# OpenPowerNet
## Simulation of Railway Power Supply Systems

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OPEN TRACK



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# 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 $\Rightarrow$ 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

- Line routing and alignment
- Track layout
- Signalling system
- Train data

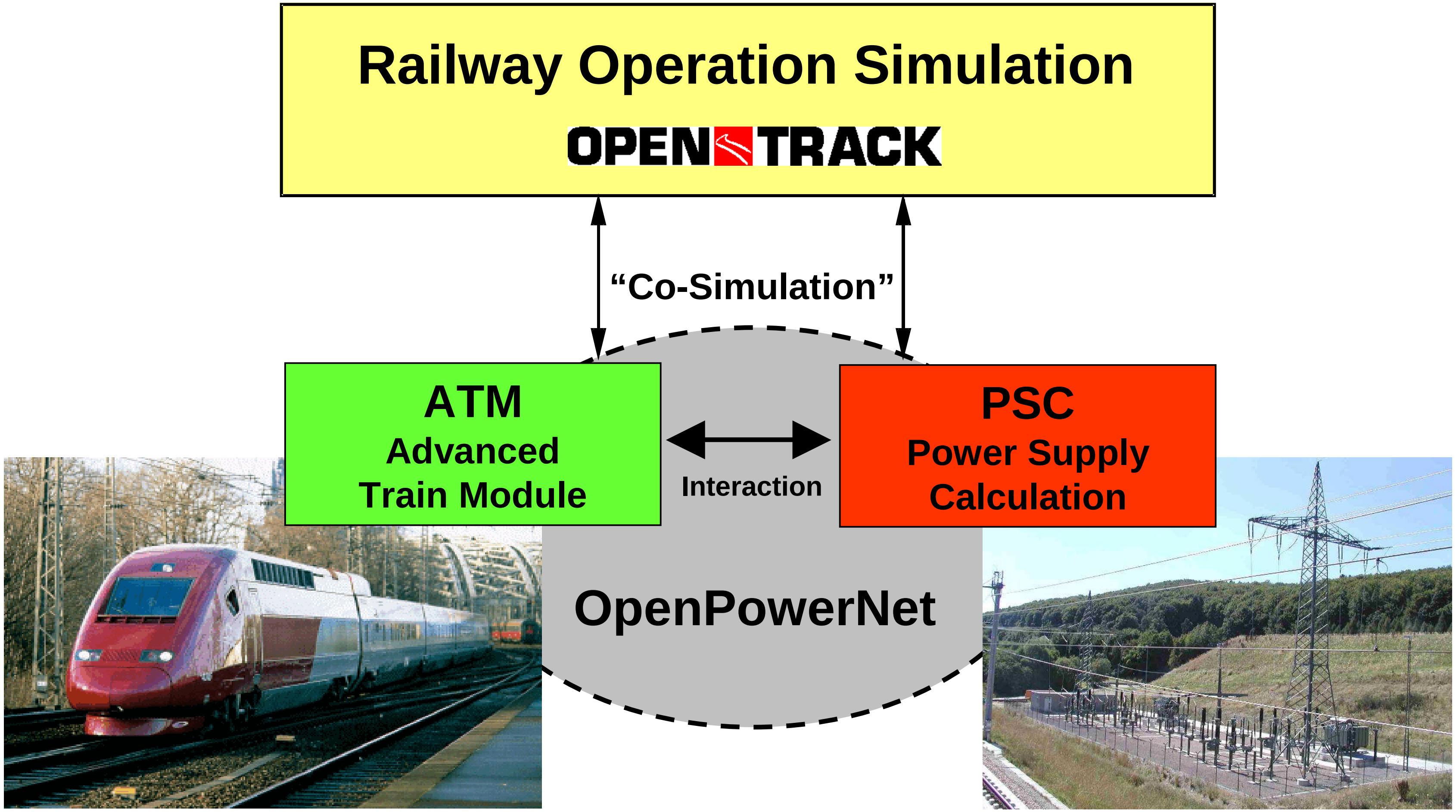
- Timetable
- Connecting conditions
- Operating rules

**Plug-in**

## Load Flow and Energy

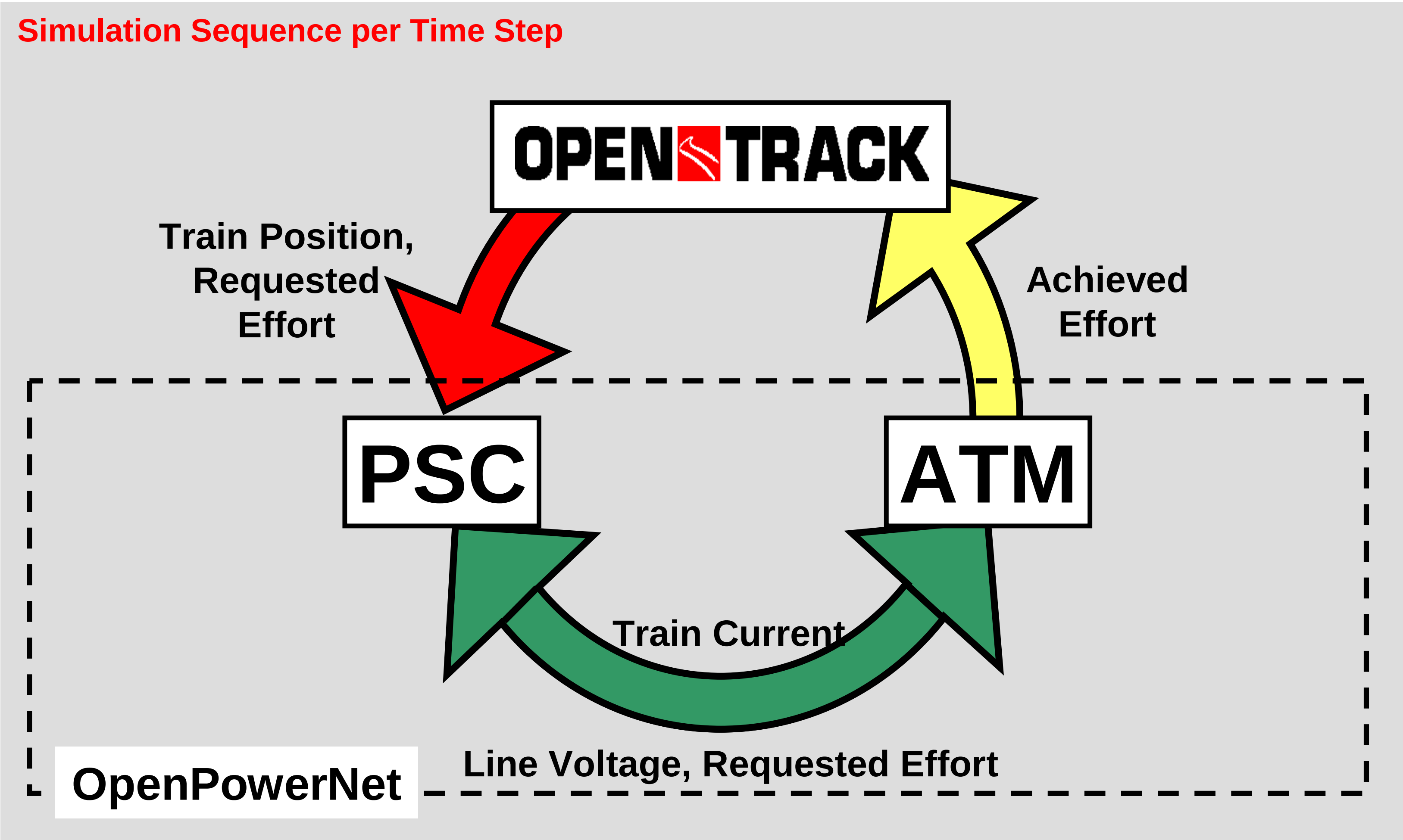
- Propulsion data

- Power grid / Substation
- Feeder lines and cables
- Catenary system




Propulsion Technology

Power Supply System


Simulation Sequence per Time Step
OPEN TRACK
Train Position, Requested Effort
Achieved Effort
PSC
ATM
Train Current
Line Voltage, Requested Effort
OpenPowerNet

# Modelling levels available for propulsion simulation

a) constant efficiency factors for propulsion equipment

b) driving state related efficiency factors

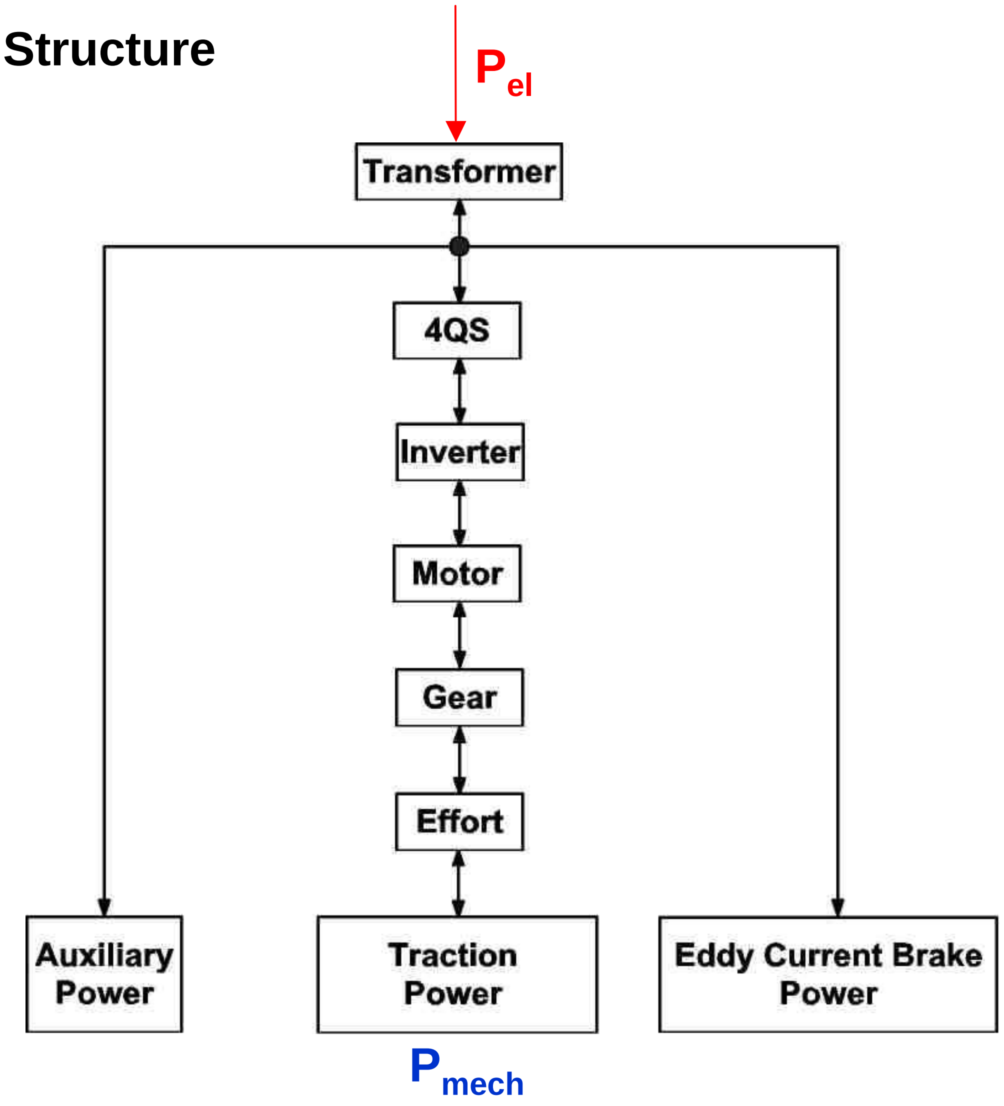
c) load depending efficiency factors of components

d) detailed engine models of components

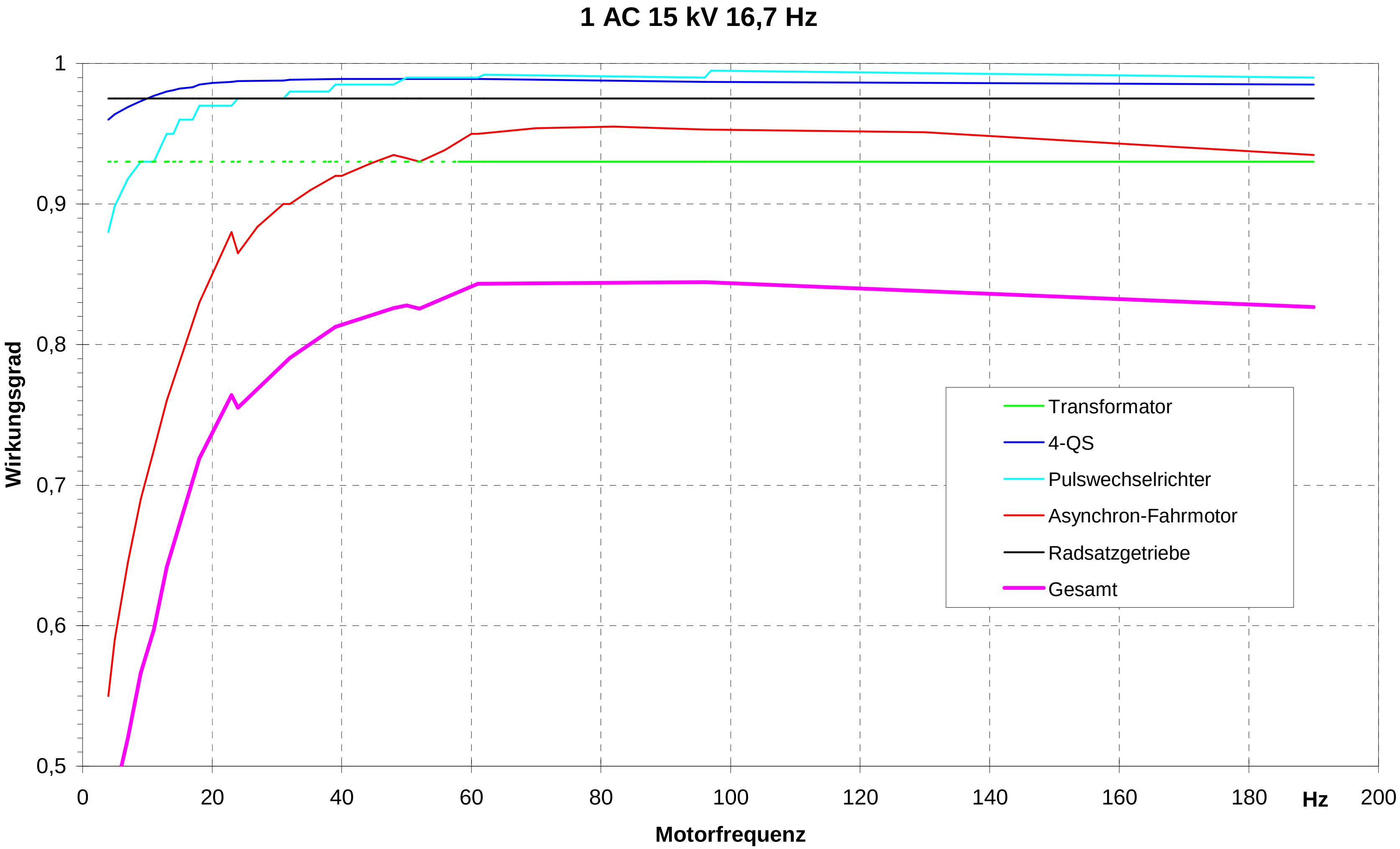
\+ auxiliary power and eddy current break

\+ additionally: limiting values of propulsion control
(e.g. voltage related current limitation)

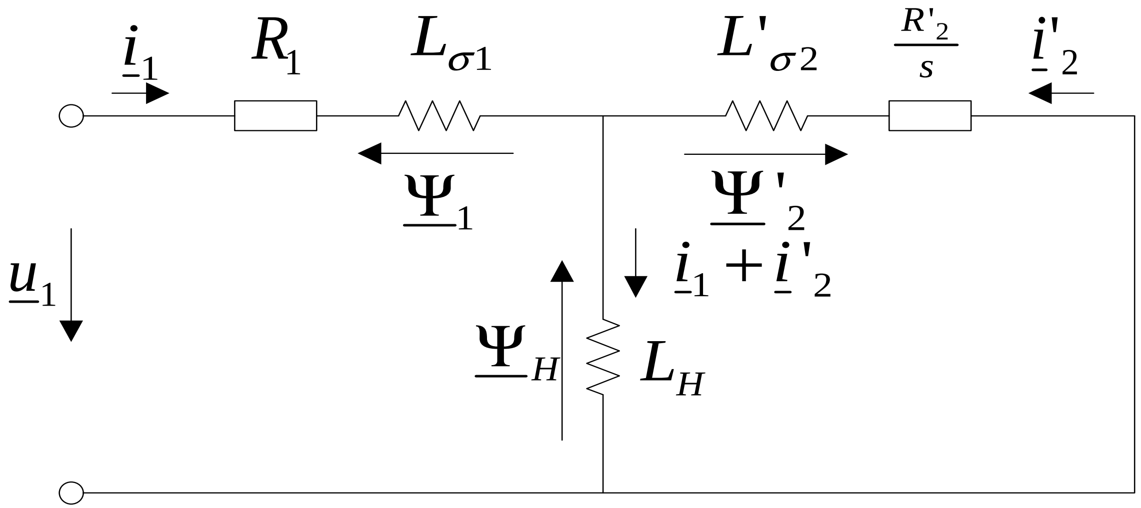
## Propulsion Structure



# Efficiency Characteristics of ICE3 train



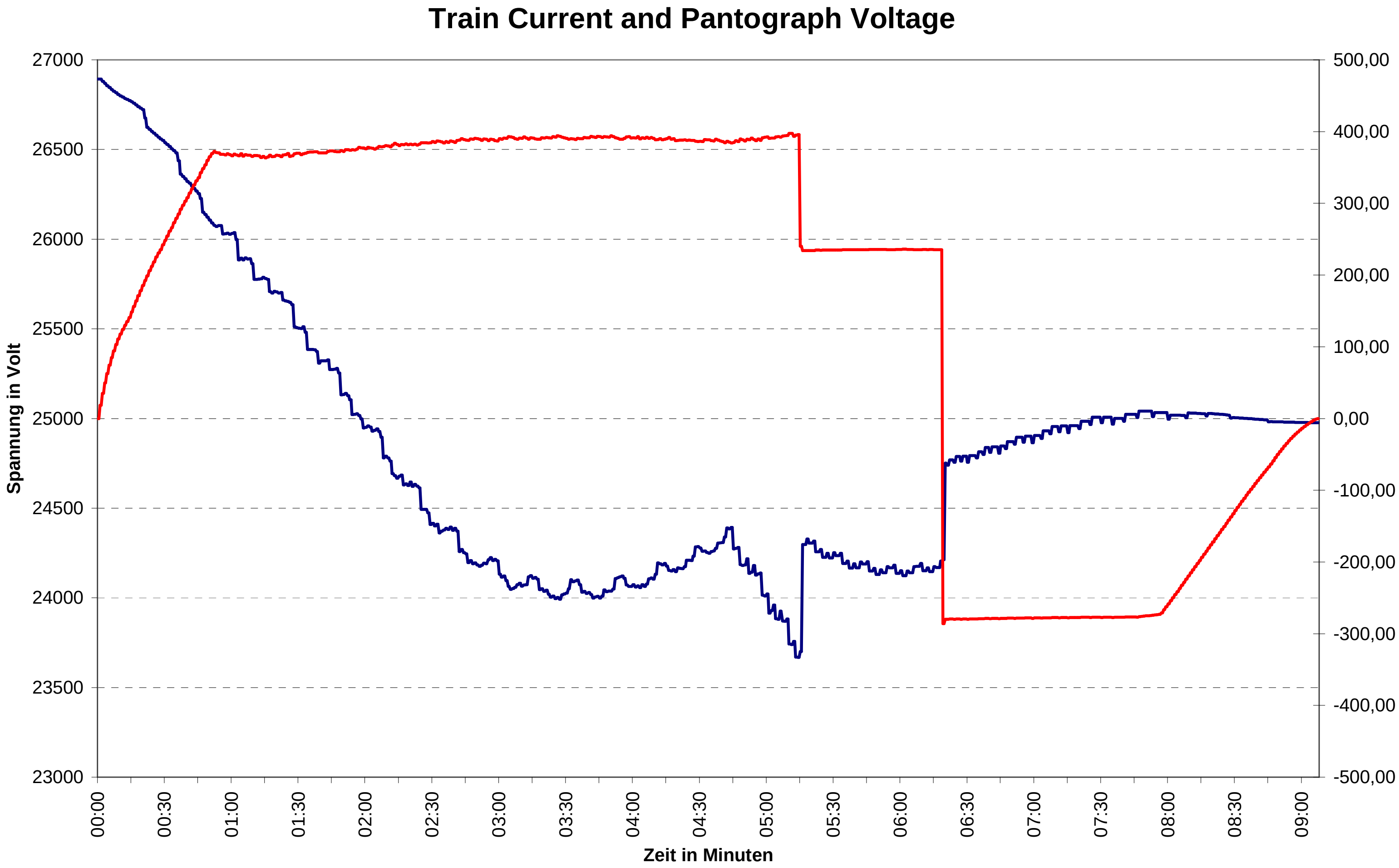
## **Propulsion Component Modelling** (example for traction motor)




$$M_{elekt} = M_{mech} + M_{Läuferverluste}$$

$$M_{Läuferverluste} = \frac{P_{Rotorverluste}}{2\pi n} = \frac{\frac{3}{2}\,\underline{i}'^{\,2}_2 \cdot R'_2}{2\pi n}$$

