transfer functions of the currents and voltages are considered, as in (3.15). These are related to the driving point admittances by the conditions given in (3.16).

\[
y_{11}(s) = \left. \frac{I_1(s)}{V_1(s)} \right|_{y_2(s) = 0}
\] (3.15a)
\[ y_{22}(s) = \left[ \frac{I_2(s)}{V_2(s)} \right]_{V_2(s)=0} \] (3.15b)

\[ y_{12}(s) = y_{21}(s) = \left[ \frac{I_2(s)}{V_1(s)} \right]_{V_1(s)=0} \] (3.15c)

\[ y_{11} = y_{11\pi} + y_{12\pi} \] (3.16a)

\[ y_{22} = y_{22\pi} + y_{12\pi} \] (3.16b)

\[ y_{12} = y_{21} = -y_{12\pi} \] (3.16c)

\[ y_{11\pi} = y_{11} + y_{12} \] (3.16d)

\[ y_{22\pi} = y_{22} + y_{12} \] (3.16e)

\[ y_{12\pi} = -y_{12} \] (3.16f)

A good method to determine the equivalent circuit component is the vector fitting method [31], where \( \pi \) admittance functions are fitted in pole \((a_i)\) and residue \((c_i)\) form as (3.17).

\[ y_{pf}(s) = \sum_{i=1}^{n} \frac{c_i}{s-a_i} + s \cdot e + d \] (3.17)

Based on [7], for every real pole, \( p_r \), a RL branch can be realized and for every complex pole, \( p_c \), a RLCG branch can be realized, as seen in Fig. 3.5. The conductance, \( G_0 \), and capacitance, \( C_0 \), are given by (3.18).

\[ G_0 = d \] (3.18a)

\[ C_0 = e \] (3.18b)
The parameters of the $RL$ branches are given by (3.19), and the parameters of the $RLCG$ branches are given by (3.20) and (3.21).

$$Y_s = \sum_{i=1}^{p_s} \frac{1}{L_{si}s + R_{si}} = \sum_{i=1}^{p_s} \frac{c_i}{s - a_i} \quad (3.19)$$

$$Y_m = \sum_{i=1}^{p_m} \frac{s}{L_{mi}} + \frac{G_{mi}}{C_{mi} \cdot L_{mi}} [s + (\Xi + j\varpi)] [s + (\Xi - j\varpi)]$$

$$= \sum_{i=1}^{p_m} c_i [2\Xi + (c_i \cdot a_i^* + c_i^* \cdot a_i)L_{mi}][s - a_i^*] + c_i^*[s - a_i]$$

$$= \frac{2\Xi}{s - a_i}[s - a_i^*][s - a_i] \quad (3.20a)$$

$$2\Xi = \frac{G_{mi}}{C_{mi}} + \frac{R_{mi}}{L_{mi}} \quad (3.20b)$$

$$\Xi^2 + \varpi^2 = \frac{G_{mi}}{C_{mi}} \cdot R_{mi} + \frac{1}{L_{mi} \cdot C_{mi}} \quad (3.20c)$$

$$L_{mi} = \frac{1}{c_i + c_i^*} \quad (3.21a)$$

$$R_{mi} = L_{mi} \cdot [2\Xi + (c_i \cdot a_i^* + c_i^* \cdot a_i)L_{mi}] \quad (3.21b)$$

$$C_{mi} = \frac{1}{L_{mi}[\Xi^2 + \varpi^2 + R_{mi} \cdot (c_i \cdot a_i^* + c_i^* \cdot a_i)]} \quad (3.21c)$$

$$G_{mi} = -L_{mi} \cdot C_{mi} \cdot (c_i \cdot a_i^* + c_i^* \cdot a_i) \quad (3.21d)$$
In the equivalent \( \pi \) model obtained for the BT each component consists of two branches as seen in Fig. 3.6, one \( RL \) and the other \( RLCG \) [7].

\[ y_{11\pi}, y_{12\pi}, y_{22\pi} \]

Fig. 3.6. The admittances \( y_{11\pi}, y_{12\pi}, y_{22\pi} \) in the \( \pi \) circuit for a BT used in the Swedish electrified railway system.

The \( y_{11\pi} \) and \( y_{22\pi} \) values obtained for the BT are equal and described by circuit components having \( R_1=1.1 \) k\( \Omega \), \( L_1=0.25 \) mH, \( R_2=-7.87 \) \( \Omega \), \( L_2=0.55 \) mH, \( C_2=1.2 \) \( \mu \)F and \( G_2=75 \) mS, and \( y_{12\pi} \) is described by circuit components having \( R_1=1.0 \) k\( \Omega \), \( L_1=0.24 \) mH, \( R_2=-7.4 \) \( \Omega \), \( L_2=0.52 \) mH, \( C_2=1.3 \) \( \mu \)F and \( G_2=80 \) mS.

The same method has been adopted to obtain the \( \pi \) model components corresponding to an AT unit. The experimental procedure is elaborated in [32]. Each of the components derived consist of totally six branches, one \( G \), one \( C \) and four \( RL \), as seen in Fig. 3.7.

\[ y_{11\pi}, y_{12\pi}, y_{22\pi} \]

Fig. 3.7. The admittances \( y_{11\pi}, y_{12\pi}, y_{22\pi} \) in the \( \pi \) circuit for an AT unit used in the Swedish electrified railway system.

