Steady State and Transient Short Circuit Analysis of 2x25 kV High Speed Railways

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Abstract

In the paper, a detailed model for the short circuit analysis of the AC 2x25 kV-50 Hz traction system has been derived and implemented. Two different methods have been used: the time domain and frequency domain approaches. The two approaches are discussed and numerical applications are reported. In particular, in order to assess the feasibility of both the two methodologies, the results have been compared in steady state condition. Then a transient analysis has been performed by means of the time domain simulator evidencing the short circuit current transient behavior.

Introduction

The 2x25 kV feeding system is considered an optimal solution for high speed railways. The reduction in the number of electric substations as well as a greater efficiency due to the use of higher transmission voltages (50 kV supply between catenary and return feeder) with lower currents and lower voltage locomotive traction equipment (25 kV rail-catenary voltage) are the main advantages of the system [1]. Moreover, other advantages are related to the reduction of electromagnetic interference between traction converters and adjacent telecommunications circuits as well as the reduction of voltage drops.

Notwithstanding, critical operating conditions related to short circuit events can occur interfering with the traction system components so compromising the functionality of the whole system. The short circuit levels are particularly critical also due to the presence of the autotransformers that increases the fault currents. Short-circuit analysis is important not only for determining the rating of power equipment and the setting of protection devices but also for checking the voltage profiles of the network and of the buses near the fault as well as the electromagnetic compatibility with adjacent circuits. Thus, a detailed short-circuit study is required in both steady state and transient condition [2-3].

The accuracy of the system components is an important concern for the short circuit analysis since it significantly affects the simulation results. A critical issue, for example, is the identification of the impedances of the system components and the configuration of the network since they mainly determine the short-circuit results. Particular attention must be paid to an accurate modeling of the autotransformers as well as of both self and mutual impedances of the contact wire, rails and feeder.

In this paper the 2x25 kV electric railway system has been modeled in order to perform detailed steady state and transient short-circuit analyses. The steady state model has been implemented by means of a sequence of impedance matrices (chain matrices) representing each component [4-5].

The same system has been implemented also by using computer simulations developed in time domain by means of Matlab Power System Blockset, allowing to easily evaluate complex system behavior by representing each power system component by an equivalent block. The toolbox is suitable for efficient time-domain simulations, allowing to capture the functional dependence of system characteristics on time and various interest parameters. Through the time domain simulation, the short circuit analysis has been performed in transient condition.

In the paper the description of the considered traction system and of the problem formulation as well as the description of both the two proposed methodologies has been detailed. Both steady state and transient conditions have been investigated. Some experimental results on a measurement campaign conducted on the actual Italian system validate the results obtained in the simulation procedure.
**Problem Description**

In the 2x25 kV traction system the substation transformer feeds the overhead contact wire that supplies the trains as well as the feeder wire that runs along the track. The voltage of the overhead contact wire and feeder are respectively +25 kV and -25 kV. Autotransformers spaced along a section of track connect the contact wire, feeder and rails through a median tap. The electrical substations are equipped with 2 single phase transformers, each one feeding a railway line section of about 25 km. Autotransformers distanced by approximately 12 km divide the line sections in cells. In this configuration the current flows through the contact line and the feeder and there is no current in the rails except in the cell occupied by the train. The simplified scheme of the system operating condition (100 A traction load) is shown in Fig.1.

![Fig.1: 2x25 kV traction system scheme](image)

A 12 km cell contains all the basic elements constituting the 2x25 kV traction system:
- the substation equipped with two single phase 60 MVA transformers;
- the parallel post (PP) equipped with two single phase 15 MVA autotransformers;
- the supply circuit containing messenger wires, contact lines, feeders and rails;
- the earth circuit containing the protection and buried earth conductors.
- capacitive compensators, located between the rails every 100 m;
- inductive bonds, connecting the rails to the earth circuit for interference mitigation, located every 1500 m.

The transversal section of Fig.2 shows 14 conductors: the double track system wires (2 contact lines, 2 feeders, 2 messenger wires, 4 rail tracks, 2 buried earth conductors, 2 overhead earth conductors).

Two alternative implementations have been considered for short-circuit analysis. The former is performed by means of the frequency domain algorithm. The latter is performed by means of time domain simulation.

![Fig.2: Transversal section of the 2x25 kV railway system.](image)

To perform the analyses in the frequency domain, each element is represented by means of an equivalent impedance matrix. The system is solved by means of algebraic matrix operations.
In the time domain simulation, each component is represented by its differential equations. Finally, the system is represented by the whole set of the differential equations. In the following the system modeling for both the two approaches is briefly discussed [6].