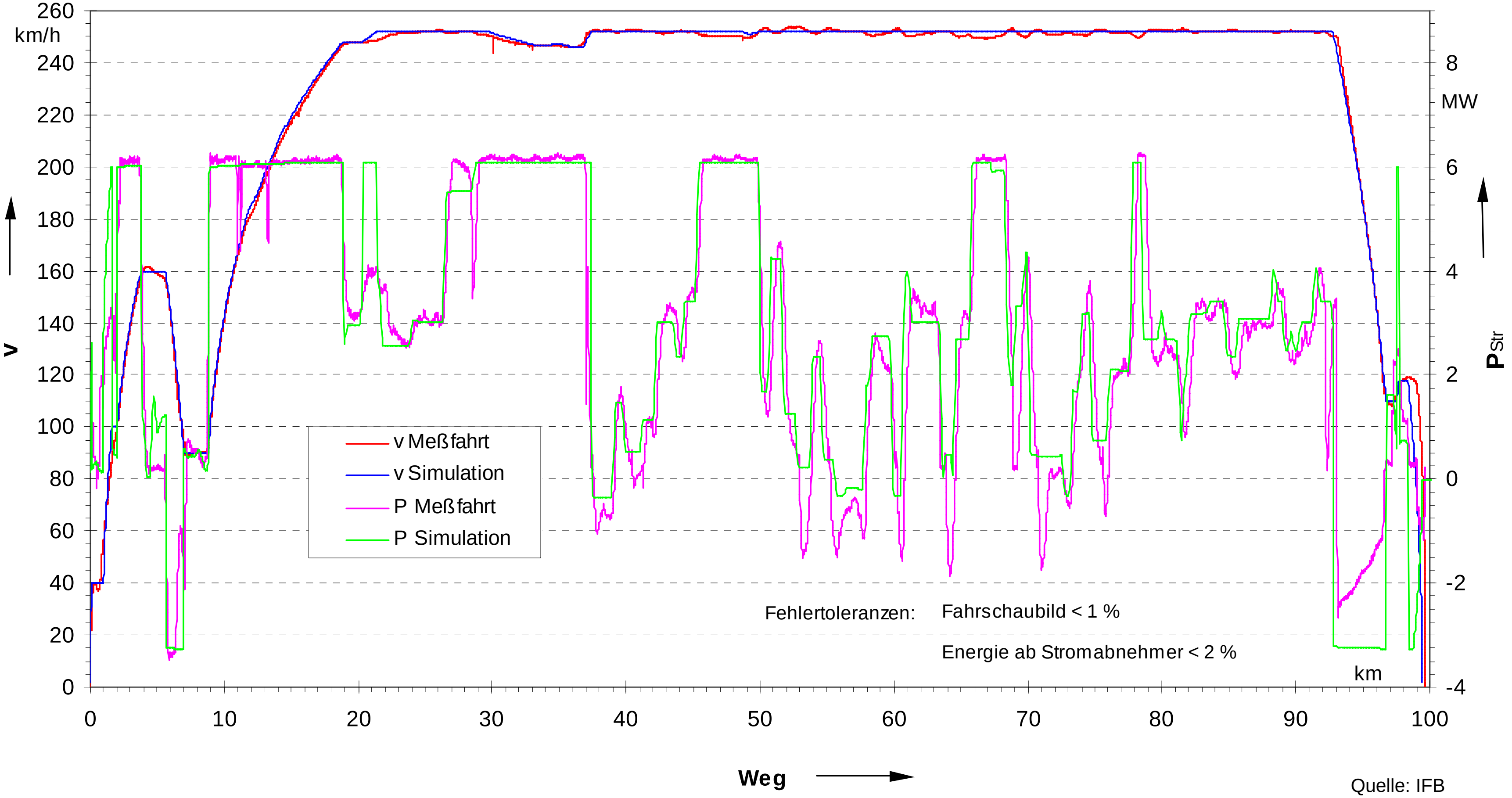
# Propulsion Model Verification



# Train Speed and Power Characteristics

## Measurement and Simulation Results

## ICE1 Hannover – Göttingen




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

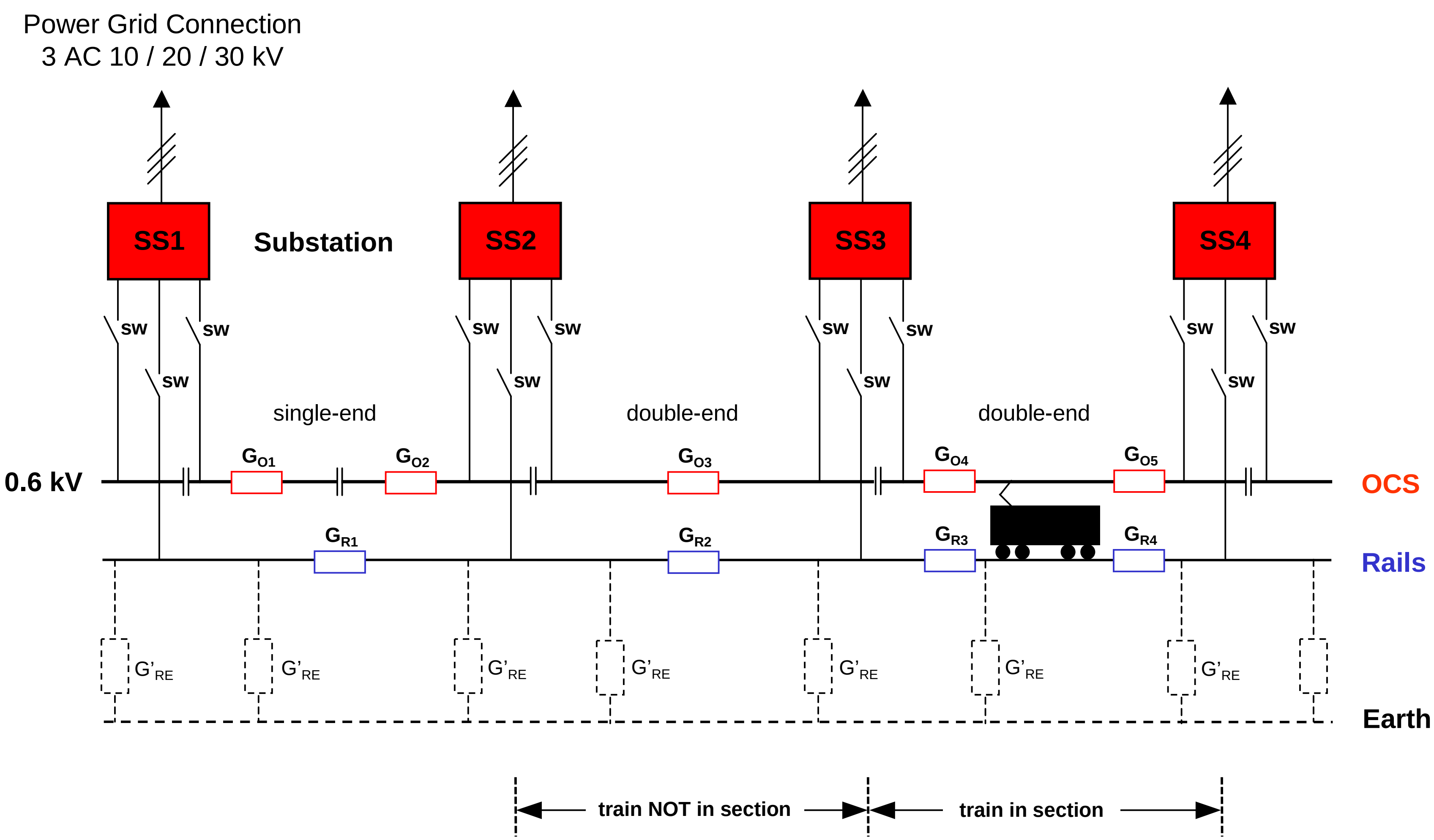
## Modelling of infrastructure

Catenary arrangement and switch state

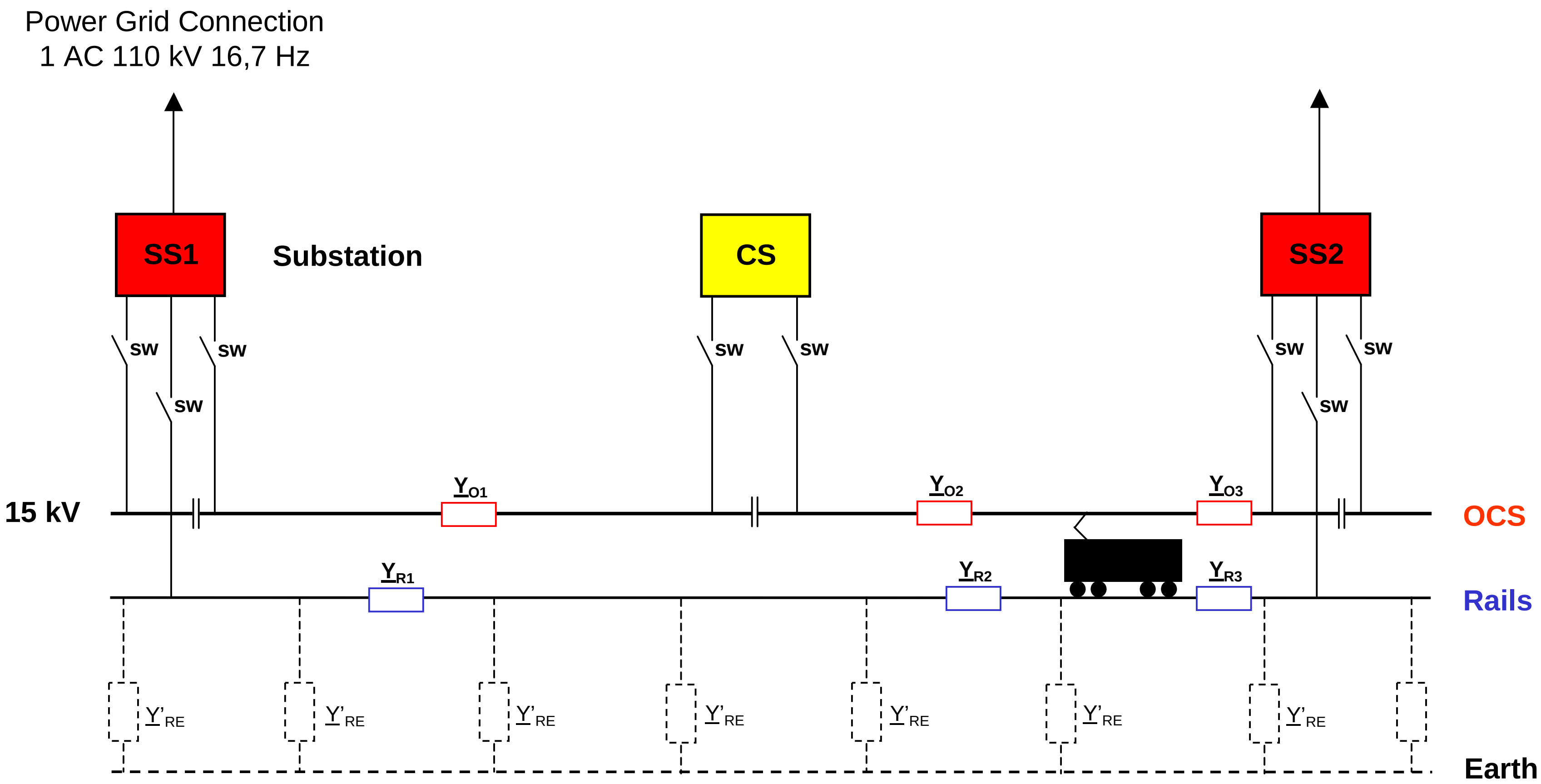
# Modelling of the Railway Power Supply System

- **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**

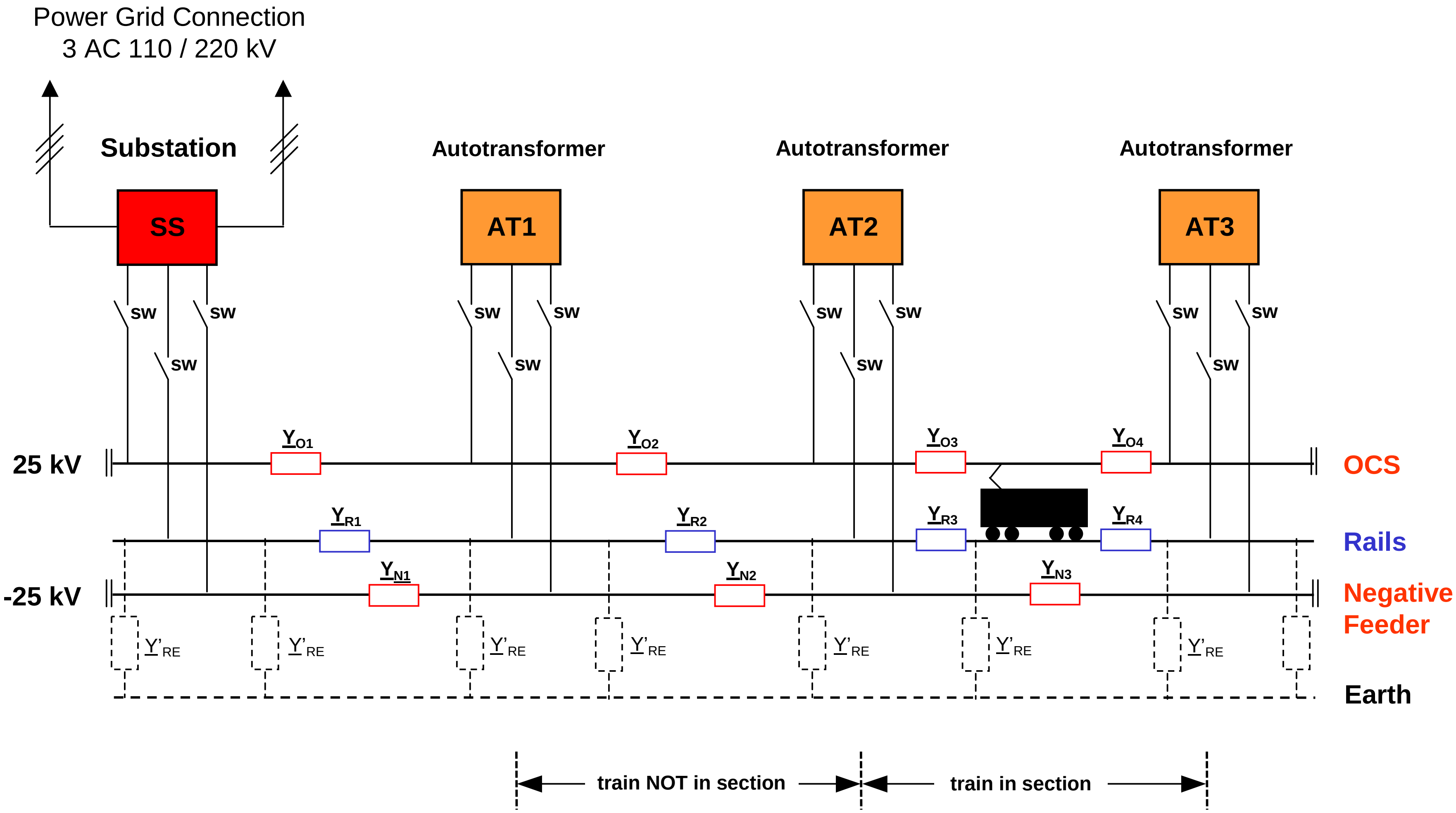
# Power Supply Network Structure (DC 0.6 … 3.0 kV)



