OpenPowerNet
The new Co-simulation Tool
for Traction Power Supply

Prof. Dr.-Ing. Arnd Stephan
Simulation of Traction Power Supply – what for?

- The voltage situation as well as the network structure influence the electrical load distribution (… current levels and current directions).
- There are energy consumers with time-dependent and position-dependent power demands (… picking up and recovering energy).

⇒ Thus the power supply system influences the energy consumption.

Simulation of these dynamic processes enables:

- Energy consumption analysis and prognosis
- Design and rating verification of the electrical installations
- EMC studies
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

G_{D1} G_{D2} G_{D3} G_{D4} G_{D5}

\[ \text{single-end} \quad \text{double-end} \quad \text{double-end} \]

\[ \text{SS1} \quad \text{SS2} \quad \text{SS3} \quad \text{SS4} \]

Earth

\[ \text{train NOT in section} \quad \text{train in section} \]

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Special Requirements

The network voltage situation affects the electrical load flows and may have retroaction to the propulsion characteristics of the trains:

• currents and power losses increase with decreasing voltage,

• under low voltage conditions current or power limitations of the train propulsion control are activated ⇒ … impact on driving dynamics,

• the network voltage influences the braking energy recovering decisively ("energy absorption capability").
Initial Situation

Energy consumption simulation for electrical railway systems requires detailed information concerning …

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

All these information are needed exactly at the same time.

In the past a number of compromises were made

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

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

Load Flow and Energy
- Train propulsion data
- Power grid parameter
- Substation arrangement
- Feeder lines and cables
- Catenary system
- Earthing system
- Switch status

Plug-in

OpenPowerNet

openPowerNet – Co-Simulation Tool for Traction Power Supply
RTS 2010
**OpenPowerNet – Co-Simulation Tool for Traction Power Supply**

**RTS 2010**

**Input Data**
- Rolling Stock
- Infrastructure
- Timetable

**Simulation**
- Interactivity
- Animation
- Diagrams
- Timetable Graphs
- Track Occupations
- Statistics

**Output Data**
- Time Graphs
- Timetable Graphs
- Track Occupations
- Statistics

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*Stephan_RTS2010_OpenPowerNet.ppt* (Figure 7)

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Geometrical Track Model
Railway Operation Simulation

ATM
Advanced Train Module

PSC
Power Supply Calculation

“Co-Simulation”

Interaction

Propulsion Technology

Power Supply System

openPowerNet – Co-Simulation Tool for Traction Power Supply

Stephan_RTS2010_OpenPowerNet.ppt  (Figure 10)
Simulation Sequence per Time Step

Stephan RTS2010 OpenPowerNet.ppt (Figure 11)
**openPowerNet – Co-Simulation Tool for Traction Power Supply**

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**OPEN TRACK**

**SOAP interface**

1. train_ID, engine_ID, line_ID, track_ID, train location, time, requested force, speed

2. line_ID, track_ID, train location, time, train current

3. train voltage, nominal voltage, nominal frequency

4. train_ID, engine_ID, requested force, speed, train voltage, nominal voltage, nominal frequency

5. achieved force, train current

6. achieved force

---

**AP Server**

**network database**

**propulsion database**

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**PSC**

**ATM**

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Stephan_RTS2010_OpenPowerNet.ppt  (Figure 12)
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

+ auxiliaries and eddy current break power
+ 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
Propulsion Component Modelling  (example for traction motor)

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

\[ M_{\text{Läuferverluste}} = \frac{P_{\text{Rotorverluste}}}{2 \pi n} = \frac{3}{2} \frac{i_2' \cdot R_2'}{2 \pi n} \]
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 effects of overhead line conductors for a.c.-systems
- Change of switching status within the power supply network
- Retroaction to the railway operation simulation (OpenTrack)
- Iterative communication with the propulsion simulation (ATM)
- Configurable data output
- Interfaces for post-processing
Power Supply Network Structure (DC 0.6 … 3.0 kV)

Power Grid Connection
3 AC 10 / 20 / 30 kV

SS1 Substation
SS2 Substation
SS3 Substation
SS4 Substation

0.6 kV

G₀₁
G₀₂
G₀₃
G₀₄
G₀₅

Gᵣ₁
Gᵣ₂
Gᵣ₃
Gᵣ₄

Gᵣₑ
Gᵣₑ
Gᵣₑ
Gᵣₑ
Gᵣₑ
Gᵣₑ
Gᵣₑ

Earth

single-end
double-end
double-end

train NOT in section
train in section

Stephan_RTS2010_OpenPowerNet.ppt  (Figure 20)
**Power Supply Network Structure (1 AC 15 kV 16.7 Hz)**