**Solving Procedures**

**Frequency domain model** This algorithm starts representing the traction system by the node impedance matrix through inspection and, then, it deduces the fault current in each branch of the traction network as well as the curve of fault current versus fault location. The algorithm has the following advantages:
- all system components are described in exactly the same manner by defining their "primitive Z-node matrix";
- some more complex cases that often require "approximations" in classical methods can be handled in a clean manner without numerical difficulties.

The basic idea of the frequency domain model is the representation of the whole system through a sequence of impedance matrices (chain matrices) representing each component. According to the aim of the approach, each element is represented by a chain matrix, which relates the output voltages and currents to the input values:

\[
\begin{bmatrix}
V_{\text{out}} \\
I_{\text{out}}
\end{bmatrix}
= [A]_s
\begin{bmatrix}
V_{\text{in}} \\
I_{\text{in}}
\end{bmatrix} = \begin{bmatrix}
A_1 & A_2 \\
A_3 & A_4
\end{bmatrix}
\begin{bmatrix}
V_{\text{in}} \\
I_{\text{in}}
\end{bmatrix}
\] (1)

where \(V_{\text{out}}\) (\(I_{\text{out}}\)) is the [nx1] output voltage (current) vector, \(V_{\text{in}}\) (\(I_{\text{in}}\)) is the [nx1] input voltage (current) vector, and \(A\) is the [2nx2n] chain matrix. Matrix \(A\) can be divided in four submatrices of [nxn], where, in particular, \(A_2\) is the impedance matrix, and \(A_3\) is the admittance matrix.

Chain matrices can be calculated as the product of the matrices of each individuated element.

Aim of the model is the identification of voltage and current phasors at all the system locations. It is worth noting that the model of the system components significantly affects the level of accuracy of the simulations.

In the following a description of each component’s frequency domain model is detailed.

**Substation model.** The substation model is basically constituted by the single phase transformer and the substation earth circuit. Fig.4 shows the equivalent circuit model adopted for the substation transformer.

![Fig.4: Substation equivalent circuit](image)

For this representation 14 equivalent circuit equations and the corresponding matrix equation have been derived:

\[
[V(0)] = [V_s] - [Z_s] \cdot [I(0)]
\] (2)

The substation model is represented by a [14x1] matrix. \(V_s\) assumes value of +25kV for messenger and contact wires, -25kV for feeder; \(Z_s\) is derived from the equivalent circuit of the figure.
**Parallel post model.** The parallel post is constituted by the autotransformer whose equivalent circuit is shown in Fig.5. The characteristic chain matrix is:

\[
\begin{bmatrix} V(x) \end{bmatrix} = \begin{bmatrix} Z_{pp} \end{bmatrix} \begin{bmatrix} I(x) \end{bmatrix}
\]

where \( Z_{pp} \) is derived from the equivalent circuit of Fig.5.

![Parallel Post equivalent circuit](image)

**Multi-conductor line model.** The line section is modeled according to the method proposed in [7]. The model includes 14 conductors whose auto and mutual impedances have been considered. The governing multi transmission line (MTL) equations are a coupled set of first-order partial differential equations:

\[
\begin{align*}
\frac{\partial}{\partial z} V(z,t) &= R I(z,t) - L \frac{\partial}{\partial z} I(z,t) \\
\frac{\partial}{\partial z} I(z,t) &= G V(z,t) - C \frac{\partial}{\partial z} V(z,t)
\end{align*}
\]

where \( V \) contains the line voltages with respect to the reference conductor; \( I \) contains the line currents; and \( R, L, G, \) and \( C \) denote the per-unit-length parameters. The parameters are calculated from the geometry of the multi-conductor line configuration and the physical characteristics of the conductors.