For the AT units \( y_{11\pi} \) and \( y_{22\pi} \) are equal and described by circuit components having \( G_0=0.700 \) mS, \( C_0=3.66 \) pF, \( R_1=64.0 \) \( \Omega \), \( L_1=3.11 \) mH, \( R_2=-2.48 \) \( \Omega \), \( L_2=-1.15 \) mH, \( R_3=0.831 \) \( \Omega \), \( L_3=0.599 \) mH, \( R_4=-0.405 \) \( \Omega \) and \( L_4=-2.25 \) mH, and \( y_{12\pi} \) is described by circuit components having \( G_0=-0.335 \) mS, \( C_0=-1.83 \) pF, \( R_1=-128 \) \( \Omega \), \( L_1=-
As seen, some of the above resistances and inductances are having negative values. These are obtained from the analytical calculations and are not representative of physical components.

More details regarding the experimental procedures, obtained waveforms and data analysis are given in Paper V.

### 3.3.2. Track Circuits

The track circuit components i.e. relay and rectifier units are connected as shunt between the rails. The relay unit consists of a 4 H inductance connected in series with a relay coil whose resistance and inductance are 1 kΩ and 2 H, respectively, and the rectifier unit consists of a voltage source across a 15 Ω resistor in series with a variable resistance of 0-6 Ω (chosen as 2 Ω in the simulations) and an inductance of 1 H, as seen in Fig. 3.8. The voltage source is not considered in the calculations as it can be approximated by an open circuit in transient analysis.

![Fig. 3.8. Equivalent circuits for the relay and rectifier units.](image)
3.4. Pole Footing Resistance and Flashovers

As explained before, the poles along the Swedish electrified railway system are used as system grounding points. But due to the nonlinear phenomenon of soil ionization [18] the pole footing is not ideally grounded. This effect can, as seen in Fig. 2.6, be represented as a series resistance, \( R_g \), between the pole footing and reference ground. This resistance is given by (3.22) in accordance with IEEE standard 1313.2 [18].

\[
R_g(t) = \frac{R_0}{\sqrt{1 + I_R/I_g}} \quad (3.22a)
\]

\[
I_g(t) = \frac{E_0}{2\pi \sigma_g R_0^2} \quad (3.22b)
\]

With \( R_0 \) as pole footing resistance measured for low currents, \( I_R \) as transient current flowing through the pole footing resistance, \( I_g \) as the current required for generating a soil gradient, \( E_0 \), of about 400 kV/m at which soil breakdown occurs. In the calculations where the pole footing resistance is present \( R_g \) is assumed to be a constant value of 50 \( \Omega \) throughout the calculation.

The poles are also used for holding the above ground wires in the air. The wires are held up by insulators connected on the pole. If the insulation impulse withstand voltage, as given by Table 2.1, is exceeded a flashover will arise between the overhead wire and the pole. As seen in Fig. 2.6 the S-rail is shorted to the pole, so the voltage appearing across the insulators will be the voltage between the overhead wires and the S-rail. As the voltage criterion is fulfilled for an overhead wire the insulator of this wire will swiftly drop from a very high to a low resistive value. This connection will
sustain until the arc current has changed polarity, to be certain of arc extinction. There are plenty of insulator arc models available [33]. In calculations made with flashover included in this work the flashover is assumed to drop from $100 \, M\Omega$ to $1 \, m\Omega$ as soon as the criteria is fulfilled and remain this value until the flashover is not sustained any more.

In the calculations the pole footing resistances and flashovers are represented as conductance matrices and solved as currents entering the nodes, $I_{\text{node}}$, and voltages, $V_{\text{node}}$, across these as given by (3.23).

\[
I_{\text{enter}} = G \cdot V_{\text{node}}
\]  

(3.23)
4. Lightning Induced Voltages along Overhead Wires

A common source of EMI for outdoor systems is lightning. As lightning cannot be avoided for large electrical systems it is good to look at how induced current and voltage pulses from this source will propagate along MTL systems. To be able to make this assessment, first fields due to lightning strikes and later the field coupling to overhead wires have to be solved for.

There are several well established methods for lightning field calculations [34]-[36] and field to wire coupling models [37]-[40]. The methods chosen for lightning field calculation and field to wire coupling in this work are the modified TL model (MTLL) with linear decay [34] and the Agrawal et al. model [37].

4.1. Lightning Field Calculation - MTLL Model

In the MTLL model the lightning channel base current is assumed to propagate up the channel with a speed, \( v \), less than that of light and linearly decay as a function of height, \( z \), as given in (4.1).

\[
I(z,t) = I\left(0, t - \frac{z}{v}\right) \cdot \left(1 - \frac{z}{H}\right), \quad t \geq \frac{z}{v}
\]  

(4.1a)
\[ I(z,t) = 0, \quad t < \frac{z}{v} \]  \hspace{1cm} (4.1b)

Where \( H \) is the height of the lightning channel.

The TL model equations for calculating the vertical, \( E_z \), and radial electric, \( E_r \), and horizontal magnetic, \( H_{\phi} \), fields above a perfectly conducting ground at a given point are given by (4.2), in cylindrical coordinates [23]. The notations used in these equations are shown in Fig. 4.1.

