OpenPowerNet
Simulation of Railway Power Supply Systems

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Stephan_080124_OpenPowerNet_engl.ppt (Figure 1)
Simulation of Railway Power Supply Systems – why?

The electrical load flow and the energy consumption within the railway power supply network depend on the running trains and the power supply system characteristics.

- There are consumers with a time-dependent and location-dependent power demand (picking up and recovering energy).
- The network structure and the voltage influence the load flow.
- The power supply system may influence the energy consumption.

Simulation of these dynamic processes allow analysis and prognosis:

- Load flow and energy consumption
- Technical layout and design of the electrical installations.
Requirements

The **voltage situation** of the railway power supply network determines the load flow and may have retroaction to the propulsion characteristics of the trains:

- current and power losses increase with decreasing voltage,
- under low voltage current and power limitations of the propulsion control are activated ⇒ with impact on the driving dynamics,
- the network voltage influences the braking energy recovering decisively (energy absorption capability).

These **retroactions** to be emulated in the simulation:

- for a.c. networks less relevant because of stable voltage level,
- for d.c. networks with high load dynamics absolutely essential
Initial Situation

Energy consumption simulation for electrical railway systems requires detailed information available at the same time concerning

• each train’s driving state and the required traction power,
• the train’s positions within the network,
• the layout and capability of the power supply system.

For that reason a number of compromises were made in the past

• either concerning the complexity of the railway operation simulation,
• or regarding the modelling depth of the propulsion technology and the electrical network.
Simulation Requirements

Railway Operation
- Line routing and alignment
- Track layout
- Signalling system
- Train data
- Propulsion data
- Timetable
- Connecting conditions
- Operating rules

Load Flow and Energy
- Line routing and alignment
- Track layout
- Signalling system
- Train data
- Propulsion data
- Timetable
- Connecting conditions
- Operating rules
- Power grid / Substations
- Feeder lines and cables
- Catenary system
Separation of Simulation Tasks

Railway Operation
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- Operating rules

Load Flow and Energy
- Propulsion data
- Power grid / Substation
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- Catenary system

Plug-in
Railway Operation Simulation

OpenPowerNet

ATM
Advanced Train Module

PSC
Power Supply Calculation

Interaction

“Co-Simulation”

Propulsion Technology

Power Supply System

OpenPowerNet – Simulation of Railway Power Supply

IT08 • Rail • Userworkshop
Simulation Sequence per Time Step

Train Position, Requested Effort

Train Current

Line Voltage, Requested Effort

Achieved Effort
Modelling levels available for propulsion simulation

a) constant efficiency factors for propulsion equipment
b) driving state related efficiency factors
c) load depending efficiency factors of components
d) detailed engine models of components

+ auxiliary power and eddy current break
+ additionally: limiting values of propulsion control (e.g. voltage related current limitation)
Propulsion Structure

\[ P_{el} \]

- Transformer
  - 4QS
  - Inverter
  - Motor
  - Gear
  - Effort

- Auxiliary Power
- Traction Power
- Eddy Current Brake Power

\[ P_{mech} \]
Efficiency Characteristics of ICE3 train

1 AC 15 kV 16,7 Hz

Motorfreqenz

Wirkungsgrad

- Transformator
- 4-QS
- Pulswechselrichter
- Asynchron-Fahrmotor
- Radsatzgetriebe
- Gesamt

Hz

Stephan_080124_OpenPowerNet_engl.ppt (Figure 11)
Propulsion Component Modelling  (example for traction motor)

\[ M_{\text{elekt}} = M_{\text{mech}} + M_{\text{Läuferverluste}} \]

\[ M_{\text{Läuferverluste}} = \frac{P_{\text{Rotorverluste}}}{2\pi n} = \frac{3}{2} \cdot \frac{i'_{2}^{2}}{2} \cdot \frac{R'_{2}}{2\pi n} \]
Propulsion Model Verification