The solution of the general phasor MTL equations for a line of length \( A \) can be written in the chain matrix form as:

\[
\begin{bmatrix} V(A) \\ I(A) \end{bmatrix} = \begin{bmatrix} \Theta_{11}(A) & \Theta_{12}(A) \\ \Theta_{21}(A) & \Theta_{22}(A) \end{bmatrix} \begin{bmatrix} V(0) \\ I(0) \end{bmatrix}
\]

**Signalling track circuit element model.** Two main components have to be considered for an accurate modelling of the system behaviour: the capacitive compensators and the inductive bonds.

a) Capacitive compensator

The chain sub-matrices of the element are calculated by output-input relations derived according to the circuit of Fig.7:

\[
\begin{bmatrix} V_{1c} \\ V_{2c} \end{bmatrix} = \begin{bmatrix} A_{c} \end{bmatrix} \begin{bmatrix} I_{1c} \\ I_{2c} \end{bmatrix} = \begin{bmatrix} A_{c1} & A_{c2} \\ A_{c3} & A_{c4} \end{bmatrix} \begin{bmatrix} I_{1c} \\ I_{2c} \end{bmatrix}
\]

where \([A_{c1}] = [A_{c4}] = [I], [A_{c4}] = 0\) and
Fig. 7: Compensator capacitor

\[
\begin{bmatrix}
0 & 0 & \ldots & 0 & \ldots & 0 & \ldots & 0 & \ldots & 0 & 0 \\
0 & 0 & \ldots & 0 & \ldots & 0 & \ldots & 0 & \ldots & 0 & 0 \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots & \vdots \\
0 & 0 & \ldots & -j\omega C & \ldots & j\omega C & \ldots & 0 & \ldots & 0 & 0 \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots & \vdots \\
0 & 0 & \ldots & j\omega C & \ldots & -j\omega C & \ldots & 0 & \ldots & 0 & 0 \\
\vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots & \vdots \\
0 & 0 & \ldots & 0 & \ldots & 0 & \ldots & 0 & \ldots & 0 & 0 \\
0 & 0 & \ldots & 0 & \ldots & 0 & \ldots & 0 & \ldots & 0 & 0
\end{bmatrix}
\]

b) Inductive bond

Similarly, the chain submatrices of the inductive bond are calculated by output-input relations derived according to the circuit of Fig. 8.

Fig. 8: Inductive bonds

**Time domain model.** The time domain simulations are developed by means of Matlab Power System Blockset (PSB). Each component is represented by a block, suitable to physically represent the behaviour of the component.

In the following the description of each component’s time domain model is detailed.

**Substation model.** The substation model is a 14 output line block basically composed by a single phase three windings transformer whose secondary windings are connected to feeders, contact wires and rails, Fig. 9.

Fig. 9: PSB Substation model
Parallel post model. For the autotransformer model, a 14 I/O line block composed by a single phase three windings transformer connected as represented in Fig. 10 has been used.

![Fig. 10: PSB parallel post model](image)

Multi-conductor line model. The multi-conductor line has been implemented by the PSB Distributed Parameters Line Block, that implements a N-phase distributed parameter line model with lumped losses. The resistance $R$, inductance $L$, capacitance $C$ line parameters are specified in $[nxn]$ matrices.

Signalling track circuit elements model. To reproduce the effects of capacitive compensators and inductive bonds, equivalent electrical lumped elements have been introduced in the model, according to the data reported in Tab. 1.

<table>
<thead>
<tr>
<th>Capacitive compensator (rail to rail)</th>
<th>25e-6 F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductive bond (rail to buried earth conductor)</td>
<td>1.2 mH</td>
</tr>
</tbody>
</table>

Table 1: Capacitive compensator and inductive bond values.

It can be noted that the time domain model allows to perform analyses in both steady state and transient conditions. The frequency domain model is an optimal tool for performing steady state analysis and is particularly suitable for harmonic studies [7,8]. It can be also used to analyze transients subject to the limitations of the superposition principle (applicable to linear systems). In the current paper the following assumptions have been made:
- According to the technical literature [8,9], the electromagnetic fields have TEM structure, which corresponds to the assumption of planewave propagation along the line.
- The multi conductor line representation does not take into account the inequalities in the earth’s surface and its lack of conductive homogeneity whose estimation can be found in [10].
- According to [11], for short circuit analyses, the lumped compensator capacitors have been neglected.