**Fig. 4.1.** Notations used for field calculations at a given point, \( P \), from a segment current along a lightning strike.

\[
\begin{align*}
\frac{dE_z}{dz}(r, z, t) &= \frac{dz'}{4\pi\varepsilon_0} \left[ \frac{2(z-z')^2 - r^2}{R^5} \cdot \int_0^t i(0, \tau') d\tau \right] \\
&\quad + \frac{2(z-z')^2 - r^2}{cR^4} \cdot i(0, \tau') \\
&\quad - \frac{r^2}{c^2R^3} \cdot \frac{di(0, \tau')}{dt}
\end{align*}
\]  \hspace{1cm} (4.2a)
\[
dE_z(r, z, t) = \frac{dz'}{4\pi\varepsilon_0} \left[ \frac{3r(z - z')}{R^5} \cdot \int_0^t i(0, \tau')d\tau \\
+ \frac{3r(z - z')}{cR^4} \cdot i(0, \tau') \\
+ \frac{r(z - z')}{c^2 R^3} \cdot \frac{di(0, \tau')}{dt} \right]
\]

(4.2b)

\[
dH_\phi(r, z, t) = \frac{dz'}{4\pi} \left[ \frac{r}{R^3} \cdot i(0, \tau') \\
+ \frac{r}{cR^2} \cdot \frac{di(0, \tau')}{dt} \right]
\]

(4.2c)

With \( c \) as the speed of light and \( i(0, \tau') \) as the lightning base current at time \( \tau' \), defined as (4.3).

\[
\tau' = \tau - \frac{z'}{v} - \frac{R}{c}
\]

(4.3)

The horizontal electric field at ground level is zero as the image channel is taken into account and, as the variation of the vertical component of the electric field as a function of the height is negligible, the incident voltage at a given height is the vertical component of the electrical field intensity at ground level multiplied by the height [41].

As finitely conducting ground is introduced the ground conductivity, \( \sigma_g \), and relative permittivity, \( \varepsilon_g \), will mainly affect the horizontal component of the electric field and the vertical component of the electric field is least affected by these parameters [23]. The horizontal component of the electric field at a given height above the finitely conducting ground, \( E_{rg} \), can be addressed as (4.4), in frequency domain, or (4.5), in time domain.
\[ E_{rg}(z = h, r, s) = E_r(z = h, r, s) - H_\phi(z = 0, r, s) \sqrt{\frac{s \mu_0}{\sigma_g + s \varepsilon_g}} \quad (4.4) \]

\[ E_{rg}(z = h, r, t) = E_r(z = h, r, t) - H_\phi(z = 0, r, t) * Z_{si}(t) \quad (4.5) \]

Where \( E_r \) and \( H_\phi \) are horizontal electric and magnetic field components above perfectly conducting ground, \( * \) represents convolution and \( Z_{si}(t) \) is as stated in (4.6).

\[
Z_{si}(t) = L^{-1} \left( \sqrt{\frac{s \mu_0}{\sigma_g + s \varepsilon_g}} \right) \\
= \sqrt{\frac{\mu_0}{\varepsilon_g}} \left( I_0 \left( \frac{\sigma_g \cdot t}{2 \varepsilon_g} \right) + I_1 \left( \frac{\sigma_g \cdot t}{2 \varepsilon_g} \right) e^{-\frac{\sigma_g t}{2 \varepsilon_g}} \right) \quad (4.6)
\]

The convolution in (4.5) is solved by adopting the ramp function technique [42]. By applying the ramp function technique the magnetic field is broken into piecewise linear sloped delayed ramps and the convolution is then the product of the slope of the magnetic field and the surface impedance in time domain (4.7).

\[ E_{rg}(t) = E_r(t) - M_{Hi}(t - t_i) \cdot Z_{si}(t - t_i) \quad (4.7) \]

With \( M_{Hi} \) as the slope at the \( i^{th} \) time instant and \( t_i \) as the time delay.

4.2. Field to Wire Coupling – Agrawal et al. Model

In accordance with the Agrawal et al. model for field to line coupling [37] the scattered voltage along a line can be obtained by expressing electric fields along a lossless line as series and shunt voltage sources, as
seen in Fig. 4.2, and the governing Telegraphers equations for this system is expressed as (4.8).

\[
\frac{\partial V^S(x,t)}{\partial x} + L_e \frac{\partial I(x,t)}{\partial t} + \int_0^t (\varsigma(t-\tau)) \cdot \frac{\partial I(x,\tau)}{\partial \tau} d\tau = E'_s(x, h, t) \quad (4.8a)
\]

\[
\frac{\partial I(x,t)}{\partial z} + C_e \frac{\partial V^S(x,t)}{\partial t} = 0 \quad (4.8b)
\]

![Diagram](image)

Fig. 4.2. TL representation for field to wire coupling.

The horizontal electric field, \( E_x \), is the field along the line, obtained from the \( E_r \) component of (4.2). The scattered voltages, \( V^S \), at the terminations of an \( L_m \) long line, terminated by \( Z_S \) and \( Z_L \) as seen in Fig 3.2, are obtained by (4.9).

\[
V^S(0,t) = -Z_s \cdot I(0,t) - V'(0,t) \quad (4.9a)
\]

\[
V^S(L,t) = -Z_L \cdot I(L,t) - V'(L,t) \quad (4.9b)
\]

The total voltage at any point along the line is the sum of the voltages induced due to the scattered voltage and the vertical component of the electric field, as seen in (4.10).

\[
V(x,t) = V^S(x,t) + V'(x,t) \quad (4.10)
\]
Where $V^i$ is expressed as (4.11).

\[ V^i(x,t) \approx -E^i_z(x,0,t) \cdot h \]  

(4.11)
5. Method Validation and Case Simulations

In chapter 3 the method for solving current and voltage wave propagations along MTL systems with lumped series and shunt connected components was introduced. This involves solving the wave propagation along the lines, using the FDTD method and also accounting for the effects of the components on the current and voltage wave propagation. It was stated that the equivalent circuit of the lumped component or an equivalent set of differential equations were needed to make these assessments.