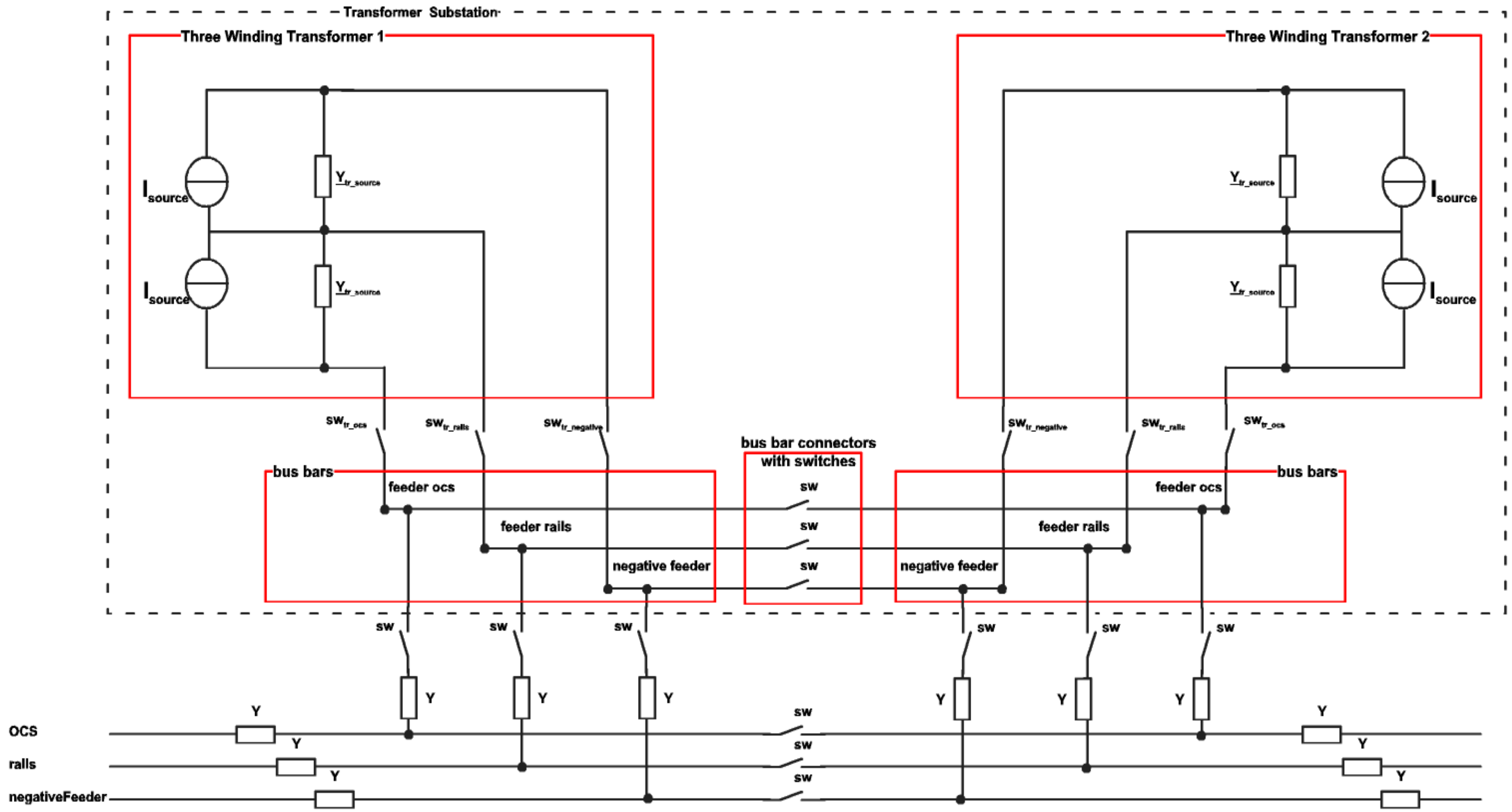
# Power Supply Network Structure (1 AC 15 kV 16,7 Hz)



# Power Supply Network Structure (2 AC 25 kV ~ 50 / 60 Hz)



# Substation / AT Structure (2 AC 25 kV ~ 50/60 Hz)



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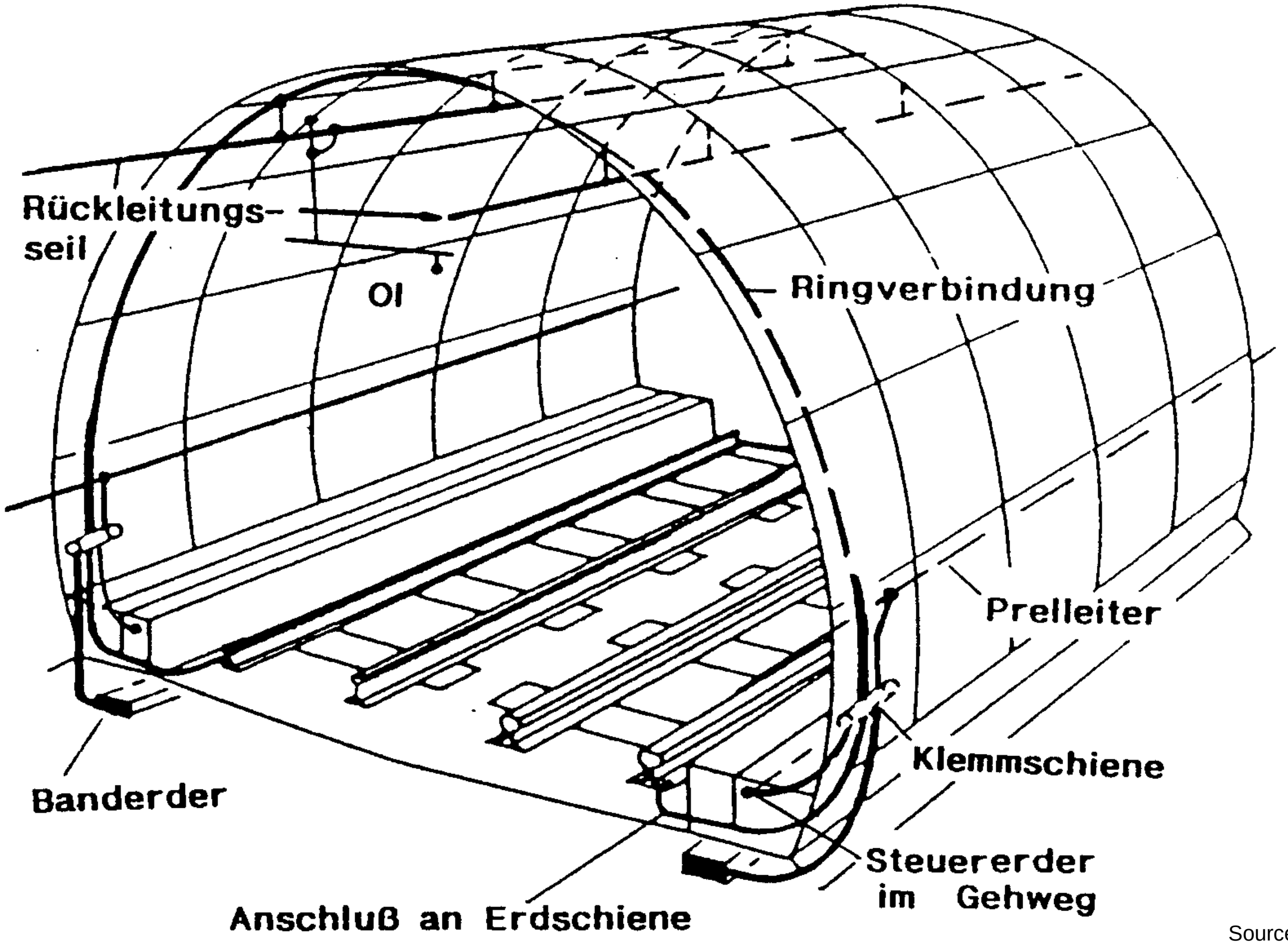
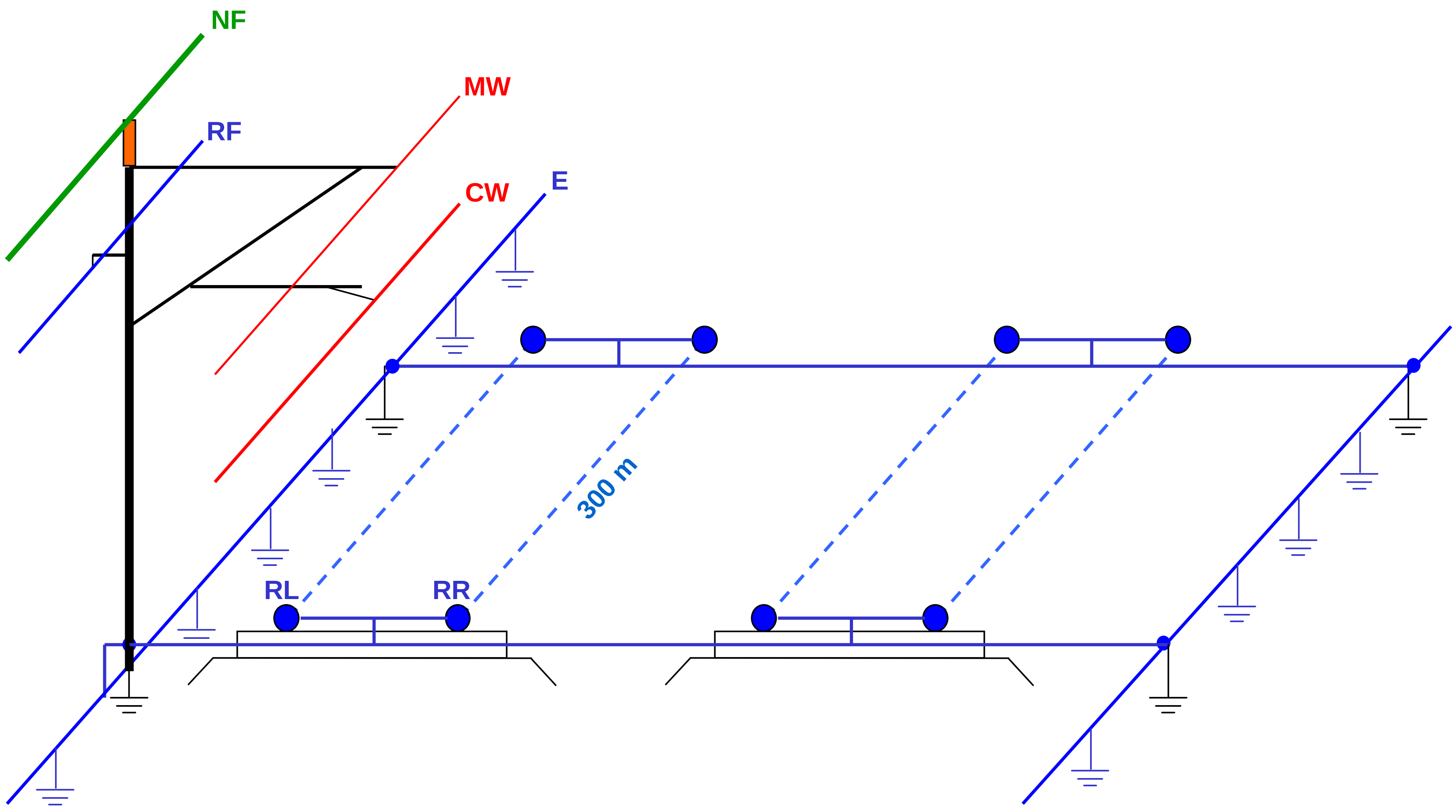
## Trackside Arrangement of Conductors