Power Grid Connection  
1 AC 110 kV 16.7 Hz

![Diagram of Power Supply Network Structure](image)
Power Supply Network Structure (2 AC 25 kV ~ 50 / 60 Hz)

Power Grid Connection
3 AC 110 / 220 kV

Substation

Autotransformer

Autotransformer

Autotransformer

OCS

Rails

Negative Feeder

Earth

train NOT in section

train in section
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
Substation / AT Structure (2 AC 25 kV ~ 50/60 Hz)
Trackside Arrangement of Conductors

Source: DB KoRiL 997
Catenary Arrangement and Conductor Model

- CL TRACK
- SH = 1600
- CWH = 5300
- TOR

1. CWH Contact wire height
2. Negative Feeder
3. System height
4. Return conductor
5. Messenger wire
6. Contact wire

„Slice“
Catenary Arrangement and Conductor Model

Slice n

- Material, diameter
- Electro-magnetic coupling effects

((x₁; y₁))
Sequence of Slices
Electrical network calculation using the advanced method of nodes

Voltage drops caused by self- and mutual induction

<table>
<thead>
<tr>
<th>nodes</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>( I_q )</th>
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<td>( G_{14} + Y_{oE} )</td>
<td>(-Y_{OE})</td>
<td>(-G_{14})</td>
<td>(-G_{14})</td>
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<tr>
<td>2</td>
<td>(-Y_{GE})</td>
<td>( G_{25} + Y_{GE})</td>
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<td>(-G_{25})</td>
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<td></td>
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<tr>
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<td>( G_{3})</td>
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<tr>
<td>4</td>
<td>(-G_{14})</td>
<td>(-Y_{4})</td>
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<tr>
<td>5</td>
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High Speed Railway
350 kph
966 km Double Track
2AC 25 kV 50 Hz
Simulation Example: High Speed Railway 966 km, Track Alignment (Detail)
Simulation Example: High Speed Railway 966 km, OCS Infeed (Detail)
Simulation Results: High Speed Railway 2AC 25 kV

Train Speed $v = f(t)$
Guangzhou direction with 2 stops, CRH 3
Simulation Results: High Speed Railway 2AC 25 kV

Train Current I = f(s)
Guangzhou direction non-stop, 1x CRH 3
Simulation Results: High Speed Railway 2AC 25 kV
Simulation Results: High Speed Railway 2AC 25 kV

Pantograph Voltage $U = f(t)$
Guangzhou direction non-stop, CRH 3
Simulation Results: High Speed Railway 2AC 25 kV

Pantograph Voltage $U = f(s)$
Guangzhou direction non-stop, CRH 3
Simulation Results: High Speed Railway 2AC 25 kV

Minimum Pantograph Voltage, Wuhan-Guangzhou
Line Wuh-Gua_1, Track Up, km 1265.75-1319.69
Simulation Results: High Speed Railway 2AC 25 kV

Busbar Power, Wuhan-Guangzhou
Substation TSS_1444_Hua, Transformer 1444_Hua_TT-02

The diagram shows the apparent power, active power, and reactive power over time for the specified substation and transformer. The x-axis represents time from 12:00:01 to 12:55:01, and the y-axis represents power in kiloamperes (kVA). The graph includes lines for different components and power parameters, illustrating the simulation results for the traction power supply system.
Simulation Results: High Speed Railway 2AC 25 kV

TSS Energy Delivery (1 h)
WGPDL - Operation Program 2028

[Bar chart showing energy delivery by substation for WGPDL operation program 2028, with energy total and energy by TSS indicated.]
Simulation Results: High Speed Railway 2AC 25 kV

Recovery Rates (peak operation)
WGPDL - Operation Program 2028
## Simulation Results: High Speed Railway 2AC 25 kV

### Vehicle Energy Consumption And Recovery Overview, Wuhan - Guangzhou

Ygm 1862-1918

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<thead>
<tr>
<th></th>
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<td>26001,806</td>
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<td>67,466</td>
<td>1755,741</td>
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<td>67,466</td>
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<td>1,596</td>
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<tr>
<td>CRH3</td>
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<td>1754,247</td>
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<tr>
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<tr>
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<tr>
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<tr>
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<td>G520-1</td>
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</table>
## Simulation Results: High Speed Railway 2AC 25 kV