The analytical validation of the interface method was shown in chapter 3. In this chapter the interface method is validated by comparing results from simulations of the whole problem solved by the FDTD method, with components represented as differential equations. To keep the level of complexity to reasonable levels in the validations, arbitrary RL components are connected in series along lossless MTL systems, consisting of up to two overhead conductors. After the validation of the interface method is made, more complex lumped devices are implemented along larger MTL systems, with more number of conductors and longer lengths, and the effects of finitely conducting ground are also included. To make the simulations more realistic, the chosen layouts of MTL systems are similar to the layout of a typical Swedish
single-track electrified railway system as described in the introduction, with the most common devices included, i.e. trackside transformers and track circuits. As customary in typical crosstalk problems with overhead conductors and ground return the conductor to which the source is connected is called as the emitter and the other conductors which suffer the interference from this are called as receptors. The EMI source used in all validations and in the first set of investigations is chosen as an ideal impulse current source with a double exponential wave shape given by

\[ I_s(t) = 1.09 \cdot (e^{-at} - e^{-bt}) \]

with \( a = 10^4 \) and \( b = 5.8 \cdot 10^5 \). Such current sources represent lightning and some switching transient waveforms as far as waveshape is concerned. A current peak of 1 A is used in simulations, even though typical first return-stroke peak current is 30 kA. In the absence of non-linearities, obtained results can be scaled up by multiplying by peak currents. However, insulators will flashover and non-linearities will be present for any reasonable direct lightning strike. Neglecting non-linearities are justified for the moment as the main interest now is method-validation. In the second set of investigations the EMI source is assumed to be an indirect lightning strike, representative of a subsequent return stroke, adopted from [41].

Effects of series connected lumped devices on the crosstalk mechanism along MTL systems exposed to direct lightning strikes are presented in Papers V-VII. The voltages appearing at some device ports in case of indirect lightning are presented in Paper VIII.

5.1. Interface Method Validation

For validating the interface method, two lossless MTL cases each with two component layouts are
considered; Case A: a lossless single overhead conductor with 5 mm radius located 10 m above ground as seen in Fig. 5.1, and Case B: a lossless MTL system consisting of two overhead conductors with same wire radii and conductor heights as in Case A with 1 m horizontal spacing between the conductors, as shown in Fig. 5.2. The total length of the lines for both cases was set to 3 km. The components connected along the lines are shown in the respective figures and described in Table 5.1. The resistance $R_s$ connected parallel to the source is kept as a very high value, representative of open circuit, for all case simulations.

![Fig. 5.1. Lossless single conductor above ground as per Case A with lumped components as per Table 5.1.](image1)

$Z_c$ is the characteristic impedance [9] of the lines, 497 $\Omega$. The calculated currents along the lines are plotted at the marks in Figs. 5.1 and 5.2, i.e. middle of the line and at line end. In these calculations the lines are assumed to be

![Fig. 5.2. Lossless two-conductor MTL system above ground as per Case B with lumped components as per Table 5.1.](image2)
lossless only for the sake of demonstration. Nevertheless, similar simulations with lossy lines have been performed with good results. The obtained current waveforms for the lossless cases studied are presented in Figs. 5.3-5.6.

Table 5.1. Lumped Components Connected Along the lossless MTLs in Figs. 5.1 and 5.2.

<table>
<thead>
<tr>
<th>Case</th>
<th>(Z_1)</th>
<th>(Z_2)</th>
<th>(Z_3)</th>
<th>(Z_4)</th>
<th>Current Waveform</th>
</tr>
</thead>
<tbody>
<tr>
<td>A–1</td>
<td>0</td>
<td>50+j(10^{-6}) NA NA</td>
<td>Fig. 5.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A–2</td>
<td>75+j(10^{-4}) (Z_c) NA NA</td>
<td>Fig. 5.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B–1</td>
<td>0</td>
<td>0</td>
<td>10+j(10^{-3}) 75+j(10^{-6})</td>
<td>Fig. 5.5</td>
<td></td>
</tr>
<tr>
<td>B–2</td>
<td>j(10^{-5})</td>
<td>750</td>
<td>(Z_c) (Z_c)</td>
<td>Fig. 5.6</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5.3. Simulations corresponding to Case A–1 as per Table 5.1.
In Figs. 5.3 and 5.4, corresponding to Cases A-1 and A-2, it is seen that the FDTD method and the interface method result in the same current waveforms for cases of lumped RL loads as line termination and series connected components.
In Figs 5.5 and 5.6, corresponding to Cases B-1 and B-2, it is again clear that both methods result in the same surge current waveforms for both methods. The squared errors for all validation simulations are below 10%. Therefore it is assumed that the interface method is valid and can thus be extended to more complex lumped components, as trackside transformers and track circuits, connected along more complex MTL systems, like electrified railway system, with the effects of finitely conducting ground accounted for.

According to the Courant condition [9]-[10], given by (5.1), the time step needed to obtain simulation stability is about $10^{-8}$ s due to the frequency content of the source used, whereas the time step needed with lumped series components had to be much smaller, about $10^{-10}$ s, for both calculation methods. This difference in time domain can be due to the frequency content of the effects of the lumped components on the pulse propagations.
\[
\frac{\Delta x}{\Delta t} \geq v_p
\]  \hspace{1cm} (5.1)

In (5.1) \(\Delta x\) and \(\Delta t\) are spatial and time steps and \(v_p\) is the maximum phase velocity of the system.

5.2. Effects of Lumped Components on Surge Wave Propagation Along MTL Systems – Direct Lightning Strike

The MTL chosen for calculations is representative of a typical Swedish single-track railway traction feeding system, with five main above ground conductors, namely, auxiliary wire, return conductor/negative feeder (here addressed as return conductor), catenary wire and two rails as shown in Fig. 5.7. The conductor radii and the values of characteristic impedances used as line terminations, as shown in Fig. 5.7, are presented in Table 5.2. The resistance \(R_S\) parallel to the current source, having the same current waveform as in the validation cases, connected at the source end of the auxiliary wire is kept as an open circuit. The line length adopted is 15 km; this is to be able to include more than one trackside transformer with realistic spatial separation. However, as said before, non-linear effects due to flashovers at pole insulators are not included at present. This is done in Section 5.4.
Fig. 5.7. MTL system representative of typical railway traction conductor feeding system used for simulations.