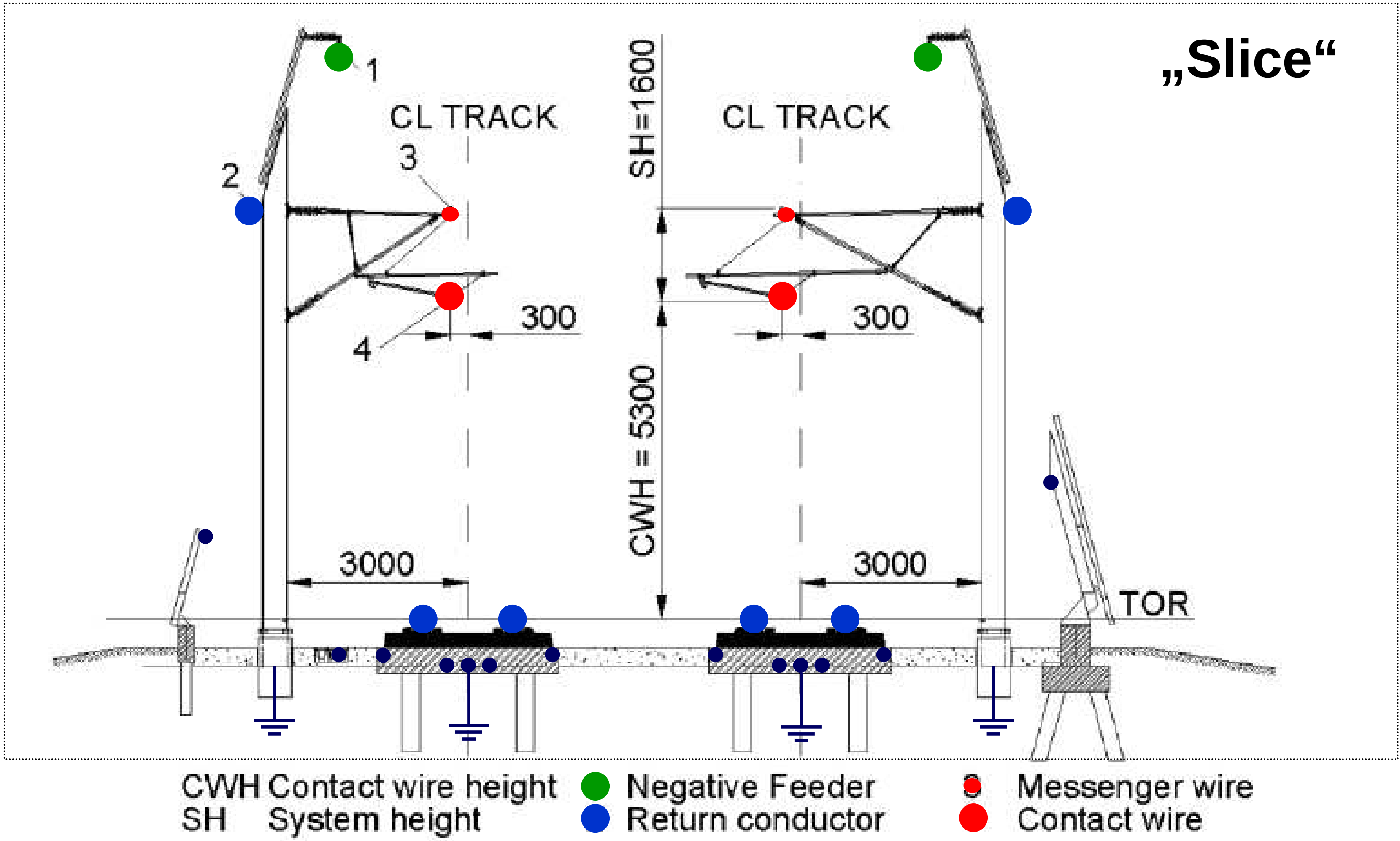



Source: DB KoRiL 997

# Trackside Arrangement of Conductors



## Catenary Arrangement and Conductor Model



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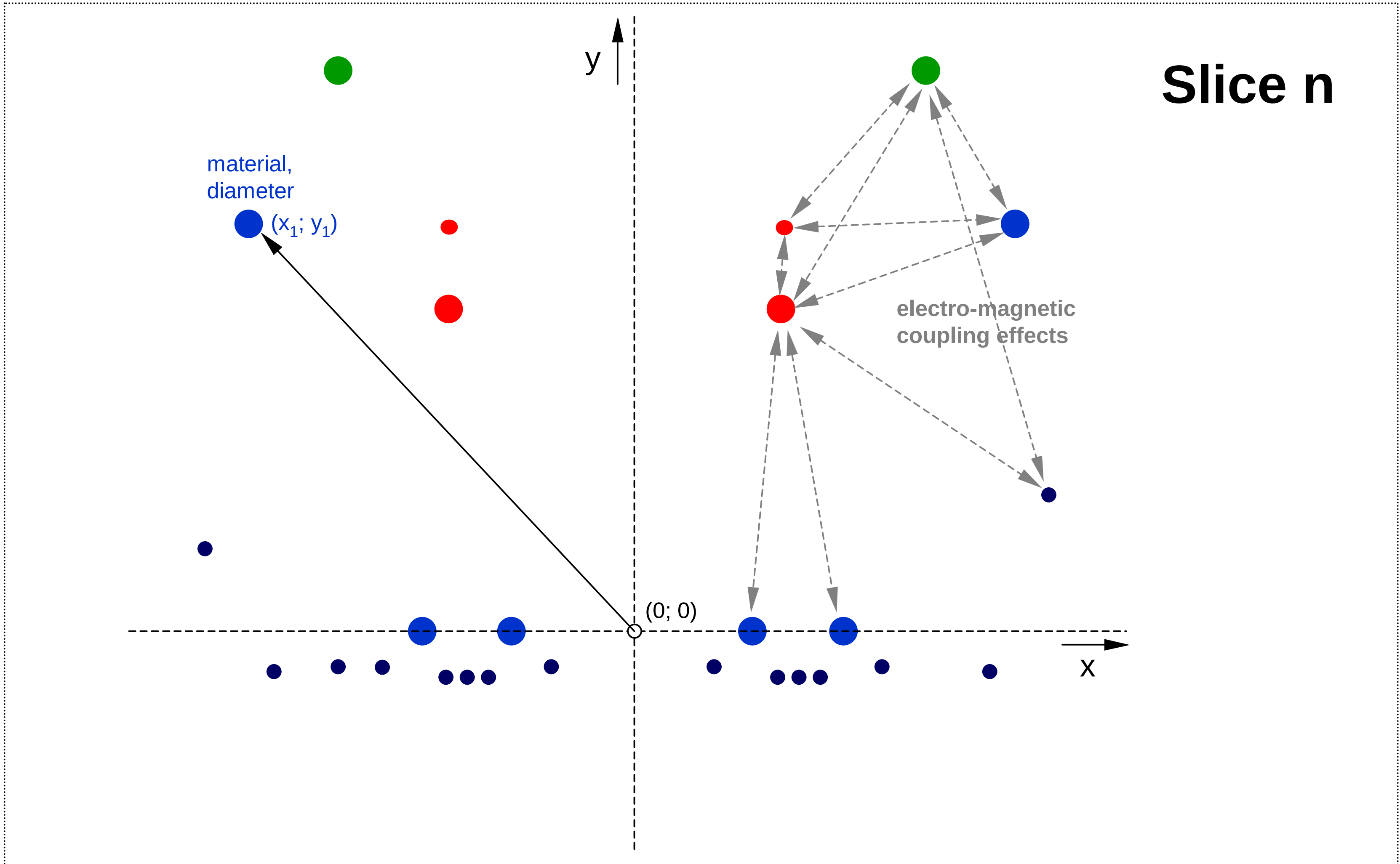
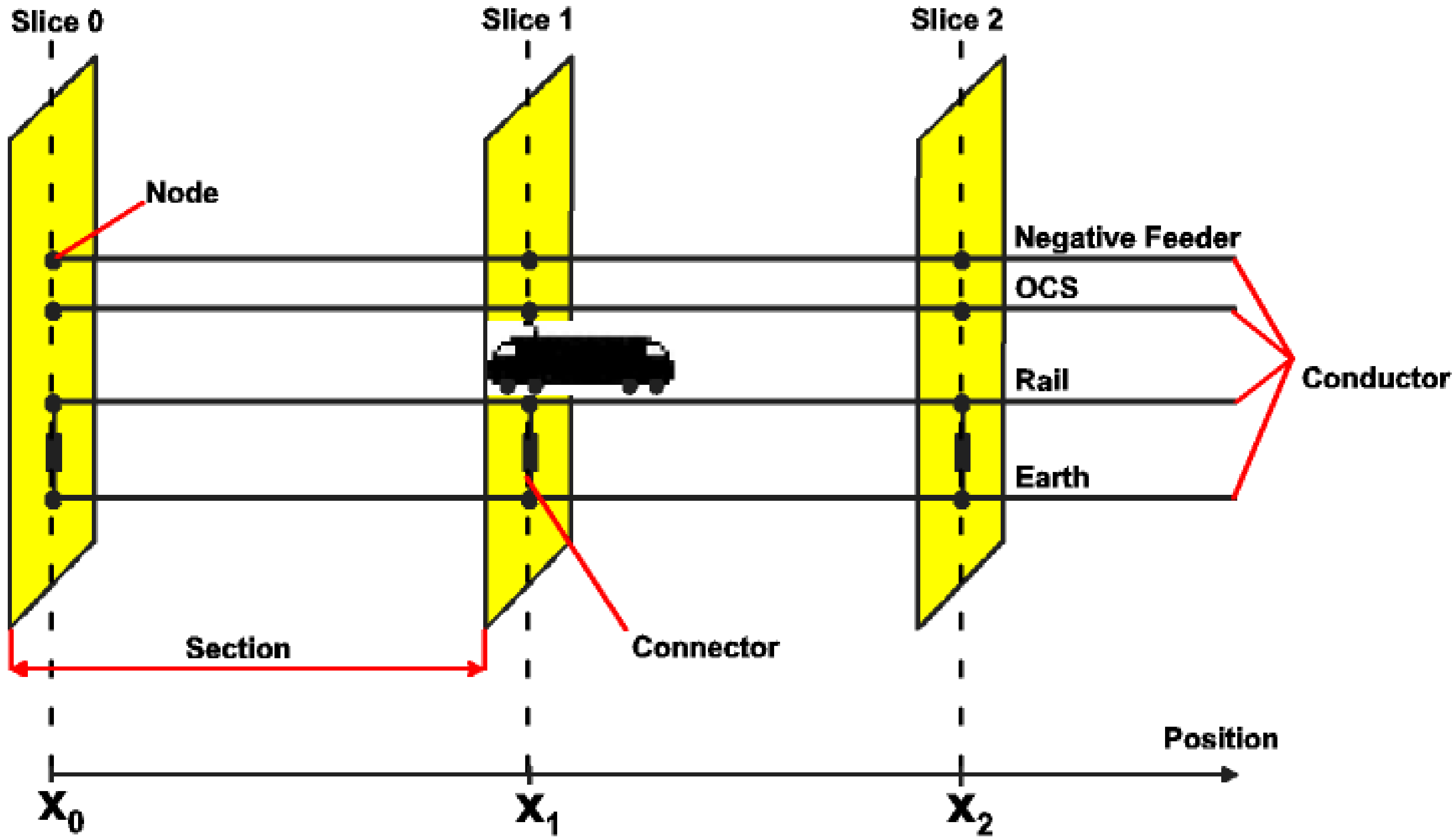
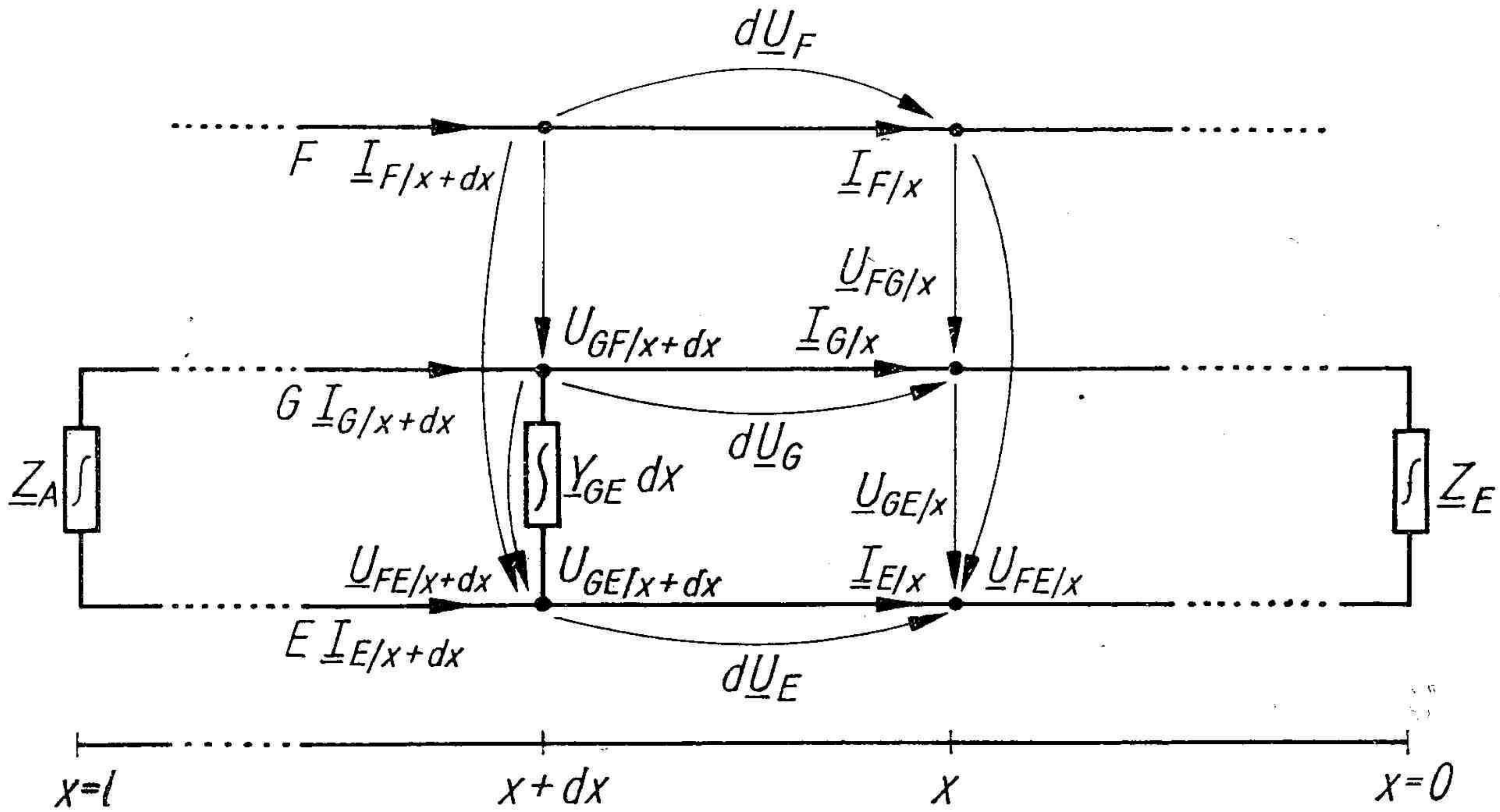
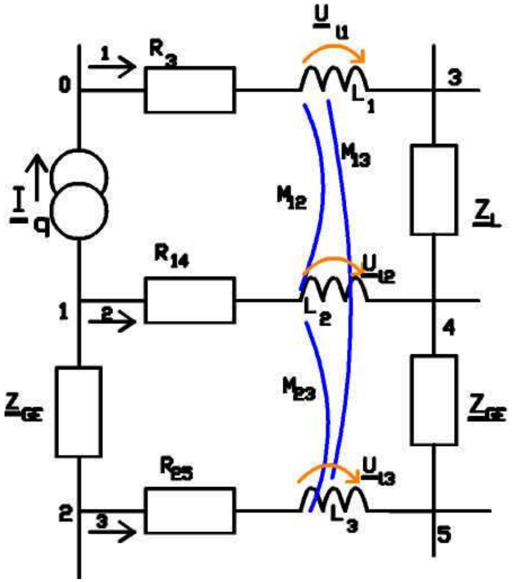


## Sequence of Slices



## Mathematical Network Model






## Electrical network calculation using the advanced method of nodes

$$[\underline{Y}]_{(\nu,\nu)}(\underline{U}_{\nu 0})_{(\nu,1)} - [\underline{Y}_2]_{(\nu,LL)}(\underline{U}_L)_{(LL,1)} = (\underline{I}_q)_{(\nu,1)}$$

**Voltage drops caused by self- and mutual induction**

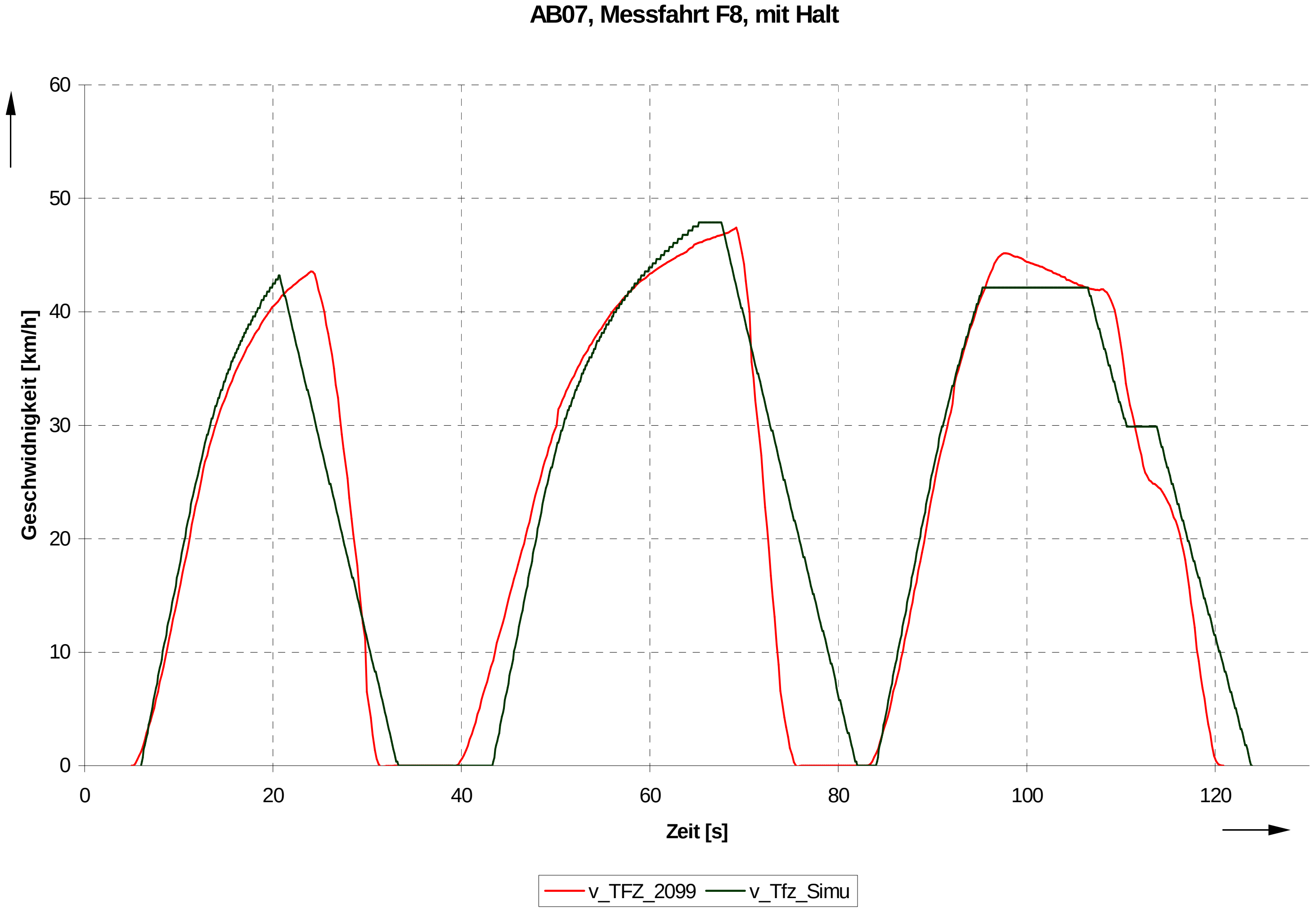
| | Knotenspannungen | | | | | Induktive Spannungen | | | Einströmungen |
|---|---|---|---|---|---|---|---|---|---|
| Knoten | $\underline{U}_{10}$ | $\underline{U}_{20}$ | $\underline{U}_{30}$ | $\underline{U}_{40}$ | $\underline{U}_{50}$ | $\underline{U}_{l1}$ | $\underline{U}_{l2}$ | $\underline{U}_{l3}$ | $\underline{I}_q$ |
| 1 | $G_{14}+\underline{Y}_{GE}$ | $-\underline{Y}_{GE}$ | | $-G_{14}$ | | | $-G_{14}$ | | $-\underline{I}_q$ |
| 2 | $-\underline{Y}_{GE}$ | $G_{25}+\underline{Y}_{GE}$ | | | $-G_{25}$ | | | $-G_{25}$ | 0 |
| 3 | | | $G_3+\underline{Y}_L$ | $-\underline{Y}_L$ | | $G_3$ | | | 0 |
| 4 | $-G_{14}$ | | $-\underline{Y}_L$ | $G_{14}+\underline{Y}_L+\underline{Y}_{GE}$ | $-\underline{Y}_{GE}$ | | $G_{14}$ | | 0 |
| 5 | | $-G_{25}$ | | $-\underline{Y}_{GE}$ | $G_{25}+\underline{Y}_{GE}$ | | | $G_{25}$ | 0 |

# Verification of the simulation

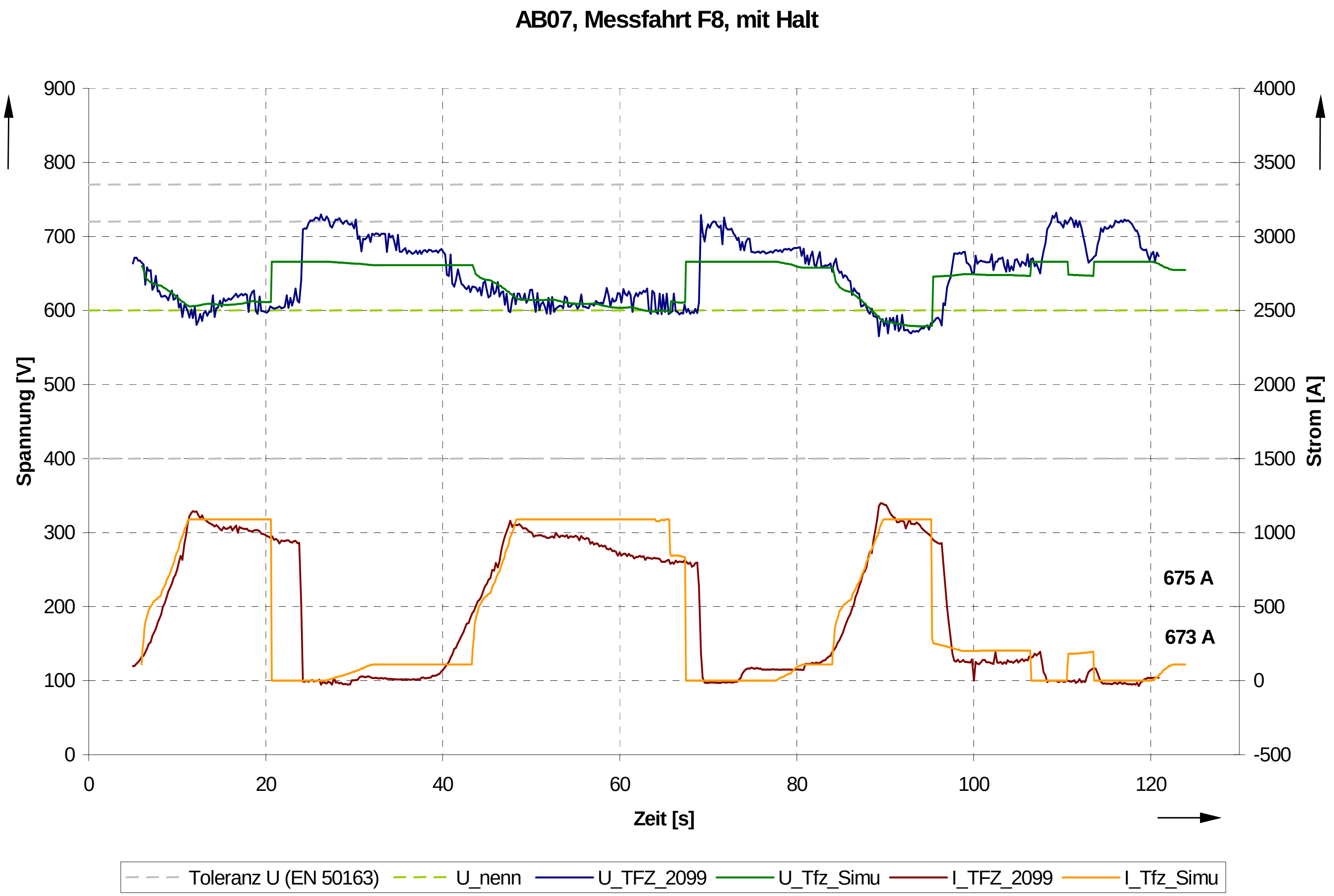
- **Punctual theoretical evaluation**
  - **current sum cero for network slices**
  - **energy picking up and recovering**
  - **correspondence of voltage minimum and maximum / jumps with the network structure during constant load test**

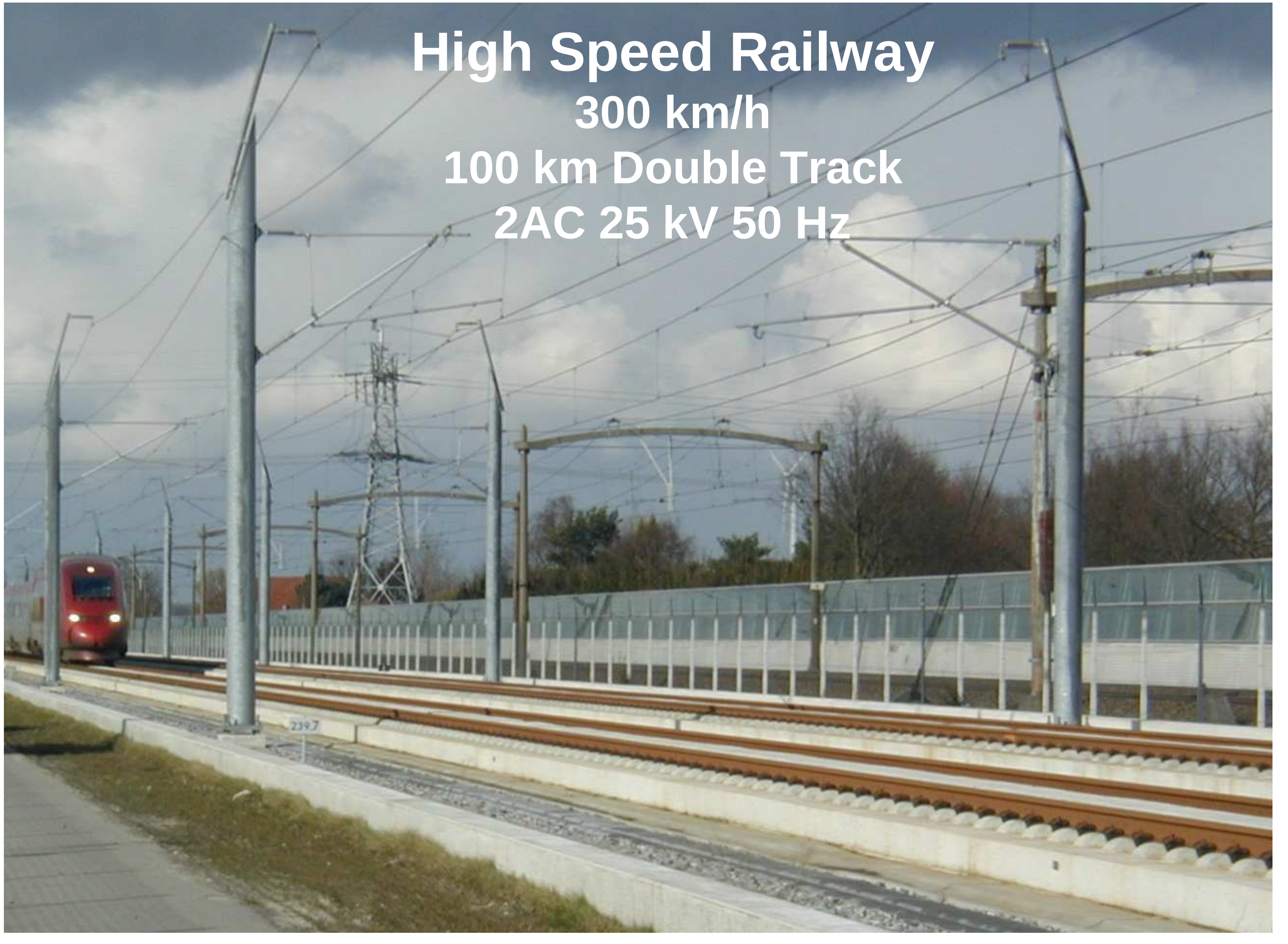
- **Comparison of measurement data with the simulation results for predefined load cases**
  - **driving dynamics of the trains**
  - **current-, voltage- and power characteristics**