Train Current and Pantograph Voltage
Train Speed and Power Characteristics

Measurement and Simulation Results

ICE1 Hannover – Göttingen

Fehlertoleranzen: Fahrschaubild < 1 %
Energie ab Stromabnehmer < 2 %

Quelle: IFB
Requirements to the electrical network model

- Simulation of all common AC- and DC-railway power supply systems
- Representation of the entire electrical network structure
- Unrestricted choice of conductor configuration along the line
- Precise consideration of electromagnetic coupling of conductors for a.c.-systems
- Switch state change within the railway power supply system
- Retroaction to the railway operation simulation (OpenTrack)
- Iterative communication with the propulsion simulation (ATM)
- Configurable data output
- Interfaces for post-processing
Modelling of infrastructure

Catenary arrangement and switch state
Modelling of the Railway Power Supply System

- Electrical network structure (feeding sections, feeding points, switch state) in congruence to the track topology
- Electrical characteristics of the feeding power grid
- Electrical characteristics of the substations
- Electrical characteristics of the conductors (cables, Catenary wires, tracks, rails)
- Electrical characteristics rail-to-earth
- Modelling of additional power consumers (e.g. switch heatings)
- Loading capacity (conductors, converters, transformers)
- Protection settings
Power Supply Network Structure (DC 0.6 ... 3.0 kV)

Power Grid Connection
3 AC 10 / 20 / 30 kV

Substation
SS1
SS2
SS3
SS4

0.6 kV

G01 G02 G03 G04 G05

G1 RE G2 RE G3 RE G4 RE G5 RE

G1 RE G2 RE G3 RE G4 RE G5 RE

G1 RE G2 RE G3 RE G4 RE G5 RE

G1 RE G2 RE G3 RE G4 RE G5 RE

G1 RE G2 RE G3 RE G4 RE G5 RE

G1 RE G2 RE G3 RE G4 RE G5 RE

G1 RE G2 RE G3 RE G4 RE G5 RE

Earth

train NOT in section

train in section

Substation: SS1, SS2, SS3, SS4

G01, G02, G03, G04, G05

G1 RE, G2 RE, G3 RE, G4 RE, G5 RE

OCS, Rails, Earth
Power Supply Network Structure (1 AC 15 kV 16.7 Hz)

Power Grid Connection
1 AC 110 kV 16.7 Hz
Power Supply Network Structure (2 AC 25 kV ~ 50 / 60 Hz)

Power Grid Connection
3 AC 110 / 220 kV

Substation
Autotransformer
Autotransformer
Autotransformer

25 kV

Y_{O1}
Y_{R1}
Y_{N1}
Y_{RE}

Y_{O2}
Y_{R2}
Y_{N2}
Y_{RE}

Y_{O3}
Y_{R3}
Y_{N3}
Y_{RE}

Y_{O4}
Y_{R4}
Y_{N4}
Y_{RE}

OCS
Rails
Negative Feeder
Earth

train NOT in section
—
train in section
—

Stephan_080124_OpenPowerNet_engl.ppt (Figure 20)
Substation / AT Structure (2 AC 25 kV ~ 50/60 Hz)
Trackside Arrangement of Conductors

Source: DB KoRiL 997
Trackside Arrangement of Conductors
Catenary Arrangement and Conductor Model

„Slice“

CWH Contact wire height  SH System height
Negative Feeder  Return conductor  Messenger wire  Contact wire
Catenary Arrangement and Conductor Model

Slice n

material, diameter

(\(x_1; y_1\))

(0; 0)

electro-magnetic coupling effects
Sequence of Slices

Slice 0

Node

Section

Slice 1

Connector

Slice 2

Negative Feeder

OCS

Rail

Conductor

Earth

Position

$X_0$

$X_1$

$X_2$
Mathematical Network Model
Electrical network calculation using the advanced method of nodes

\[
\begin{pmatrix}
Y_{1,1} & U_{1,0} & U_{2,0} & U_{3,0} & U_{4,0} & U_{5,0} \\
U_{1,0} & U_{1,1} & U_{1,2} & U_{1,3} & U_{1,4} \\
U_{2,0} & U_{2,1} & U_{2,2} & U_{2,3} & U_{2,4} \\
U_{3,0} & U_{3,1} & U_{3,2} & U_{3,3} & U_{3,4} \\
U_{4,0} & U_{4,1} & U_{4,2} & U_{4,3} & U_{4,4} \\
U_{5,0} & U_{5,1} & U_{5,2} & U_{5,3} & U_{5,4}
\end{pmatrix}
= \begin{pmatrix}
I_{1,1} \\
I_{1,2} \\
I_{1,3} \\
I_{1,4} \\
I_{1,5}
\end{pmatrix}
\]