### Energy Consumption And Losses Overview, Wuhan - Guangzhou

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<thead>
<tr>
<th>Description</th>
<th>Value</th>
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<tr>
<td>Energy output to catenary at substation [kWh]</td>
<td>72300,187</td>
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<tr>
<td>Energy input from catenary at substation [kWh]</td>
<td>1154,082</td>
</tr>
<tr>
<td><strong>Total energy at substation [kWh]</strong></td>
<td><strong>71146,105</strong></td>
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<tr>
<td>Vehichles energy consumption [kWh]</td>
<td>78540,848</td>
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<tr>
<td>Vehicles braking energy used for auxiliaries [kWh]</td>
<td>639,139</td>
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<tr>
<td>Vehicles braking energy recovered by catenary [kWh]</td>
<td>9230,867</td>
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<tr>
<td><strong>Total used vehicles braking energy [kWh]</strong></td>
<td><strong>9870,007</strong></td>
</tr>
<tr>
<td><strong>Total vehicles energy [kWh]</strong></td>
<td><strong>69309,980</strong></td>
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<tr>
<td><strong>Total energy consumption [kWh]</strong></td>
<td><strong>81016,112</strong></td>
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<tr>
<td>Energy consumption from national power grid [kWh]</td>
<td>71233,480</td>
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<tr>
<td><strong>Average efficiency of traction power supply</strong></td>
<td><strong>97,6%</strong></td>
</tr>
<tr>
<td>Losses in contact wire [kWh]</td>
<td>525,588</td>
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<tr>
<td>Losses in messenger wire [kWh]</td>
<td>565,248</td>
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<tr>
<td>Losses in negative feeder [kWh]</td>
<td>481,426</td>
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<td>Losses in return conductor [kWh]</td>
<td>138,879</td>
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<td>Losses in left rail [kWh]</td>
<td>13,174</td>
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<td>Losses in right rail [kWh]</td>
<td>13,196</td>
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<td>Losses in LEBC [kWh]</td>
<td>31,117</td>
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<td><strong>Total losses in conductors [kWh]</strong></td>
<td><strong>1768,629</strong></td>
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<td>Losses in connectors [kWh]</td>
<td>1,495</td>
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<td>Losses in autotransformers [kWh]</td>
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<td><strong>Total losses in catenary system [kWh]</strong></td>
<td><strong>1792,020</strong></td>
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<td>Losses in feeders [kWh]</td>
<td>44,072</td>
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<tr>
<td>Losses in traction transformers [kWh]</td>
<td>87,375</td>
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</table>
Simulation Results: High Speed Railway 2AC 25 kV

Maximum Substation Power
WGPDL - Operation Program 2028

Apparent Power [MVA]

WU dir.
GUA dir.
Simulation Results: High Speed Railway 2AC 25 kV

Maximum Return Cable Current
WGPDL - Operation Program 2028

- SP WU dir.
- ATS WU dir.
- ATS GUA dir.
- SP GUA dir.
Simulation Results: High Speed Railway 2AC 25 kV

Short Circuit Current, Wuhan-Guangzhou
Line Wuh-Gua_2, Track Up, km 1961.2-2015.12

[Graph showing short circuit current with various markers indicating isolators, ATs, and infed points along the track.]
Simulation Results: High Speed Railway 2AC 25 kV

Maximum Rail-Earth Potential, Wuhan-Guangzhou
Line Wuh-Gua_2, Track Up, km 1961.2-2015.12

Position [km]

Voltage [V]

78 V
Simulation Results: High Speed Railway 2AC 25 kV

- **TSS SHA km 1986,8**
- **ATS km 1997,4**
- **SP km 2015,1**

Diagram showing currents and power distribution along the railway, including:
- OCS: 1150 A
- Rails: 363 A, 136 A, 74 A
- RC: 148 A, 60 A
- LEBC: 163 A, 7 A, 13 A
- NF: 603 A
- **2x CRH 3**: 880 A
- **387 A**: 2x CRH 3

Currents and power values are shown for different sections and years:
-EMC 1 / EMC 2 1987,000
-EMC 3 1997,000
-EMC 4 1998,000

Institut für Bahntechnik GmbH
Simulation Results: High Speed Railway 2AC 25 kV
City Light Rail Network
300 km TRAM
220 km Trolleybus
DC 600 V
Graphical time table
Minimum voltage: catenary and pantograph

Normal operation

![Graph showing minimum voltage for traction power supply system.](Stephan_RTS2010_OpenPowerNet.ppt (Figure 53))
Rail-to-earth potential  Normal operation

[Graph showing rail-to-earth potential over a distance in km, with various locations marked along the x-axis and voltage levels on the y-axis.]
Converter current and bus-bar-voltage  Depot gateway 4:50 - 7:05 h
Load and loading capacity

Substation DC Converter

Normal operation, blackout in neighbouring subst.