# Verification: Measurement and Simulation

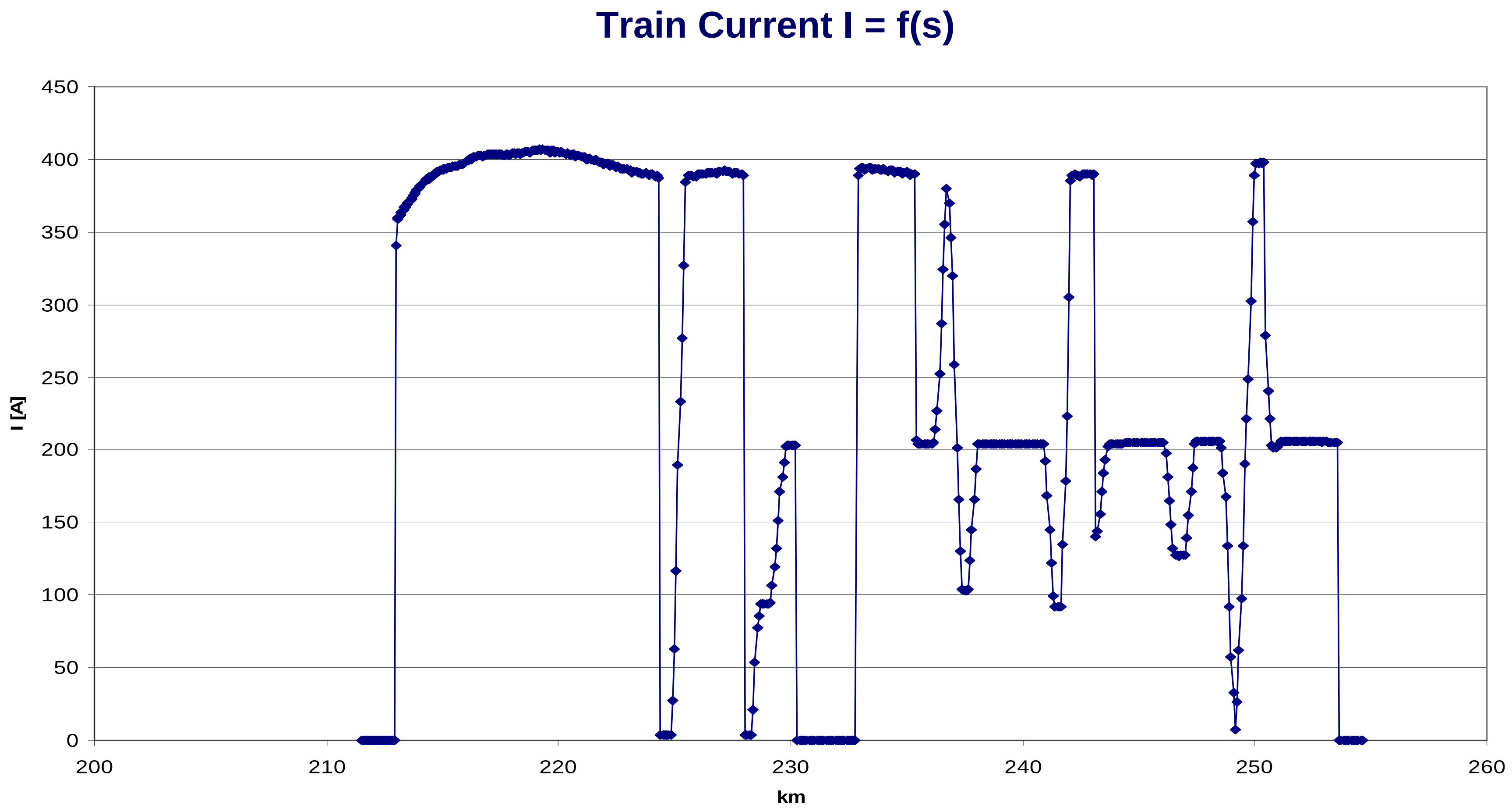


# Verification: Measurement and Simulation



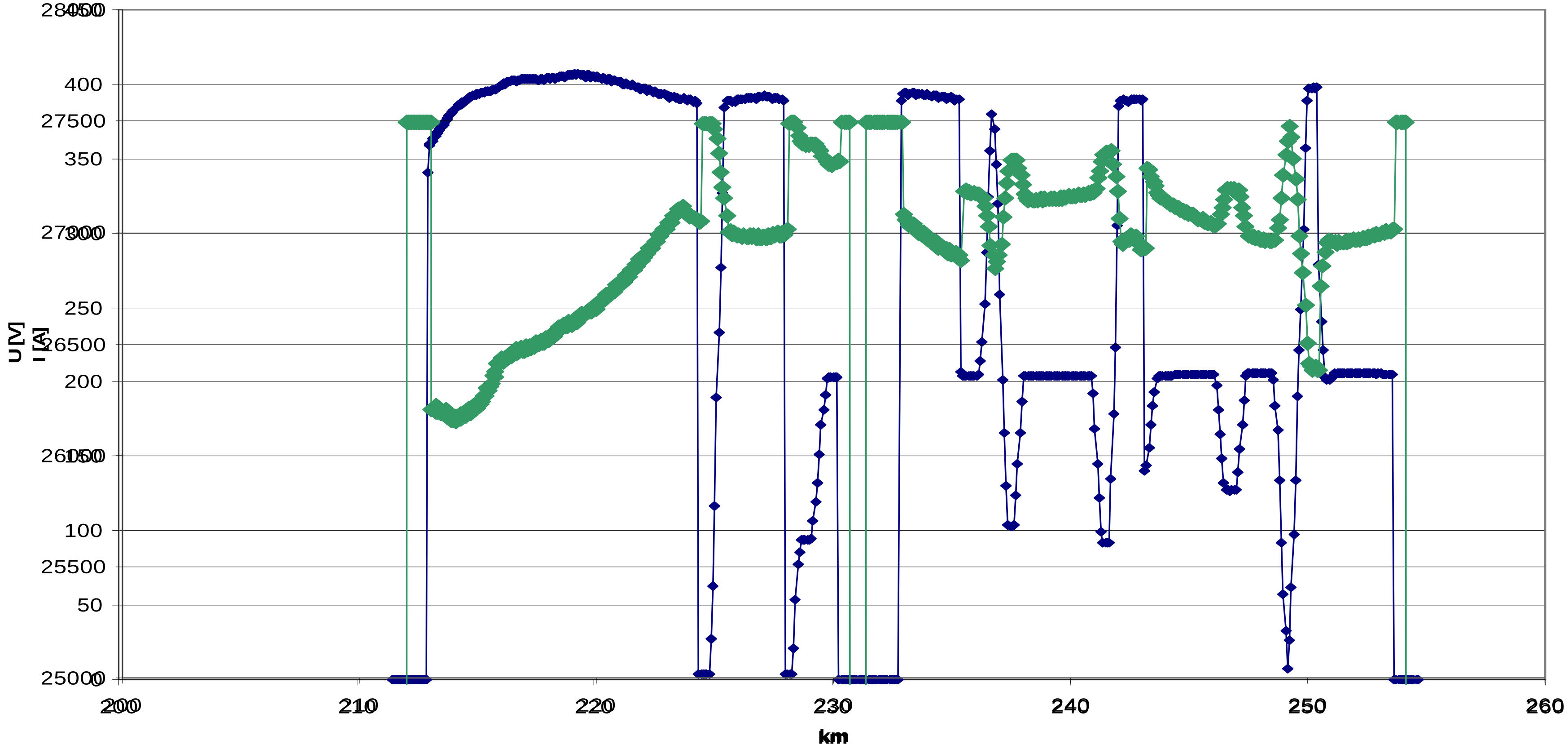

High Speed Railway
300 km/h
100 km Double Track
2AC 25 kV 50 Hz

## **Simulation Results:** High Speed Railway 2AC 25 kV



## **Simulation Results:** High Speed Railway 2AC 25 kV

### Train Current I = f(s), Line Voltage at Pantograph U = f(s)



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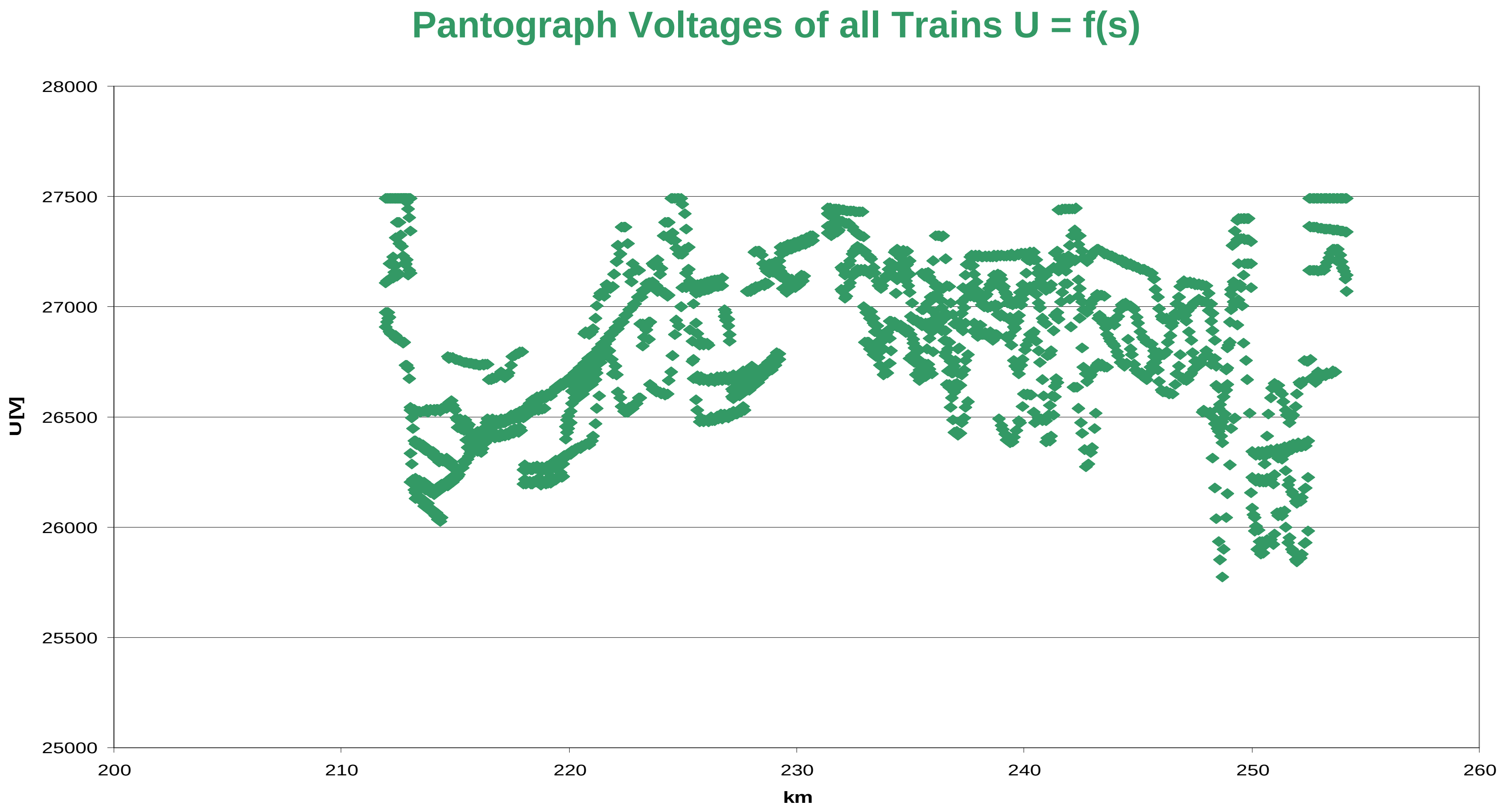

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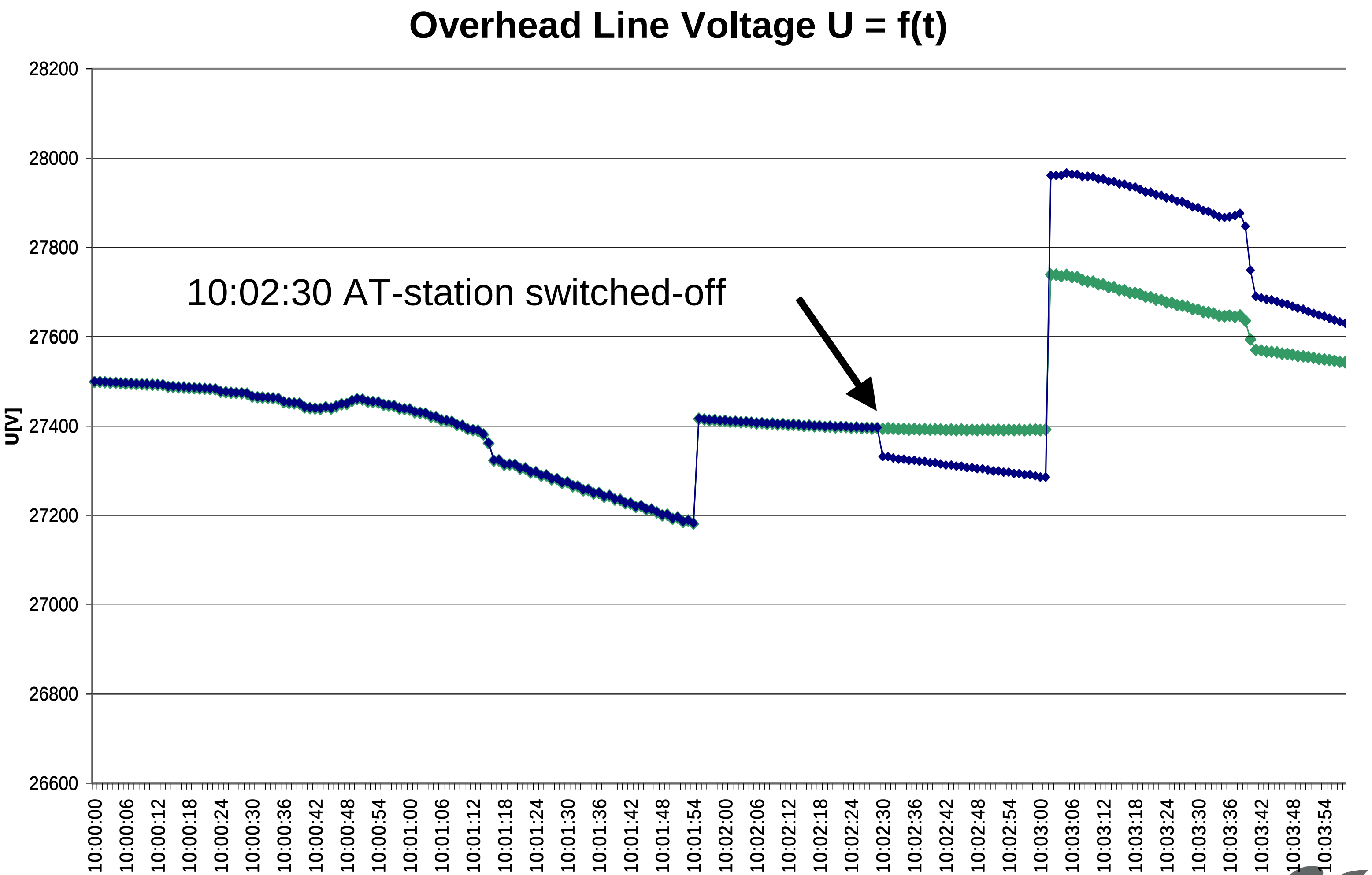
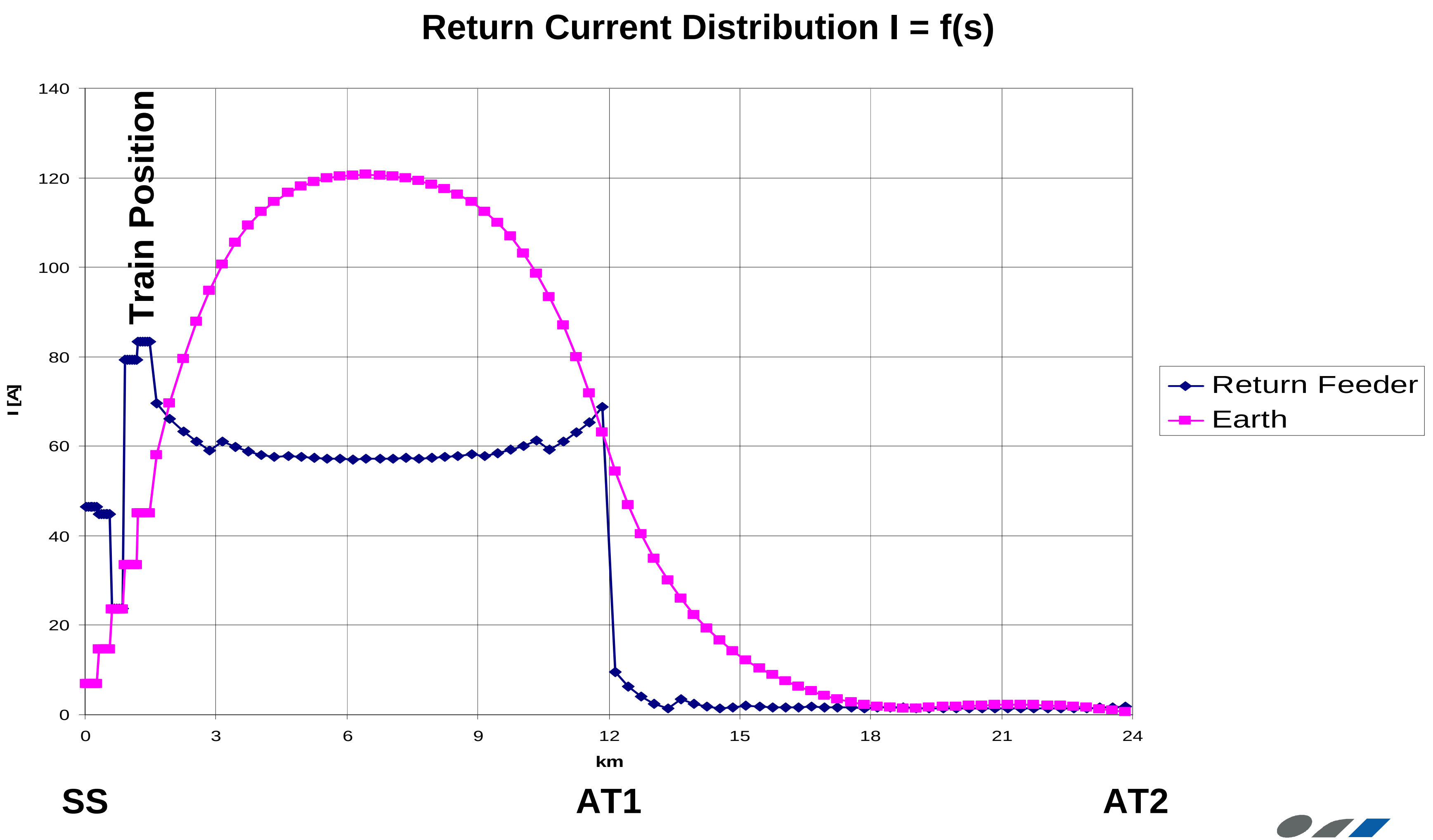
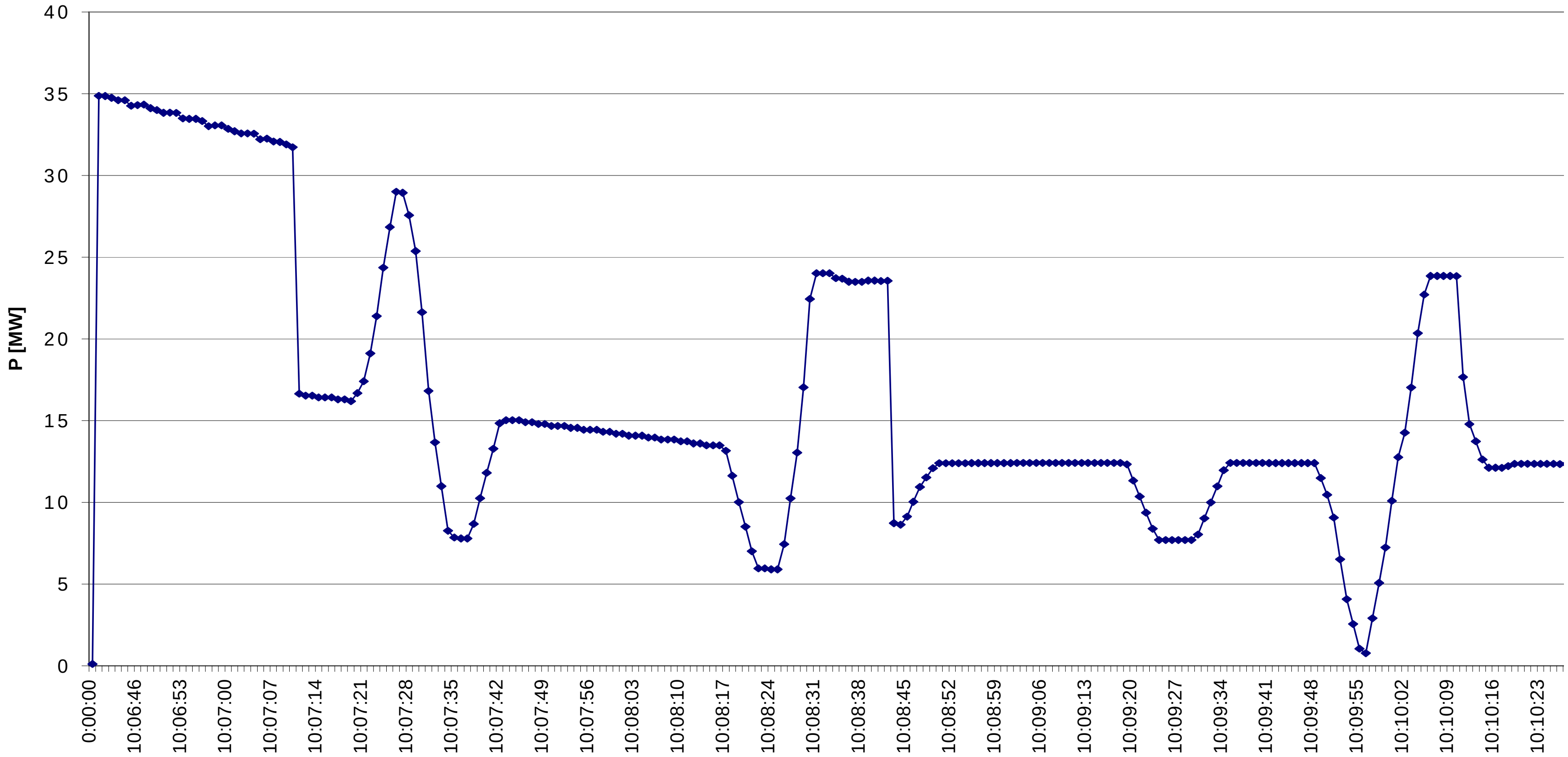