Voltage drops caused by self- and mutual induction

<table>
<thead>
<tr>
<th>Knoten</th>
<th>(U_{10})</th>
<th>(U_{20})</th>
<th>(U_{30})</th>
<th>(U_{40})</th>
<th>(U_{50})</th>
<th>(U_{11})</th>
<th>(U_{12})</th>
<th>(U_{13})</th>
<th>(U_{14})</th>
<th>(U_{15})</th>
<th>(I_q)</th>
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<td>1</td>
<td>(G_{14} + \frac{X}{G}e)</td>
<td>(-\frac{X}{G}e)</td>
<td>(-G_{14})</td>
<td>(\frac{X}{G}e)</td>
<td>(-\frac{X}{G}e)</td>
<td>(-G_{15})</td>
<td>(-G_{16})</td>
<td>(-G_{17})</td>
<td>(-G_{18})</td>
<td>(-G_{19})</td>
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<td>(-\frac{X}{G}e)</td>
<td>(G_{25} + \frac{X}{G}e)</td>
<td>(-G_{25})</td>
<td>(-\frac{X}{G}e)</td>
<td>(G_{25})</td>
<td>(-G_{25})</td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>3</td>
<td>(G_{3} + \frac{X}{G}e)</td>
<td>(-\frac{X}{G}e)</td>
<td>(-G_{26})</td>
<td>(-\frac{X}{G}e)</td>
<td>(G_{3})</td>
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<tr>
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<td>(-G_{26})</td>
<td>(-\frac{X}{G}e)</td>
<td>(G_{26} + \frac{X}{G}e)</td>
<td>(-\frac{X}{G}e)</td>
<td>(G_{26})</td>
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<tr>
<td>5</td>
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<td>(-\frac{X}{G}e)</td>
<td>(G_{26} + \frac{X}{G}e)</td>
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<td>(G_{26})</td>
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</table>
Verification of the simulation

- Punctual theoretical evaluation
  - current sum cero for network slices
  - energy picking up and recovering
  - correspondence of voltage minimum and maximum / jumps with the network structure during constant load test

- Comparison of measurement data with the simulation results for predefined load cases
  - driving dynamics of the trains
  - current-, voltage- and power characteristics
Verification: Measurement and Simulation

AB07, Messfahrt F8, mit Halt

Zeit [s] vs. Geschwindigkeit [km/h]

- v_TFZ_2099
- v_Tfz_Simu
Verification: Measurement and Simulation

AB07, Messfahrt F8, mit Halt

![Graph showing voltage and current over time with various labels and annotations.](image-url)
High Speed Railway
300 km/h
100 km Double Track
2AC 25 kV 50 Hz
Simulation Results: High Speed Railway 2AC 25 kV

Train Current \( I = f(s) \)
Simulation Results: High Speed Railway 2AC 25 kV

Train Current $I = f(s)$, Line Voltage at Pantograph $U = f(s)$
Simulation Results: High Speed Railway 2AC 25 kV

Pantograph Voltages of all Trains $U = f(s)$
Simulation Results: High Speed Railway 2AC 25 kV

Overhead Line Voltage $U = f(t)$

10:02:30 AT-station switched-off
Simulation Results: High Speed Railway 2AC 25 kV

Return Current Distribution $I = f(s)$

![Graph showing current distribution along the railway line with three substations: SS, AT1, and AT2. The graph illustrates the current distribution at different points along the track, with peaks at AT1 and SS, and a continuous decrease towards AT2. The graph also shows two different current paths: Return Feeder and Earth.](Stephan_080124_OpenPowerNet_engl.ppt (Figure 37))
Simulation Results: High Speed Railway 2AC 25 kV