![Graph showing load and loading capacity of substations](Stephan_RTS2010_OpenPowerNet.ppt)
Load values **Substation Feeders**, Normal operation without blackouts

<table>
<thead>
<tr>
<th>Station</th>
<th>Sektor</th>
<th>$I_{\text{max}}$</th>
<th>$I_{\text{eff}}$</th>
<th>$P_{\text{max}}$</th>
<th>$E_{\text{ab}}$</th>
<th>$E_{\text{auf}}$</th>
<th>$E_{\text{verl}}$</th>
<th>$I_{\text{Einst}}$</th>
<th>$I_{\text{Kmin}}$</th>
<th>$I_{\text{Kmin}}/I_{\text{Einst}}$</th>
<th>$I_{\text{max}}/I_{\text{Einst}}$</th>
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<tr>
<td>SK</td>
<td>-</td>
<td>1915</td>
<td>588</td>
<td>1221</td>
<td>520</td>
<td>-10</td>
<td>4</td>
<td>3.5</td>
<td>14.0</td>
<td>400%</td>
<td>54.7%</td>
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<td>SK</td>
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<td>11.7</td>
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<td>1252</td>
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<td>10.4</td>
<td>347%</td>
<td>65.4%</td>
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<tr>
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<td>1665</td>
<td>332</td>
<td>1048</td>
<td>257</td>
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<tr>
<td>SK</td>
<td>-</td>
<td><strong>3710</strong></td>
<td><strong>1018</strong></td>
<td><strong>2312</strong></td>
<td><strong>1000</strong></td>
<td><strong>-33</strong></td>
<td><strong>36</strong></td>
<td><strong>4.2</strong></td>
<td><strong>12.7</strong></td>
<td><strong>302%</strong></td>
<td><strong>88.3%</strong></td>
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</table>

SK: Feeder cable  
RK: Return current cable
Load and loading capacity  Catenary wire at feeding point
Normal operation, blackout in neighbouring subst.

![Graph showing load and loading capacity over time]
Energy balance

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

Recovered energy
Delivered energy of all substations

Stephan_RTS2010_OpenPowerNet.ppt (Figure 59)
Power losses balance

Case 1  Case 2  Case 3  Case 4

5.8%  5.8%  5.6%  5.7%

Energie [kWh]

- Verluste in Kabeln (GUw)
- Verluste Fahrdienst (Tram+TB)
- Verluste in Gleisen (Tram)

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Recovering balance

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<th>Available Energy (kWh)</th>
<th>Used Energy (kWh)</th>
<th>Energy Returned to Grid (kWh)</th>
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<td>25.2%</td>
<td>15.0%</td>
<td>0.0%</td>
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<td>Case 2</td>
<td>26.7%</td>
<td>16.2%</td>
<td>0.0%</td>
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<tr>
<td>Case 3</td>
<td>36.1%</td>
<td>22.2%</td>
<td>0.0%</td>
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<td>Case 4</td>
<td>70.9%</td>
<td>43.3%</td>
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</table>
Conclusions

- **OpenPowerNet** is able to simulate all common a.c. and d.c. railway power supply systems.

- **OpenPowerNet** works as a co-simulation with the commercial OpenTrack railway operation simulator.

- The Co-simulation principle is profitably for modelling, data handling and independent software further development.

- The accuracy of the electrical network simulation was verified by field measurements.

- Simulation service can be provided including or excluding the operation modelling (… already existing models can be used easily).

- **OpenPowerNet** was officially put into the market in 2009.
Eine Expertenrunde für das Gesamtsystem Bahn
The Expert Team for the Complete Railway System

IFB Dresden Branch, Wiener Str. 114-116, 01219 Dresden, Germany
Phone: +49 351 87759-0, E-Mail: ifb-dresden@bahntechnik.de, Web: www.bahntechnik.de