Table 5.2. Conductor Radii and Characteristic Impedances for Line Terminations in Fig. 5.7.

<table>
<thead>
<tr>
<th>S-Rail</th>
<th>I-Rail</th>
<th>Catenary</th>
<th>Return Conductor</th>
<th>Auxiliary Wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radii (mm)</td>
<td>Zc (Ω)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>49.5</td>
<td>186</td>
<td>49.5</td>
<td>186</td>
<td>50.6</td>
</tr>
</tbody>
</table>

For simulations, the rails are represented by conductors with equivalent round cross-section. It is again worth mentioning that the bundled catenary wire radius is determined using the principle of bundled conductors [14]. To study on the influence of different types of trackside transformers and track circuits on current propagation along the MTL system in Fig. 5.7 three cases are simulated, as seen in Table 5.3. In Case 1 the I-rail is assumed to be continuous, but in the other cases the I-rail is discontinuous, as it should be in a real system, and track circuits are connected. In Case 2 interconnections between the return conductor and the S-rail are also incorporated at equidistance between two consecutive BT along the line, see Fig. 2.1.

Standard ground resistivity, 1000 Ωm, was used in the calculations to get more realistic current waveforms. The transient ground impedance used in
these calculations is obtained from Semlyens ground impedance equations [24]. The corresponding current waveforms obtained for the cases are shown in Figs. 5.8-5.10. For one-to-one comparisons the vertical axis of the figures are kept constant. The current in the emitter (auxiliary wire) is not shown.

The interface method, validation and the case simulations are compiled into a journal article and a conference paper, see Paper V and Paper VII.

As seen in the current wave shapes of Figs. 5.8-5.10 the lumped series and shunt connected components affect the current (and correspondingly voltage) waveforms. It is worth noting that, as for the validation cases, it was again noticed that the time step which had to be used in the calculations, as series components were included, was much less than that given by the Courant condition. The time step needed was the same as for the validation cases presented earlier.

Table 5.3. System Topology For the Cases Simulated.

<table>
<thead>
<tr>
<th>Case</th>
<th>Components connected along the MTL. In all cases, ground impedance is included.</th>
<th>Obtained current waveforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No Components, No Interconnections Between Conductors and I-rail continuous</td>
<td>Fig. 5.8</td>
</tr>
<tr>
<td>2</td>
<td>3 BTs, Relevant Interconnections Between Conductors and I-rail broken</td>
<td>Fig. 5.9</td>
</tr>
<tr>
<td>3</td>
<td>2 ATs, No Interconnections Between Conductors and I-rail broken</td>
<td>Fig. 5.10</td>
</tr>
</tbody>
</table>
Fig. 5.8. Current distribution along the MTL system of Fig. 5.7 corresponding to Case 1. Top window shows currents in the rails (solid lines for S-rail and dashed lines for I-rail). Bottom window shows currents in the catenary (solid lines) and return conductor (dashed lines).

Fig. 5.9. Current distribution along the conductors in the MTL system of Fig. 5.7 with three BTs connected, corresponding to Case 2. Top window shows currents in the rails (solid lines for S-rail and dashed lines for I-rail). Bottom window shows currents in the catenary (solid lines) and return conductor (dashed lines).
5.2.1. Currents at Source End

As the source end currents are looked into it is seen that the induced currents in the rails are similar, for all cases up to about 10 $\mu$s. After this time the induced currents in both the rails are similar for Case 1, whereas for Cases 2 and 3, S-rail currents amplitude increases with the same polarity while the I-rail current polarity has changed and the amplitude is the same as was the peak in the 0-10 $\mu$s interval. For Case 2 after 40 $\mu$s, the S-rail current peak reduces as a function of time but for Case 3, the S-rail current peak increase by three times compared to the peak at around 20 $\mu$s. For Cases 2 and 3 after 40 $\mu$s, the I-rail current peak in general reduces as a function of time. Note that in Cases 2 and 3 the current peak from which both the polarity and amplitudes deviate for the rails compared
to Case 1 is at about 6 $\mu$s due to the location of the first track circuit at about 900 m from the source end.

Interestingly the currents at source end in the catenary and return conductor have similar amplitudes for all cases. It is found that current amplitudes for catenary and return conductor in general have been affected in Cases 2 and 3 from about 17 $\mu$s as the BT or AT are located at a distance of 2.5 km from the source end. The currents in the catenary are somewhat higher than the return conductor currents possibly due to the presence of finitely conducting ground [8].

5.2.2. Currents at Middle of The Line

The currents at the middle of the lines generally have higher amplitudes and also show dispersion when the currents are propagating along a TL in dispersive media [8]. The current in the rails, for all the cases, are initially of positive polarity and after about 8-10 $\mu$s the polarity is the same as that of the source end. The currents in the rails for Cases 2 and 3 show polarity variable oscillations with different amplitudes due to both reflections from track circuits and also due to the interconnections. Variable amplitudes are also attributed to sharing of the currents between wires through interconnections.