# **Simulation Results:** High Speed Railway 2AC 25 kV

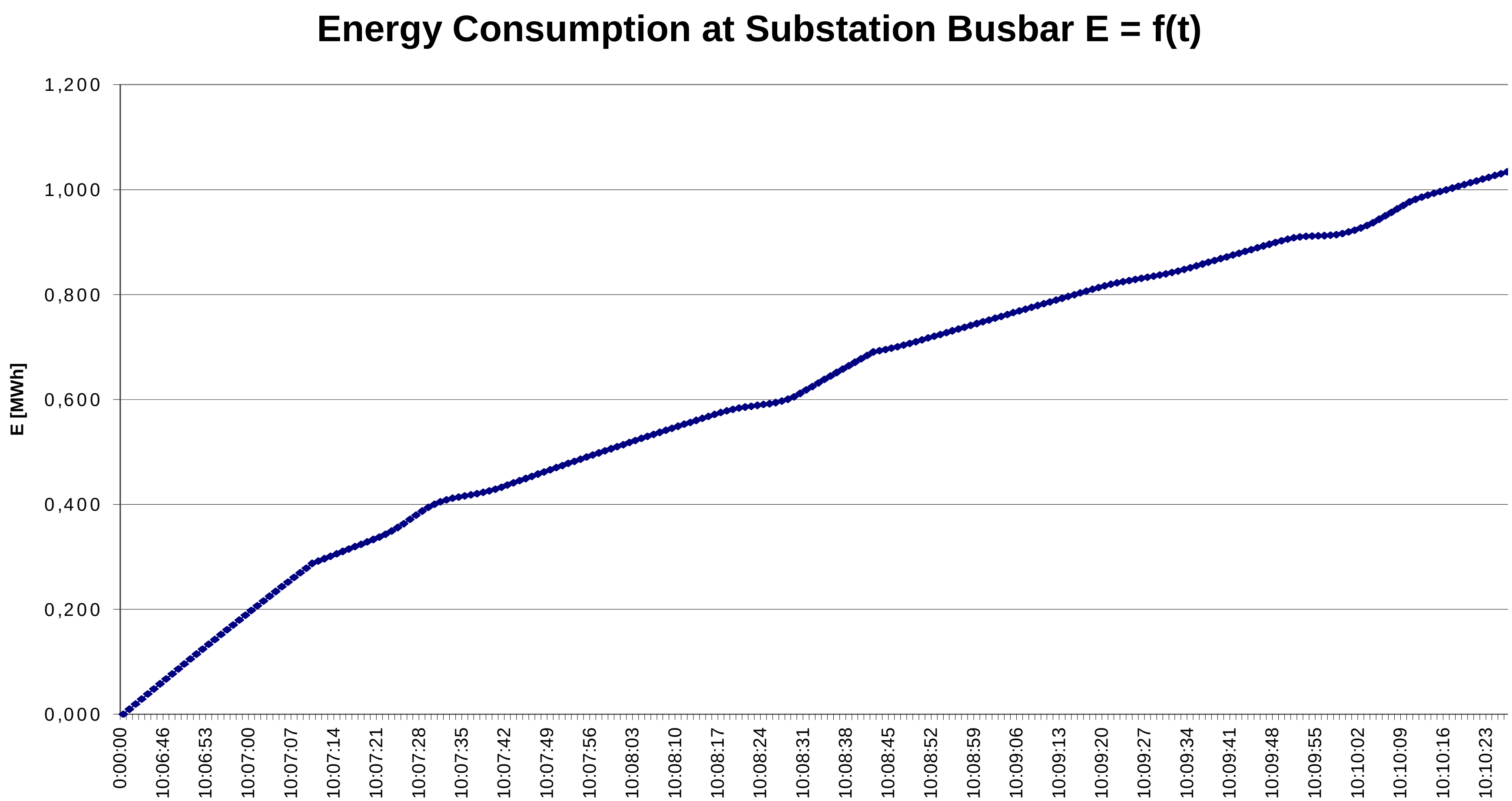


# **Simulation Results:** High Speed Railway 2AC 25 kV

## Substation Transformer Power P = f(t)



## **Simulation Results:** High Speed Railway 2AC 25 kV




City Light Rail
300 km TRAM
220 km Trolley
DC 600 V

## Vehicle modelling

TRAM und Trolleybus


2 x Mirage


Cobra


Tram2000


Tram2000+Pony


Tram2000 Sänfte

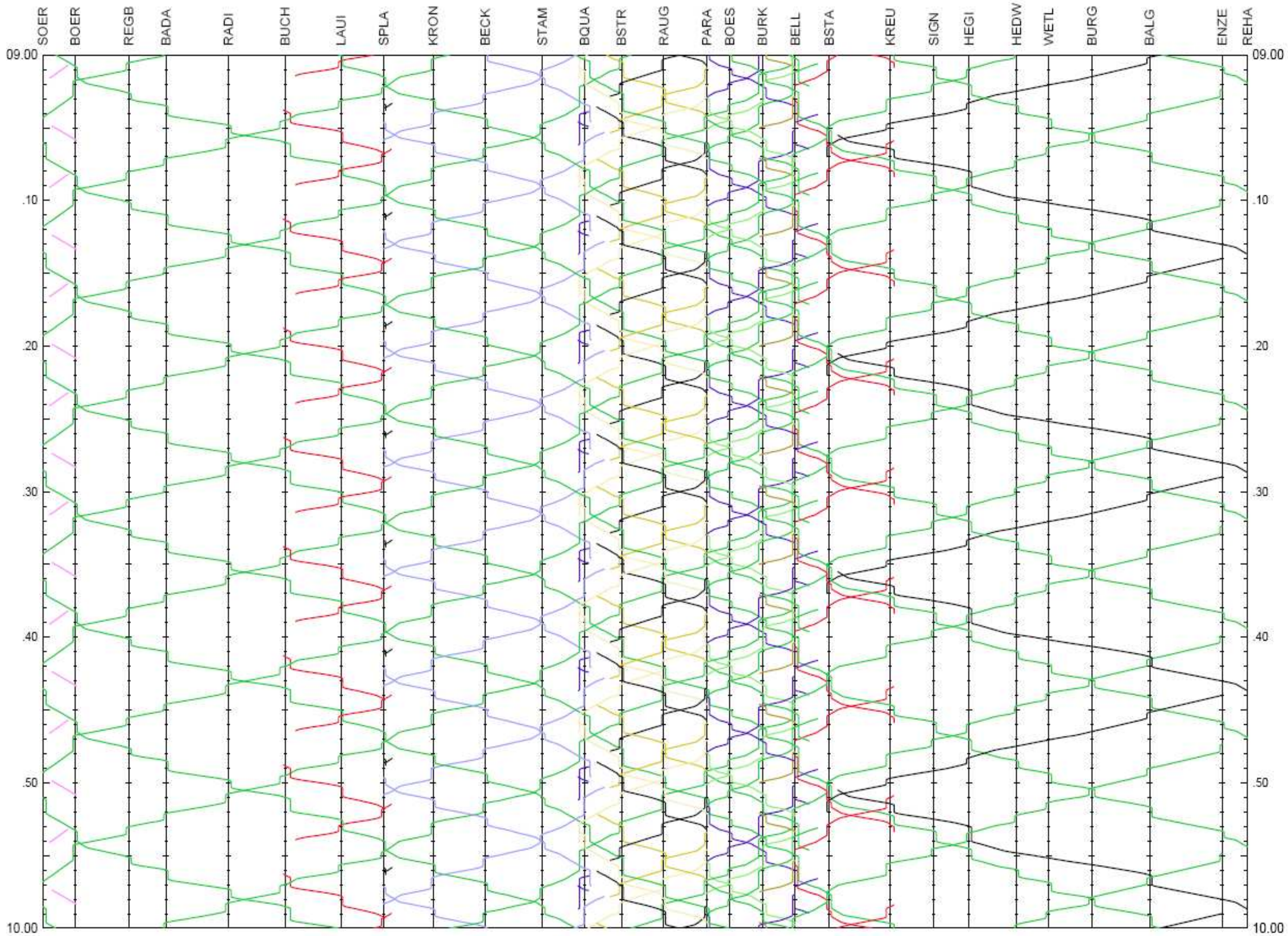

Mercedes


GTB Hess

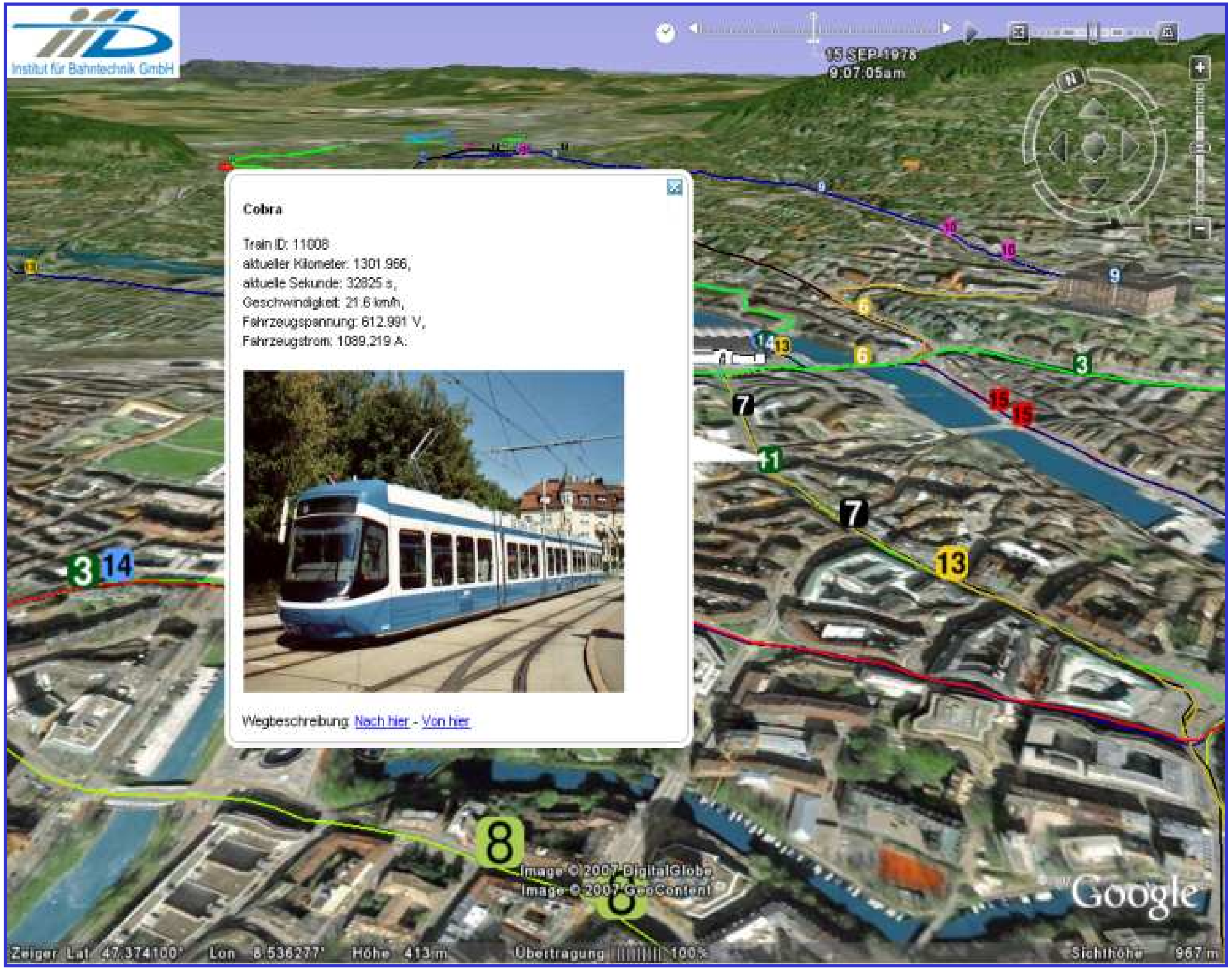

DGTB Hess

## Graphical time table

Line A