Substation Transformer Power $P = f(t)$
Simulation Results: High Speed Railway 2AC 25 kV

Energy Consumption at Substation Busbar $E = f(t)$
City Light Rail
300 km TRAM
220 km Trolley
DC 600 V
Vehicle modelling
TRAM und Trolleybus
Graphical time table

Line A
Minimum voltage: catenary and pantograph

Normal operation

[Graph showing voltage levels over distance with labels for various locations and voltage ranges.]
Rail-to-earth potential

Normal operation

Spannung [V]

Weg [km]
Converter current and bus-bar voltage

Normal operation
Converter current and bus-bar-voltage

Depot gateway 4:50 - 7:05 h
Load and loading capacity

Substation

Normal operation, blackout in neighbouring subst.
### Load values

**Substation**, Normal operation without blackouts

<table>
<thead>
<tr>
<th>Station</th>
<th>Sektor</th>
<th>$I_{max} \ [A]$</th>
<th>$I_{eff} \ [A]$</th>
<th>$P_{max} \ [kW]$</th>
<th>$E_{ab} \ [kWh]$</th>
<th>$E_{auf} \ [kWh]$</th>
<th>$E_{verl} \ [kWh]$</th>
<th>$I_{Einst} \ [kA]$</th>
<th>$I_{Kmin} \ [kA]$</th>
<th>$I_{Kmin}/I_{Einst}$</th>
<th>$I_{max}/I_{Einst}$</th>
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<td>Promenade</td>
<td>SK - Rämistraße</td>
<td>1915</td>
<td>588</td>
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<td>520</td>
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<td>14.0</td>
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<td>0</td>
<td>2</td>
<td>3.0</td>
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<td>3.5</td>
<td>10.4</td>
<td>297%</td>
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<td>720</td>
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<td>2.5</td>
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<td><strong>108%</strong></td>
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<td>3.6</td>
<td>2.7</td>
<td>108%</td>
<td>36.5%</td>
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</tbody>
</table>

SK: Speisekabel
RK: Rückleiterkabel
Load and loading capacity  
Catenary wire at feeding point  
Normal operation, blackout in neighbouring subst.
Energy balance

- Case 1: 5.7%
- Case 2: 6.2%
- Case 3: 8.6%
- Case 4: 17.8%

Legend:
- □ ins Netz zurückgespeiste Bremsenergie
- □ abgegebene Energie aller Unterwerke
Power losses balance

Case 1    Case 2    Case 3    Case 4
5.8%      5.8%      5.6%      5.7%

- Verluste in Kabeln (GUw)
- Verluste Fahreitung (Tram+TB)
- Verluste in Gleisen (Tram)
Recovering balance

Case 1  Case 2  Case 3  Case 4

Available braking energy
Utilized braking energy
Energy returned to the network
Post-processing: Electro-magnetic Field Exposition 1AC 15 kV 16,7 Hz
Summary

1. Operation Simulation (OpenTrack)
   • Precise railway operation simulation using a commercial simulator
   • Co-simulation with electrical network calculation of OpenPowerNet (New!)
   • Online-communication between operation and electrical network simulation via SOAP-Interface (New!)
   • Retroaction of electrical network calculation to train driving dynamics
   • Automatic disturbance generation caused by the power supply (New!)

2. Load Flow and Energy Calculation (OpenPowerNet)
   • Complete electrical network calculation by the PSC module considering all electromagnetic coupling effects (New!)
   • Input of the electrical network parameters by geometrical conductor arrangement and material properties, unrestricted configurable (New!)
   • Switch state changes of the electrical network during simulation (New!)
   • Configurable modelling depth for train propulsion system in the ATM module: constant efficiency / characteristic curves / engine models + control (New!)
   • Comprehensive analyzing and interpreting tools (energy, load flows, currents, voltages, temporal / local) as well as data export for post-processing

Stephan_080124_OpenPowerNet_engl.ppt   (Figure 55)
Eine Expertenrunde für das Gesamtsystem Bahn
The Expert Team for the Complete Railway System

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