The currents, at the middle of the line, in catenary and return conductor do not show any polarity variable oscillations, for Cases 2 and 3 and it largely resembles Case 1. The peak amplitudes for the currents in the catenary and return conductor have not been affected, however at late times the waveforms present amplitude oscillations due to BTs and ATs and interconnections.
5.2.3. Currents at Load End

The currents at the load end are similar to the currents in the middle of the line for Case 1. The currents in the rails for Cases 2 and 3 are oscillatory and vary depending on the number of reflections that arrive from track circuits, interconnections and source end. These are seen for the S-rail currents which are increasing in the late times.

The currents, at the source end, in the catenary and return conductor follow a similar trend as was the case in the middle of the line.

5.2.4. Voltages Across The Rails

The voltages across the rails are of interest, in general, for EMC studies. This includes providing protection for track circuits against lightning and switching transients. It is evident from the previous analyses that currents in the rails vary significantly due to the presence of lumped loads and interconnections along the MTL. The voltages for four different relay positions for the cases as per Table 5.3 are shown in Fig. 5.11.

The main observation is that the value of the peak voltages across the rails for Cases 2 and 3 are about 50-100 times higher as compared to Case 1. Further the voltages wave shapes have been significantly affected. This indicates that while deciding protection for equipment, realistic simulations with all possible lumped devices along the MTL should be considered.
5.3. Induced Voltages at Component Ports – Indirect Lightning Strike

In the calculations for assessing the induced voltages across ports of lumped components connected along MTL systems, the same MTL systems and cases as shown in Fig. 5.7 and Tables 5.2-5.3 will be used, with the same realistic ground resistivity. The transient ground impedance is here calculated using Sundes ground impedance equations [43], as this is more accurate for wires at low heights (i.e. the rails), as compared to Semlyens expression, used in the previous section [24]. The source of EMI used in these calculations is the more common source of indirect lightning. The channel base current wave shape used in these calculations is representative of subsequent return strokes adopted from [41], scaled to 1 A peak current, to see the induced voltage dependency on the lightning base current magnitude, propagating with a
speed of $1.3 \times 10^8$ m/s up the channel. The lightning is simulated to strike at 50 m perpendicular distance from the center of the MTL system (catenary wire). The lightning fields and field to wire coupling models used are the MTLL model and Agrawal et al. model, as stated in chapter 3, and the series components will be accounted for using the interface model.

It is worth noting that, as the effect of lumped series and shunt devices on induced voltages at device ports, due to indirect lightning strikes (or distributed series and shunt voltage sources along MTL systems) are studied, the non-linear phenomenon of flashover has been disregarded in these calculations.

As source end and load end does not have any meaning for indirect lightning strikes, as the sources are scattered along the lines, the ends are defined as right end (RE) and left end (LE) with respect to Fig. 5.7. In Figs. 5.12-5.15 the voltages appearing across the BT and AT ports/windings and track circuits for Cases 2 and 3 are presented. The grey colored voltage waveforms in each of the figures are the voltages at the same ports/locations for Case 1.

5.3.1. Voltages Across BT Windings

The general trend is that with the BT components the induced voltages at the BT winding ports are lower compared to Case 1 as seen in Fig 5.12. The voltage amplitudes were less than 0.4 V across the windings for BTs closer to the line ends. However, for the BT unit that is located at the middle the line the corresponding voltage was about 0.8 V (note the late time oscillations or ringing or resonances after 65 $\mu$s are ignored). Note that the voltages across a given BT on either side windings are similar.
5.3.2. Voltages Across AT Windings

The general trend again is that with the AT components the induced voltages at the AT winding ports are lower compared to Case 1 as seen in Fig 5.13. For Case 3, the two AT components are connected only near the line ends, for the system under study. The induced voltages at both AT windings are symmetrical. Also note that at a given AT, the voltage across the winding between catenary and S-rail is similar to voltage across the winding between return and S-rail. The peak voltage across the windings was about a 1 V. This voltage is about two times higher as compared to the corresponding BT case, with BT located at either ends of the line.

Fig. 5.12. Voltages waveforms across BT windings along return conductors (catenary voltage waveforms are similar hence not shown) for Cases 1 and 2 as per Table 5.3 and Fig. 5.7.
5.3.3. Voltages Across Track Circuits

The relay units suffering the highest peak voltages are the ones closer to the middle of the line (relay unit no. 4 and 5) in both Cases 2 and 3, see Figs. 2.3 and 5.7 for the locations of the relay and rectifier units. The peak voltages across the relay units are about 3 V, with either BT or AT system (Figs. 5.14 and 5.15). The corresponding peak voltages for Case 1 at the same points across the rail conductors were about 0.5 V.
Fig. 5.14. Voltages appearing across the relay units suffering the highest voltage peaks for Cases 1 and 2 as per Table 5.3 and Fig. 5.7.

Fig. 5.15. Voltages appearing across the relay units suffering the highest voltage peaks for Cases 1 and 3 as per Table 5.3 and Fig. 5.7.
5.4. Induced Voltages at Component Ports With Poles Included – Indirect Lightning Strike

To make more realistic assessments of voltages appearing across transformer windings and relay units, S-rail grounding points along the MTL system and conductor to pole flashovers, at pole locations, have to be included in the calculations. In the next calculations the MTL system under study is again split up in three cases, corresponding to the cases presented in Table 5.3, but for the MTL system of Fig. 5.16. In Fig. 5.16 the MTL is considered to be 6 km with I-rail discontinuities, track circuits and one trackside transformer. The same conductor radii and line characteristic impedances are used as shown in Table 5.2. The EMI source used in these calculations is representative of an indirect lightning strike, striking at 50 m perpendicular distance from the center of the MTL system, with the same base current wave shape as described in the previous section, but with peak base current amplitude of about 12 kA, representative of a subsequent-return stroke.