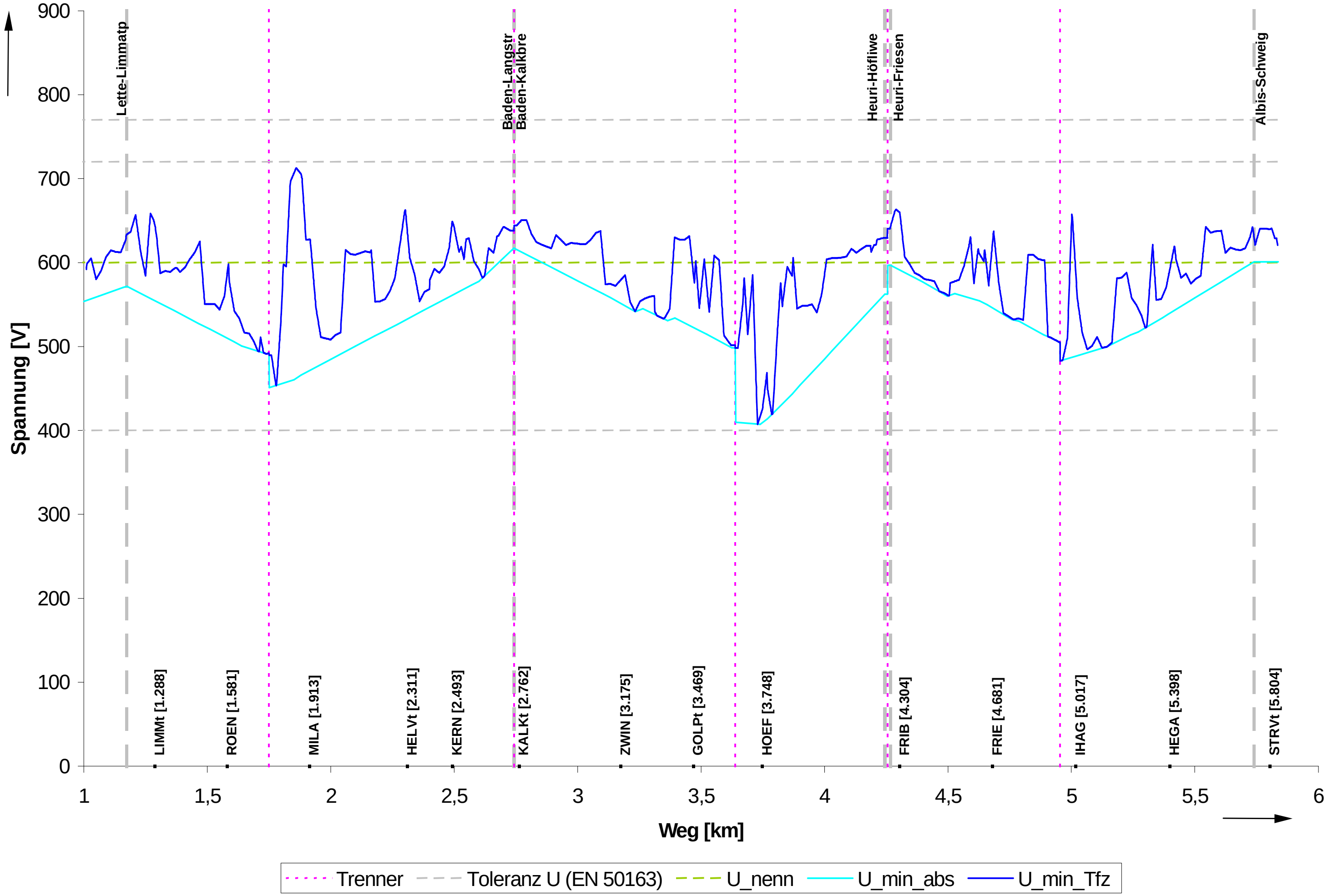


# OpenPowerNet – Simulation of Railway Power Supply

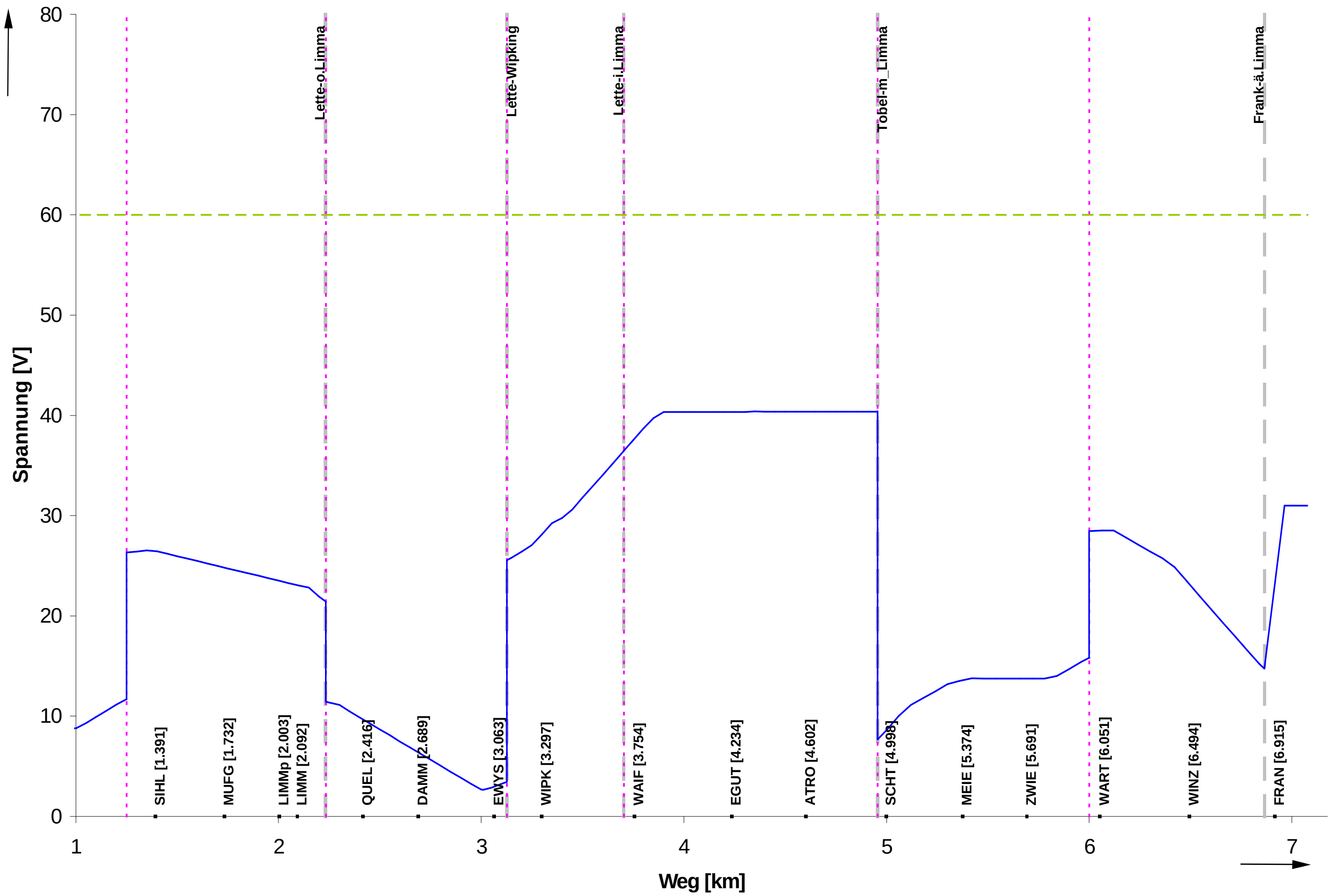


# Minimum voltage: catenary and pantograph

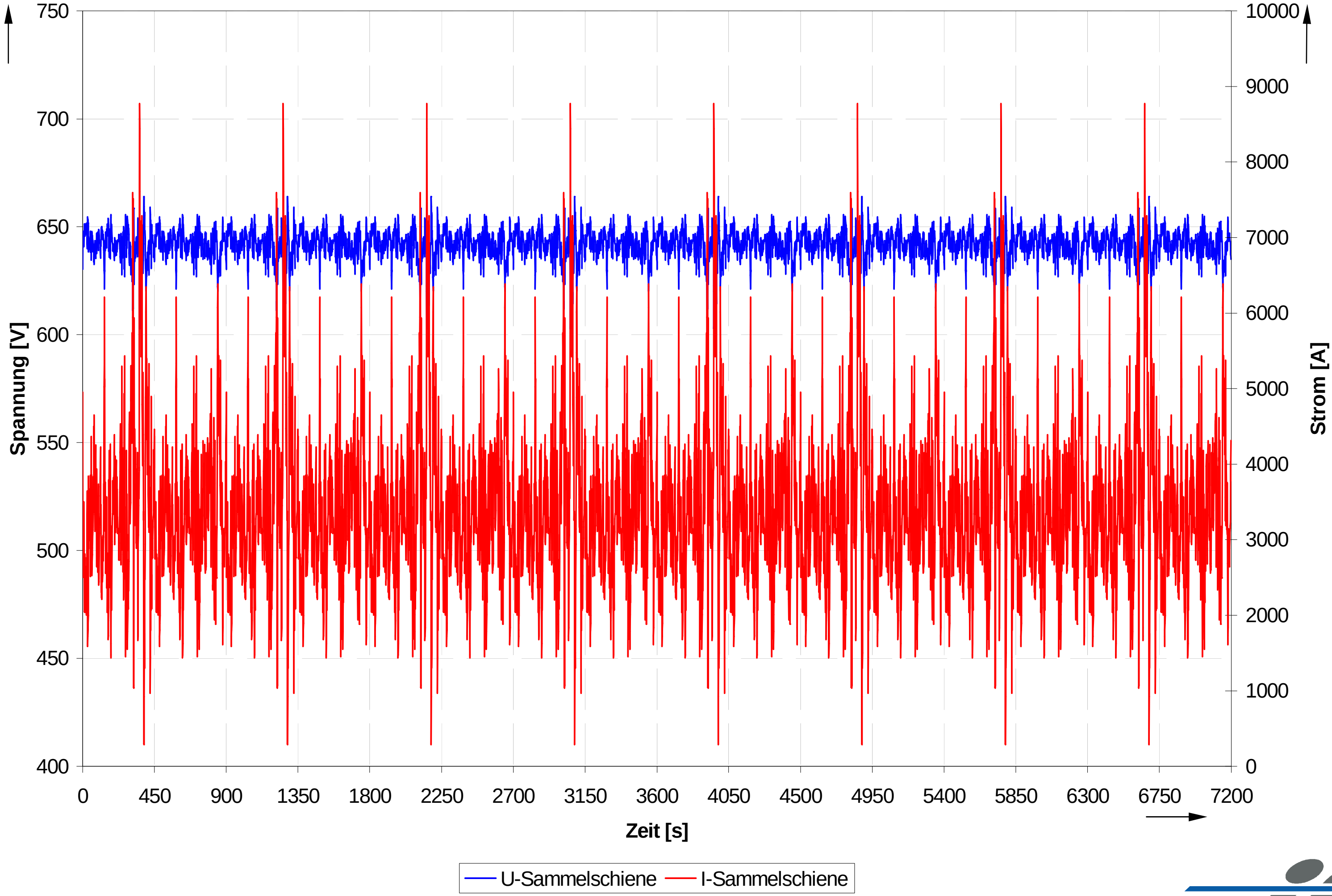
Normal operation



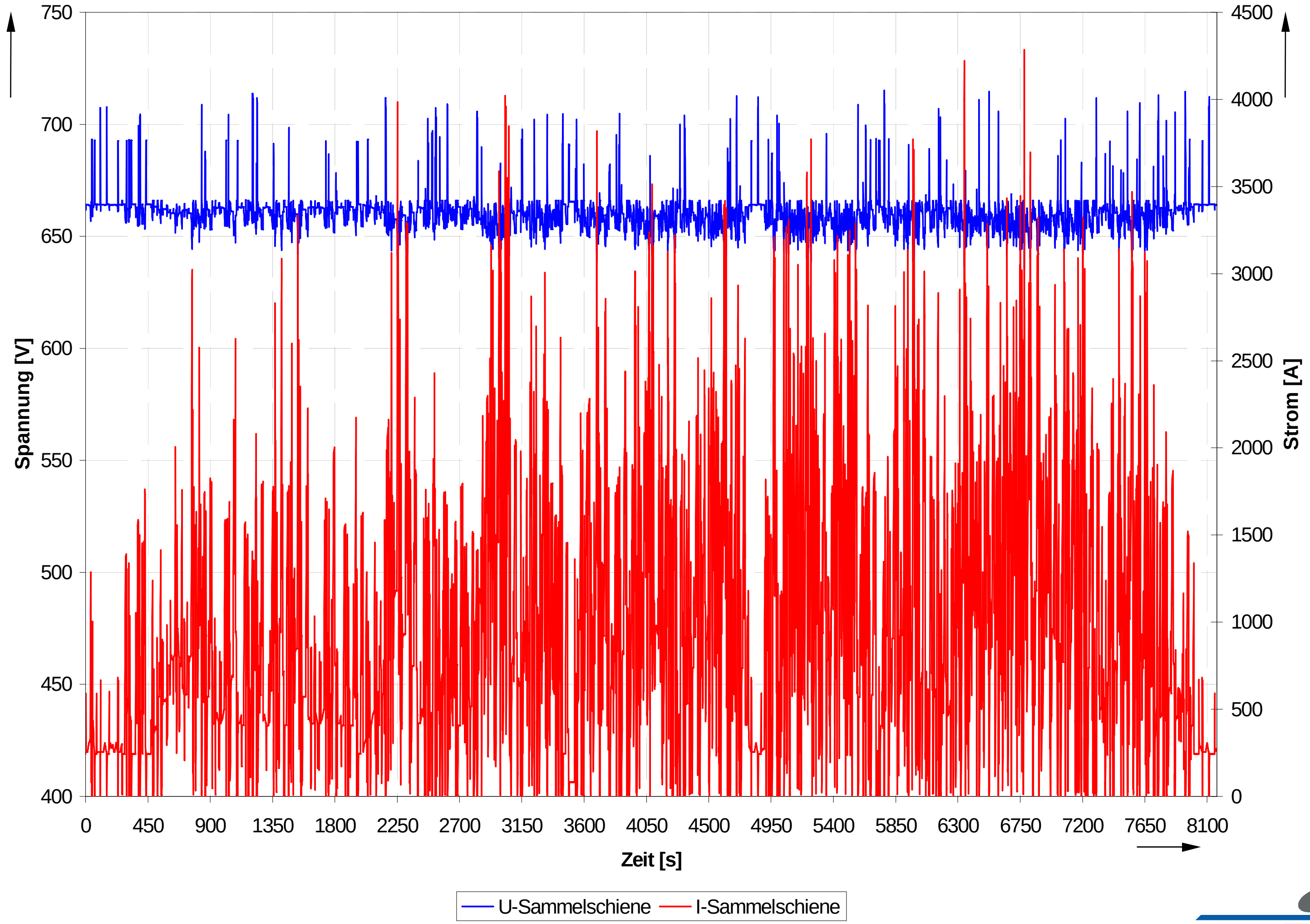
## Rail-to-earth potential Normal operation



# Converter current and bus-bar voltage Normal operation

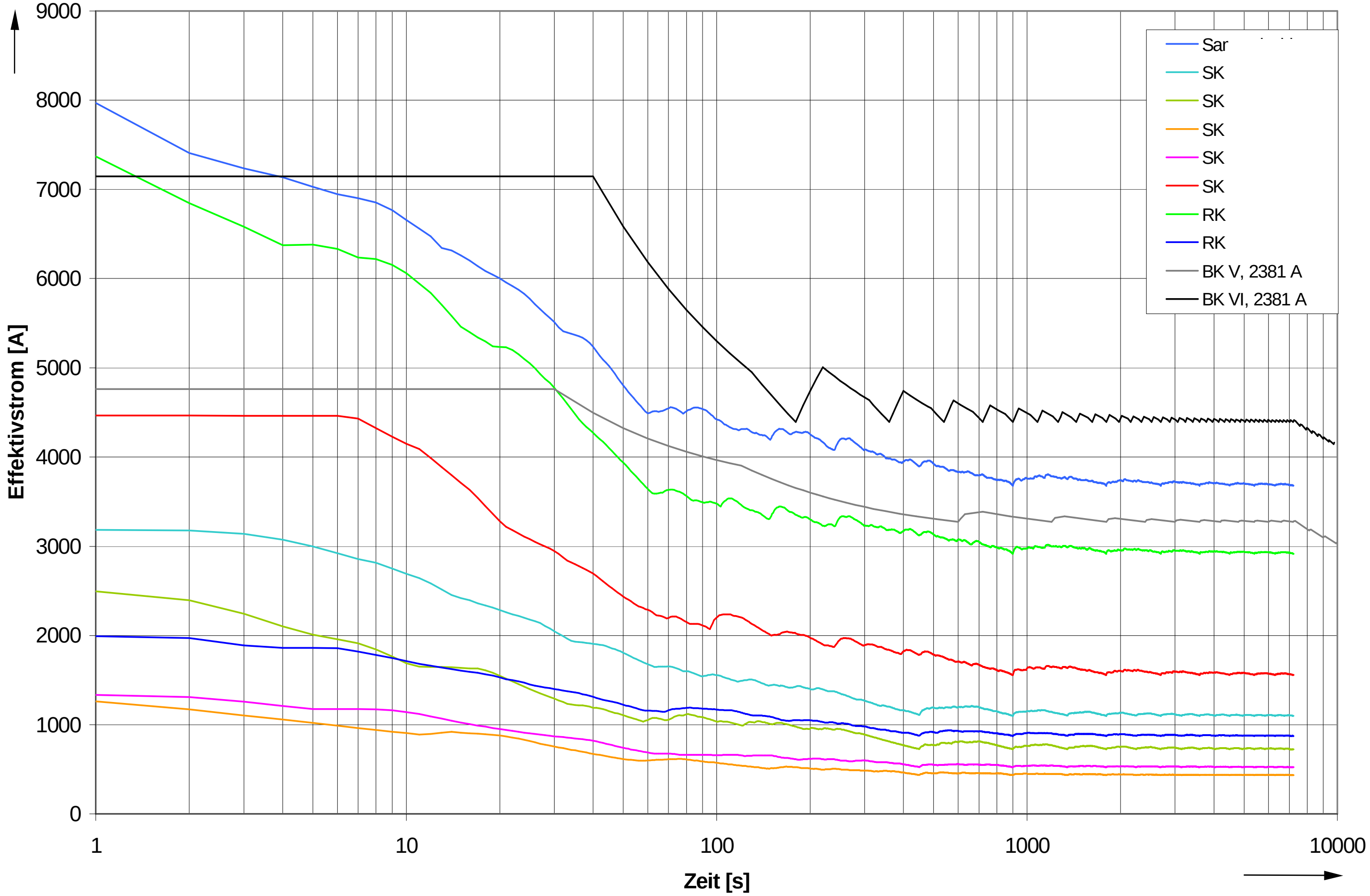


## Converter current and bus-bar-voltage    Depot gateway 4:50 - 7:05 h



## Load and loading capacity Substation

Normal operation, blackout in neighbouring subst.