Numerical Applications

In order to test the two implemented simulation methods for the short circuit analysis, several system configurations have been considered. In the following the results obtained for two system configurations: a single cell of 12 km and a 4-cell system of about 50 km. The first case implemented consists of a short circuit (between the overhead catenary and rail) located at 0.7 km far from the substation. The single cell is included between the substation and the parallel post. The short circuit has been simulated with a resistance of 0.001 $\Omega$. Tab. 1 shows the numerical results in steady state conditions.
Monitored RMS values

<table>
<thead>
<tr>
<th>Distances from the substation [km]</th>
<th>Time Domain</th>
<th>Frequency domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_f ) 0.7</td>
<td>9973</td>
<td>9597</td>
</tr>
<tr>
<td>( I_{cl} ) 12</td>
<td>936.7</td>
<td>844.7</td>
</tr>
<tr>
<td>( I_{fe} ) 12</td>
<td>924.1</td>
<td>868.3</td>
</tr>
<tr>
<td>( I_{rail} ) 12</td>
<td>414.6</td>
<td>473.2</td>
</tr>
<tr>
<td>( I_{cl} ) 0</td>
<td>9036</td>
<td>8753</td>
</tr>
<tr>
<td>( I_{fe} ) 0</td>
<td>923.5</td>
<td>867.7</td>
</tr>
<tr>
<td>( I_{rail} ) 0</td>
<td>6652</td>
<td>7518</td>
</tr>
</tbody>
</table>

Table 2: Comparison of the results of the steady state short circuit analysis [6]

Tab. 2 evidences that the two models give similar results. A slightly higher fault current can be observed in the time domain simulation.

In order to test the system in transient condition a 50 km traction system has been considered. The system of 4 cells includes 1 feeding substation and 4 parallel posts. The short circuit is located at the distance of 50 km from the substation in correspondence of the fourth parallel post. The short circuit occurs at 0.5 ms between overhead and buried earth wires. Fig. 11 shows the instantaneous waveform of the peak fault current.

![Fig. 11: Waveform of the fault current in case of overhead-buried earth wire short circuit](image)

By the analysis of the figure it can be noted that the system is characterized by a typical first order dynamic where the peak value depends on the instantaneous system conditions when the short circuit occurs. The time constant is a function of the system parameters and for severe short circuit it very slightly depends on the short circuit resistance value. To focus on the transient in Fig. 12 the positive peak values of the fault current are reported.
Conclusions

Two methodologies for short circuit current calculation in the 2x25 kV traction system have been proposed. The two approaches are performed in frequency and time domains. They both represent the physical components by means of respectively the chain matrix and partial differential equation mathematical models.

The numerical application reported investigates on steady state and transient operating conditions. The results of the application are able to assess the suitability to perform short circuit analyses by both the two models.

Future works will be aimed at validating the numerical applications with experimental results obtained through a measurement campaign.

References


Appendix

The results reported are obtained for following parameters of the traction system:
Substation transformer parameters
Power: 60 MVA, voltage ratio: 132/2x27.5 kV, short circuit voltage: 10%
Auto-transformer Parameters
Power: 15 MVA, voltage ratio: 27.5/0/-27.5 kV, short circuit voltage: 1%.
Multi conductor line parameters
Tab. A shows the materials, resistivity (Ω/km), sections and positions of all the conductors involved in the systems.

<table>
<thead>
<tr>
<th>Description</th>
<th>Material</th>
<th>Resistance [Ω/km]</th>
<th>Section [mm²]</th>
<th>X [m]</th>
<th>Y [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Left side track system</td>
<td></td>
</tr>
<tr>
<td>Feeder</td>
<td>Al</td>
<td>0.109</td>
<td>307</td>
<td>-6.60</td>
<td>8.00</td>
</tr>
<tr>
<td>Messenger</td>
<td>Cu</td>
<td>0.15</td>
<td>120</td>
<td>-2.50</td>
<td>6.55</td>
</tr>
<tr>
<td>Contact line</td>
<td>Cu</td>
<td>0.12</td>
<td>150</td>
<td>-2.50</td>
<td>5.30</td>
</tr>
<tr>
<td>External Rail</td>
<td>UNI60</td>
<td></td>
<td></td>
<td>-3.26</td>
<td>0.01</td>
</tr>
<tr>
<td>Internal Rail</td>
<td>UNI60</td>
<td></td>
<td></td>
<td>-1.74</td>
<td>0.01</td>
</tr>
<tr>
<td>Buried earth wire</td>
<td>Cu</td>
<td>0.19</td>
<td>95</td>
<td>-5.00</td>
<td>-1.12</td>
</tr>
<tr>
<td>Protection wire</td>
<td>Al</td>
<td>0.225</td>
<td>150</td>
<td>-6.12</td>
<td>5.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Right side track system</td>
<td></td>
</tr>
<tr>
<td>Feeder</td>
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<td>0.109</td>
<td>307</td>
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<td>0.225</td>
<td>150</td>
<td>6.12</td>
<td>5.50</td>
</tr>
</tbody>
</table>

Table A: Track line parameters