Fig. 5.16. Typical railway traction conductor feeding system used for simulations.
In Figs. 5.17-5.22 the voltages appearing across BT and AT windings and track circuits are shown. From the calculations it was seen that the poles subjected to flashovers were the poles in the range of about 300 m away from the center of the line, in both directions. The insulators subjected to these flashovers were mainly the return conductor and auxiliary wire insulators within this range and also one of the catenary wire insulators located directly to the left of the middle of the line. The grey voltage waveforms in each of the figures are the voltages at the same ports/locations for the MTL case corresponding to Case 1, with no devices connected along the MTL system.

5.4.1. Voltages Across BT Windings

In Fig. 5.17 it is seen that the voltages across the windings along the catenary wire and return conductor are similar and as for the previous calculations larger than for the corresponding Case 1 in Table 5.3. The peak voltages across these transformer windings, 15 kV, are comparable to the voltages across the transformer windings at the middle of the line in the previous simulations, where the nonlinear effects, i.e. grounding point resistance and flashovers, were not taken into account. But the waveforms show much more oscillatory behavior. Please keep in mind that the peak base lightning flash currents are different in the two calculations and that the time windows are differing.
5.4.2. Voltages Across AT Windings

In contrary to the previous calculations it is seen that the peak voltages for calculations corresponding to Cases 1 and 3 are having comparable peak voltages across the AT windings. It is also seen in Fig. 5.18 that the transformer winding across the negative feeder to the S-rail is suffering the highest induced voltage of more than 35 kV, which is much higher than for the previous calculations. Again it is seen that the voltage waveforms are much more oscillatory than for the case without nonlinear elements.
5.4.3. Voltages Across Track Circuits

The peak induced voltages appearing across the relay units closer to the ends of the system are similar and comparable to the peak voltages in the previous calculations. It is only for relay unit no. 5 in the BT system the voltage peak is doubled.

As of the induced voltages at the middle relay units, these are similar for Cases 2 and 3 and show very oscillatory behavior after a short time. These oscillations are due to the flashovers occurring in the vicinity of these relay units. The voltage peaks before the oscillatory parts are lower as nonlinearities are introduced in the calculations.

Fig. 5.18. Voltages appearing across AT windings for cases corresponding to Cases 1 and 3 as per Table 5.3 and Fig. 5.16.
Fig. 5.19. Voltages appearing across relay units closer to the line ends for cases corresponding to Cases 1 and 2 as per Table 5.3 and Fig. 5.16.

Fig. 5.20. Voltages appearing across relay units closer to the middle of the line for cases corresponding to Cases 1 and 2 as per Table 5.3 and Fig. 5.16.
Fig. 5.21. Voltages appearing across relay units closer to the line ends for cases corresponding to Cases 1 and 3 as per Table 5.3 and Fig. 5.16.

Fig. 5.22. Voltages appearing across relay units closer to the middle of the line for cases corresponding to Cases 1 and 3 as per Table 5.3 and Fig. 5.16.
As seen in the above figures, depending on the relative position of the lumped device/component with respect to lightning, the peak voltages across these can even exceed 35 kV, for the given lightning source. These voltages (or currents) obtained from system simulations can be used as inputs to physical devices in laboratory to see if failures are occurring. The lightning at any amplitude can be made to strike at any distance to the tracks. If the calculated peak voltages exceed the laboratory determined threshold values, a decision has to be made if the existing transient protection of the relays and rectifier units has to be upgraded or not. This methodology is a powerful tool for risk analysis.
6. Summary of Papers

The papers on which this thesis is based are in the subject of presenting a method for inclusion of lumped series and shunt connected components along MTL systems. This method is useful for making EMI and EMC assessments on large distributed electrical systems. In these papers, and in this thesis, effects of some of the most common devices along the Swedish electrified railway system, on surge current and voltage propagations along MTL systems, and the voltages induced at the ports of these devices are investigated.

Papers I-III deal with the work previously done in this project. In these papers the reasons for initiating this project and the EMC problems of large distributed systems, with particular reference to lightning interaction with Swedish rail network, are dealt with. In these papers theories of lightning attachment to large distributed MTL systems, like the electrified railway network, surge current and voltage wave propagation along TL systems in cases of direct and indirect lightning strikes for above ground and buried wires with ground impedance accounted for are also dealt with. The experimental procedures and results obtained on identification of failure modes for common devices connected along Swedish electrified railway networks and induced currents and voltages in case of indirect lightning strikes in the vicinity of the railway
network are presented. However, these studies were conducted without lumped devices such as BT and AT.

The authors’ contribution consisted of composing these papers (papers I and III, and the English version of paper II) and to present the work at conferences (papers I and III). Authors contribution to these works was about 15% each.

In Paper IV the differences between conventional power systems and the electrified railway system are explained, i.e. the presence of series and shunt connected lumped components, and a methodology for implementing series and shunt devices along MTL systems, and the accuracy of this method, is presented.

The author developed the method, wrote this paper and presented the same at the conference Author’s contribution to this work was about 90%.

In Paper V the differences between conventional power systems and the electrified railway system are highlighted and it is explained how the lumped components can experimentally be determined and interfaced with the FDTD method, using a circuit solver software. The error introduced with this method is investigated and quantified. Using the proposed method three case studies of a five conductor MTL system, representative of Swedish single track electrified railway systems, without series lumped components, BT and AT feeding systems, respectively, with relevant track circuits are presented. The induced currents at different line segments, along the system, as the line is hit by direct lightning, are considered and compared. It is noticed that the presence of series and shunt lumped components are needed to be accounted for realistic current/voltage distribution assessments.

The authors’ contribution to this work was to develop the method used, write the simulation routine and test
it, make the calculations and write the paper. Author’s contribution to this paper was 80%.