# Load values    Substation, Normal operation without blackouts

| Station | Sektor | $I_{max}$ [A] 1 s | $I_{eff}$ [A] 7200 s 2 h | $P_{max}$ [kW] | $E_{ab}$ [kWh] | $E_{auf}$ [kWh] | $E_{verl}$ [kWh] | $I_{Einst}$ [kA] | $I_{Kmin}$ [kA] | $I_{Kmin}/I_{Einst}$ soll > 110% | $I_{max}/I_{Einst}$ soll < 90% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Promenade | SK | 1915 | 588 | 1221 | 520 | -10 | 4 | 3,5 | 14,0 | 400% | 54,7% |
| | SK | 1686 | 404 | 1072 | 264 | 0 | 2 | 3,0 | 11,7 | 390% | 56,2% |
| | SK | 1961 | 475 | 1252 | 417 | 0 | 3 | 3,0 | 10,4 | 347% | 65,4% |
| | SK | 1665 | 332 | 1048 | 257 | 0 | 4 | 3,5 | 10,4 | 297% | 47,6% |
| | SK | **3710** | 1018 | 2312 | 1000 | -33 | 36 | **4,2** | 12,7 | 302% | **88,3%** |
| | SK | 1128 | 310 | 720 | 290 | 0 | 1 | 3,0 | 34,0 | 1133% | 37,6% |
| | SK | 172 | 50 | 111 | 36 | 0 | 0 | 3,0 | 23,0 | 767% | 5,7% |
| | SK | 1145 | 316 | 738 | 220 | 0 | 1 | 3,0 | | | 38,2% |
| | SK | 2824 | 1075 | 1770 | 1226 | -6 | 18 | 3,5 | 16,6 | 474% | 80,7% |
| | SK | 912 | 279 | 582 | 153 | -28 | 1 | **2,5** | **2,7** | **108%** | 36,5% |
| | RK | -1242 | 513 | -749 | 0 | -627 | 3 | | | | |
| | RK | -2164 | 678 | -1324 | 2 | -789 | 8 | | | | |
| | RK | -649 | 238 | -393 | 0 | -281 | 2 | | | | |
| | RK | -3425 | 1375 | -2065 | 0 | -1683 | 8 | | | | |
| | RK | -1742 | 657 | -1050 | 0 | -804 | 7 | | | | |
| | RK | -912 | 279 | -582 | 28 | -153 | 1 | | | | |
| | **gesamt** | **8773** | **3527** | **5289** | **4305** | **0** | **97** | | | | |

SK: Speisekabel
RK: Rückleiterkabel



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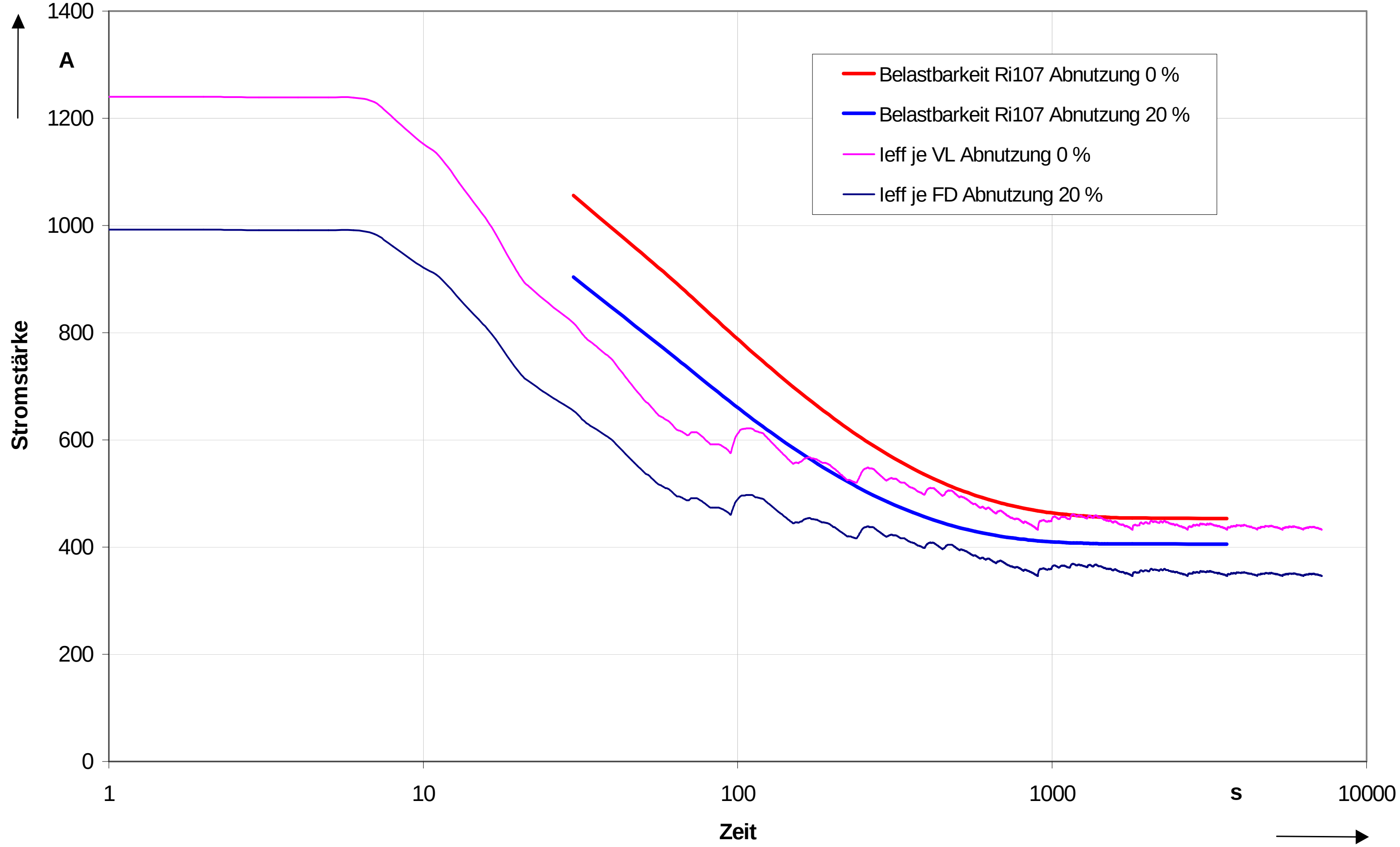
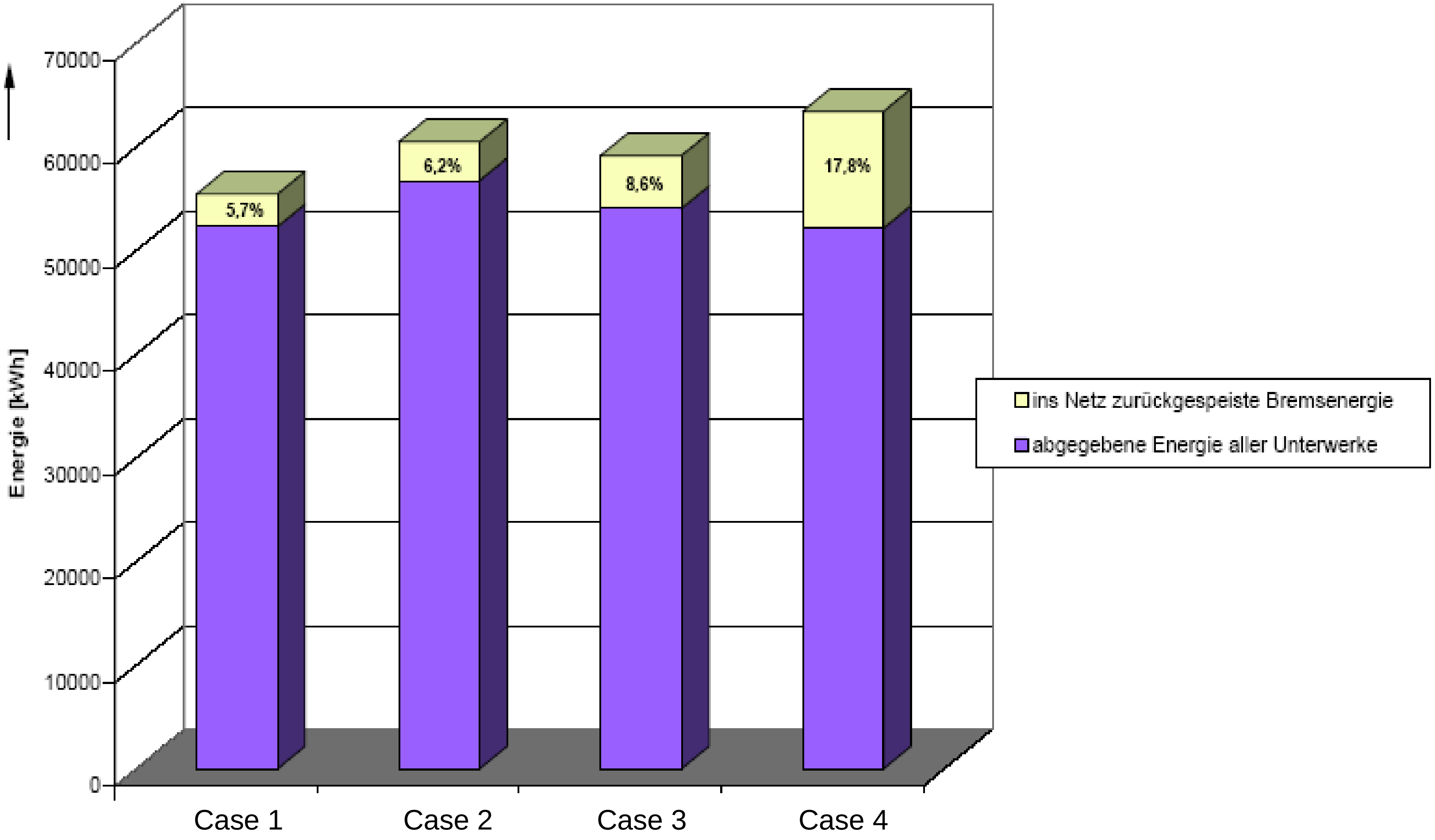
## Load and loading capacity

## Catenary wire at feeding point

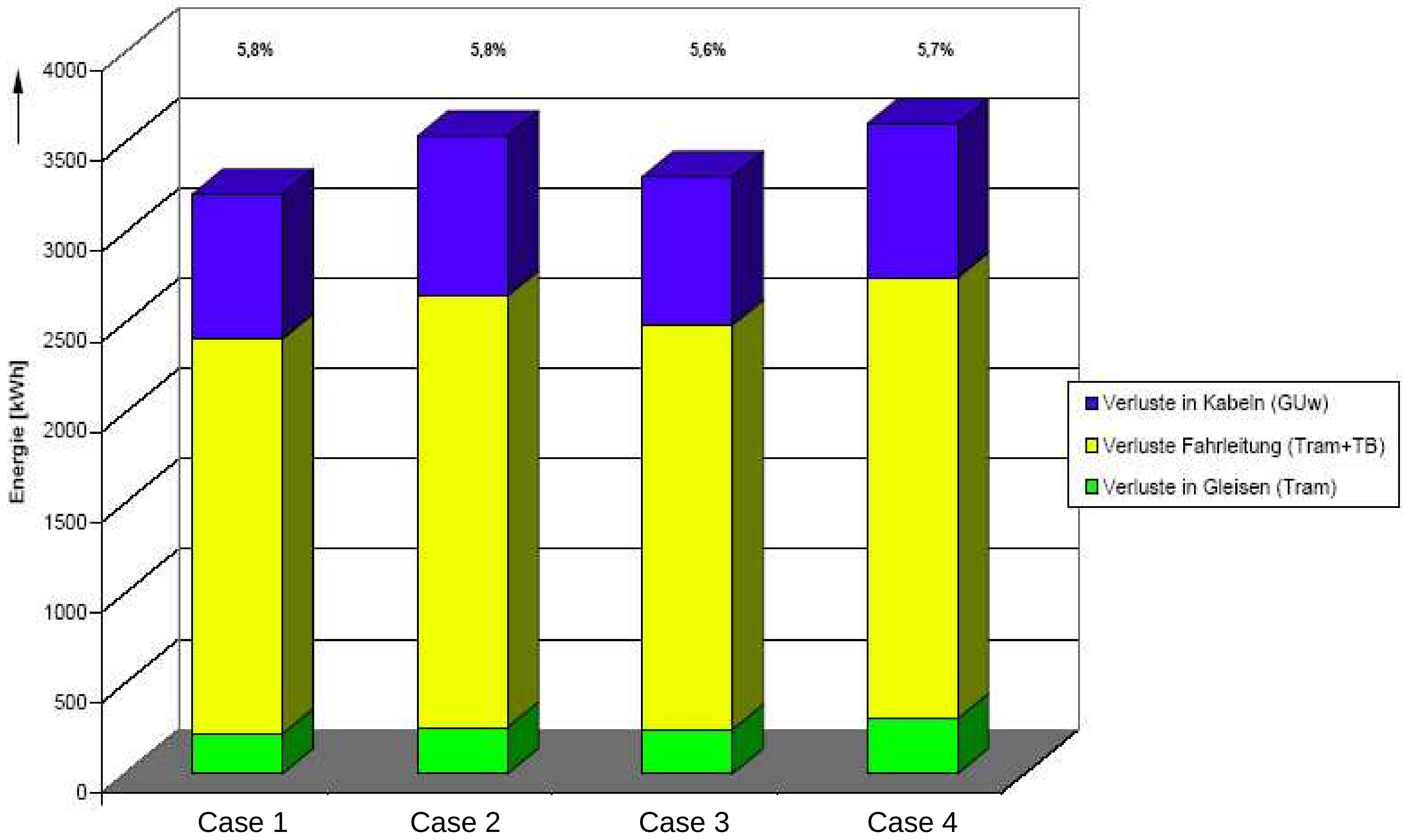
Normal operation, blackout in neighbouring subst.



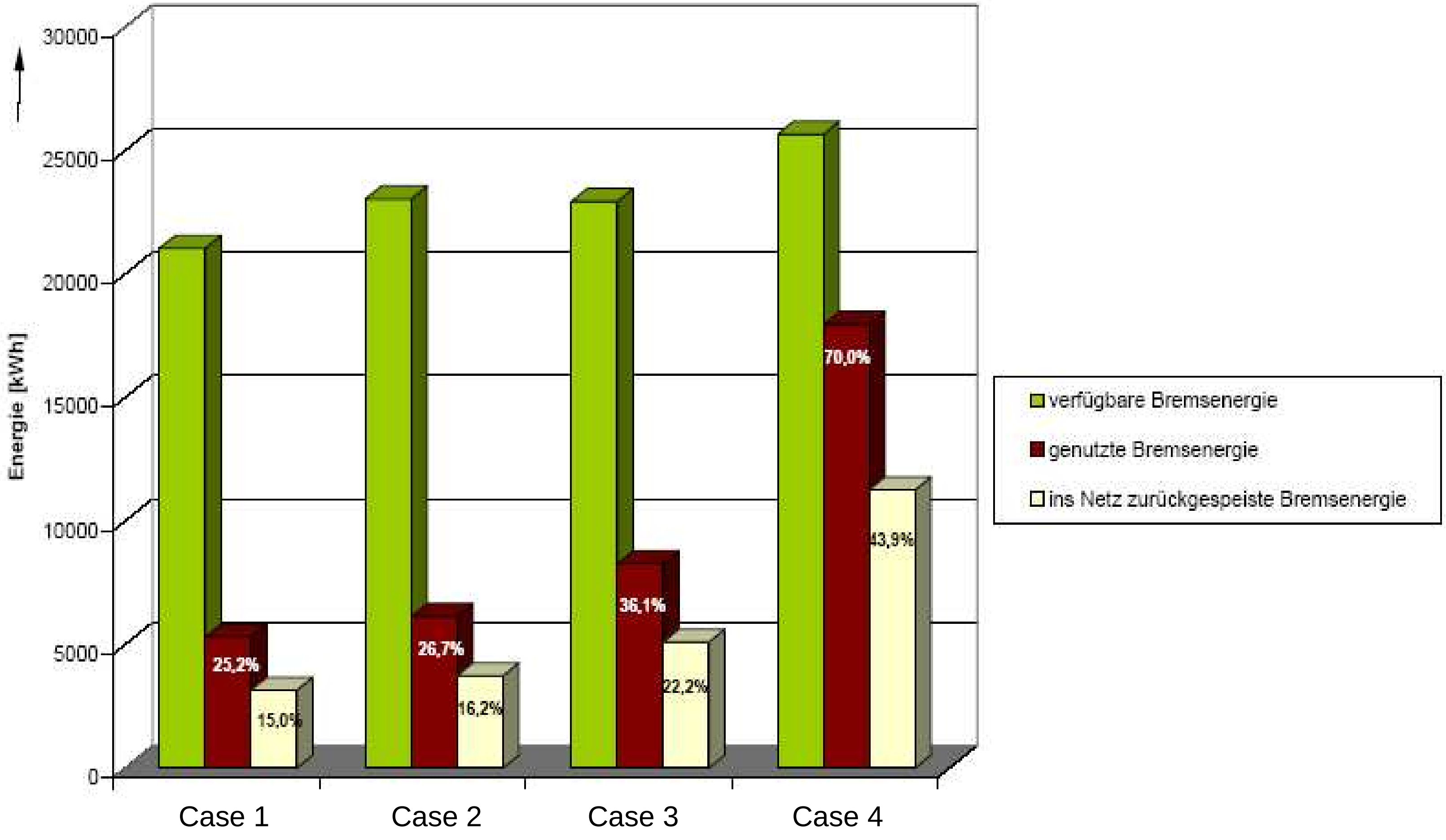
## Energy balance



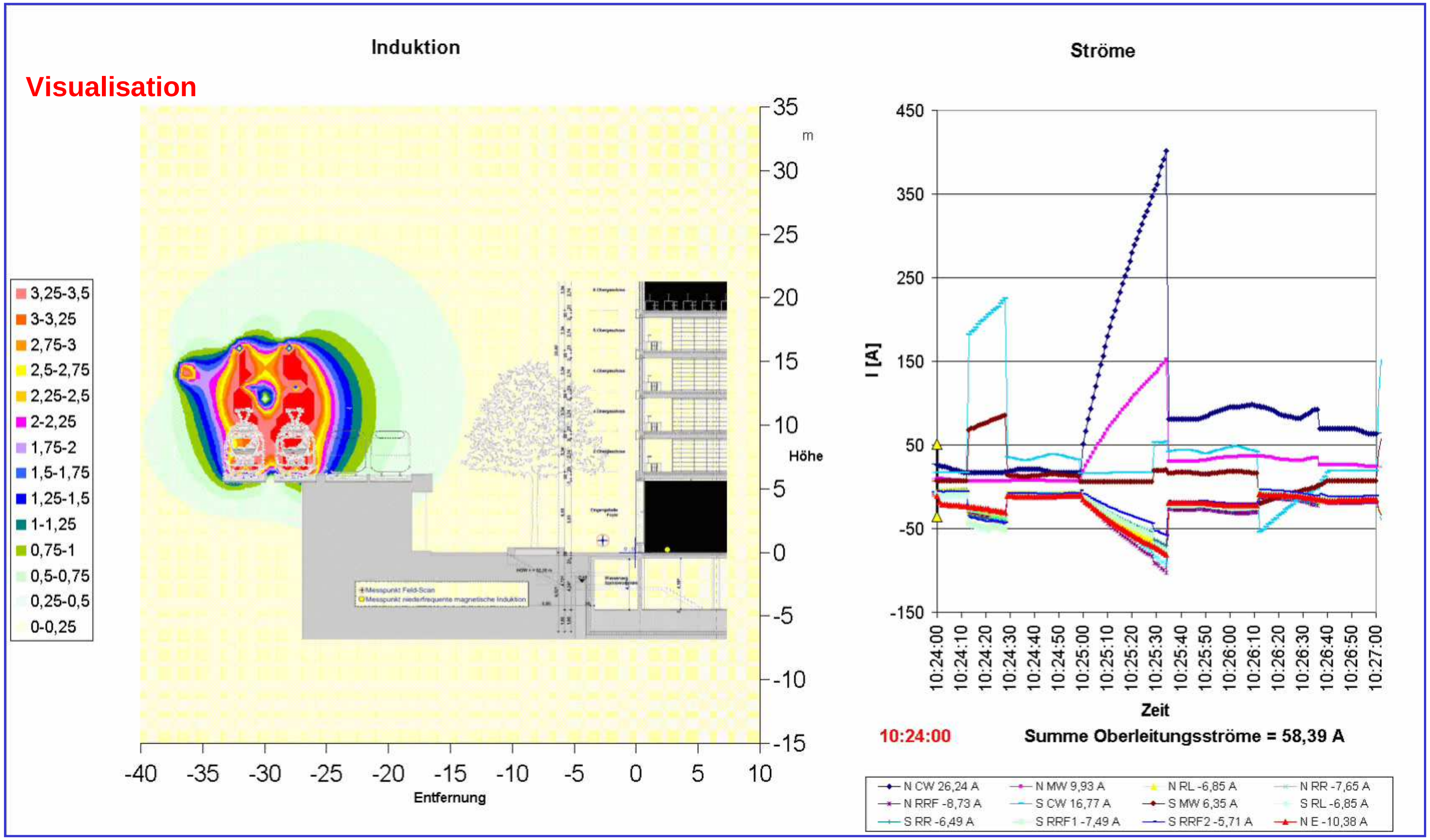
# Power losses balance



# Recovering balance



# **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

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Berlin - Dresden - Wildenrath

**Eine Expertenrunde für das Gesamtsystem Bahn**

The Expert Team for the Complete Railway System

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