**Paper VI** again touches the methodology issue and how to implement series devices along MTL systems. In this paper the effect of a lumped component, similar to the BT unit, along a simple MTL system is investigated.

In this work the author made the calculations, wrote the paper and presented this work at the conference. Author’s contribution was about 90%.

In **Paper VII** the method used for including the effects of lumped components along MTL systems were presented. At this conference one of the case studies in paper V (BT feeding system) is presented.

The contribution from the author was to run the simulations, write the paper. Author’s contribution was about 85%.

In **Paper VIII** the method presented in previous papers is adopted and used for calculations determining the indirect lightning effects on a typical railway catenary-track multiconductor transmission line system. The same three cases as per paper V were used in this paper. The peak voltages appearing across transformer windings or device ports were studied. It was found that the induced voltage wave shapes and amplitudes at any point along the line were dominated by BT or AT system type, and that the voltages appearing across AT windings were higher than for corresponding BT windings. However, the induced voltages across the track circuits were less dependent on system type and most affected by the introduction of components. It was also seen that the induced voltage appearing across a relay or rectifier unit along the rails were similar, whether it be a BT or AT system.

The author wrote the simulation routine, made the calculations, analysis and wrote the paper. Author’s contribution was 80%.
Papers IX, X, and XI are not explicitly included in this thesis because those topics are not directly connected to the work presented in this thesis and/or appeared in other theses from the EMC group. The author’s contribution to those papers was about 35%, 10%, and 10%, respectively.
7. Conclusion

Due to the practical difficulties associated with simulating MTL systems in conjunction with complex circuits (representative of lumped components and interconnections) an interfacing method between the FDTD method (which solves TL equations accurately) and a circuit solver (any circuit solver software) which solves equivalent linear or non linear circuit models is proposed. The proposed interface method for solving effects of series lumped devices along MTL systems is analytically verified to be the same as the well established FDTD method. By calculations, using systems with series connected lumped resistive and inductive components, it is shown that the difference in currents between the FDTD method and the interface model is lower than 10%. The series and shunt connected devices are later expanded to more complex devices, i.e., BT, AT, rectifier and relay units, which are connected in series and as shunts along a MTL system representative of a typical single track electrified railway system consisting of five overhead conductors as shown in Fig. 5.7. The effect of finitely conducting ground on pulse current and voltage propagation and also the effects of non-linear pole footing resistance, wire to pole insulator flashovers are also included in the calculations. The sources used in the calculations are direct injection of a double exponential current wave shape in one of the wires and series voltage sources due to exposure to electromagnetic fields,
representative of direct and indirect lightning strikes, respectively.

The extraction of frequency dependent circuit models, for the aforementioned lumped BT and AT, by means of SC tests and terminal modeling based on vector fitting technique has also been discussed and the equivalent frequency dependent models have been derived and presented.

All calculations are made for three MTL system topologies, namely, Case 1: without any lumped devices or interconnections or discontinuities along the MTL system, Case 2: BT system with all interconnections, discontinuities and track circuits, and Case 3: AT system with all interconnections, discontinuities and track circuits. Some of the trends of these devices, which are foreseeable, verify the applicability of the method on estimating the effects of complex lumped devices connected in series and as shunt along MTL systems. Before running the calculations the interface method was verified, not only analytically, but also by comparing results from the interface method, that is, with results obtained by the FDTD method with simple lumped resistive and inductive loads along lossless MTL systems consisting of up to two overhead wires.

It is demonstrated that peak current and voltage distributions and the device port voltages obtained in all the above cases are different, and that in Cases 2 and 3 reflections are very significant to bring about attenuation, amplification, or dispersion of propagating voltages and currents along the MTL system. Thus it is clear that while dealing with MTL systems representative of large electrical networks every lumped component, e.g., BT, AT, track circuits, line interconnections, etc., should be considered for realistic pulse current/voltage distribution and waveform assessments, which could be useful for the
protection and mitigation studies for distributed electrical systems such as electrified railways.

This work will expectedly result in a mitigation tool used by engineers at Banverket while planning for expanding or modernizing the existing electrified railway system by replacing old electromechanical devices by new devices containing integrated circuits and circuit boards, as well as estimating the impact of EMI sources on the normal operation of present electrified railway systems. The tool can be used for risk analysis, in conjunction with the failure-mode analysis of individual railway component in the laboratory.
8. Future Work

A method for incorporating series connected devices along MTL systems is presented and verified. In the work presented here the effects of ground impedance on the surge pulse propagation and the effect of lumped series and shunt connected devices along MTL systems on the current and voltage distribution and wave shapes are accounted for in the event of EMI, such as direct and indirect lightning strike, to a MTL similar to a typical Swedish single-track railway system. In this work the coupling to the buried wire present in a typical Swedish single-track railway system is not regarded. It would be very interesting to investigate on how the current wave shapes inducing in the shield of the buried wire (bare wire or insulated cable) would look like as the system is exposed to a source of EMI. From an EMC point of view it is beneficial to make an assessment on how the voltages across inner conductors of the communication cable would appear during a lightning strike to over-the-ground conductor system or due to indirect lightning.

Now that a method for incorporation of series and shunt components along MTL systems is available and it is possible to investigate the influence of surge protectors along MTL systems. A Monte Carlo simulation on an electrified railway system similar to a real single and/or double track railway system with all interconnections, grounding points, series connected devices, etc., can be preformed for making
assessments on how vulnerable a real railway system is to specific EMI sources. The study can also give an idea of voltages and currents that are to be expected across device ports connected to the railway system in events like lightning storms or switching transients or pantograph arcing.
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References


