OpenPowerNet

Simulation of Railway Power Supply Systems

AC Railway

DC Railway / Trolleybus

Institut für Bahntechnik GmbH

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Prof. Dr.-Ing. Arnd Stephan

Institut für Bahntechnik GmbH

Simulation of Railway Power Supply Systems – why?

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

Special Requirements

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

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- 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

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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
- Substations arrangement
- Switch states
- Feeder lines and cables
- Catenary system
- Earthing system

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OPEN TRACK

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Plug-in

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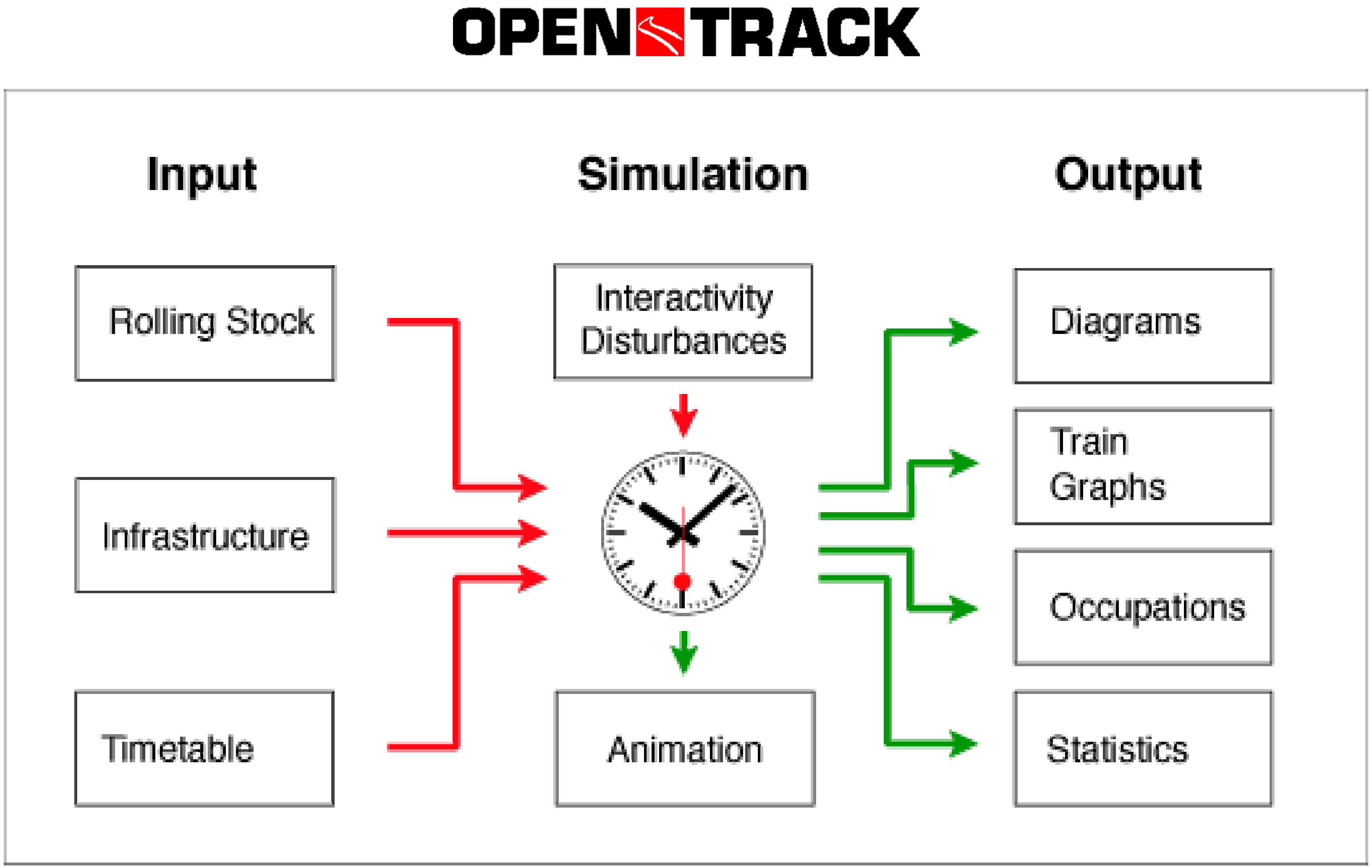
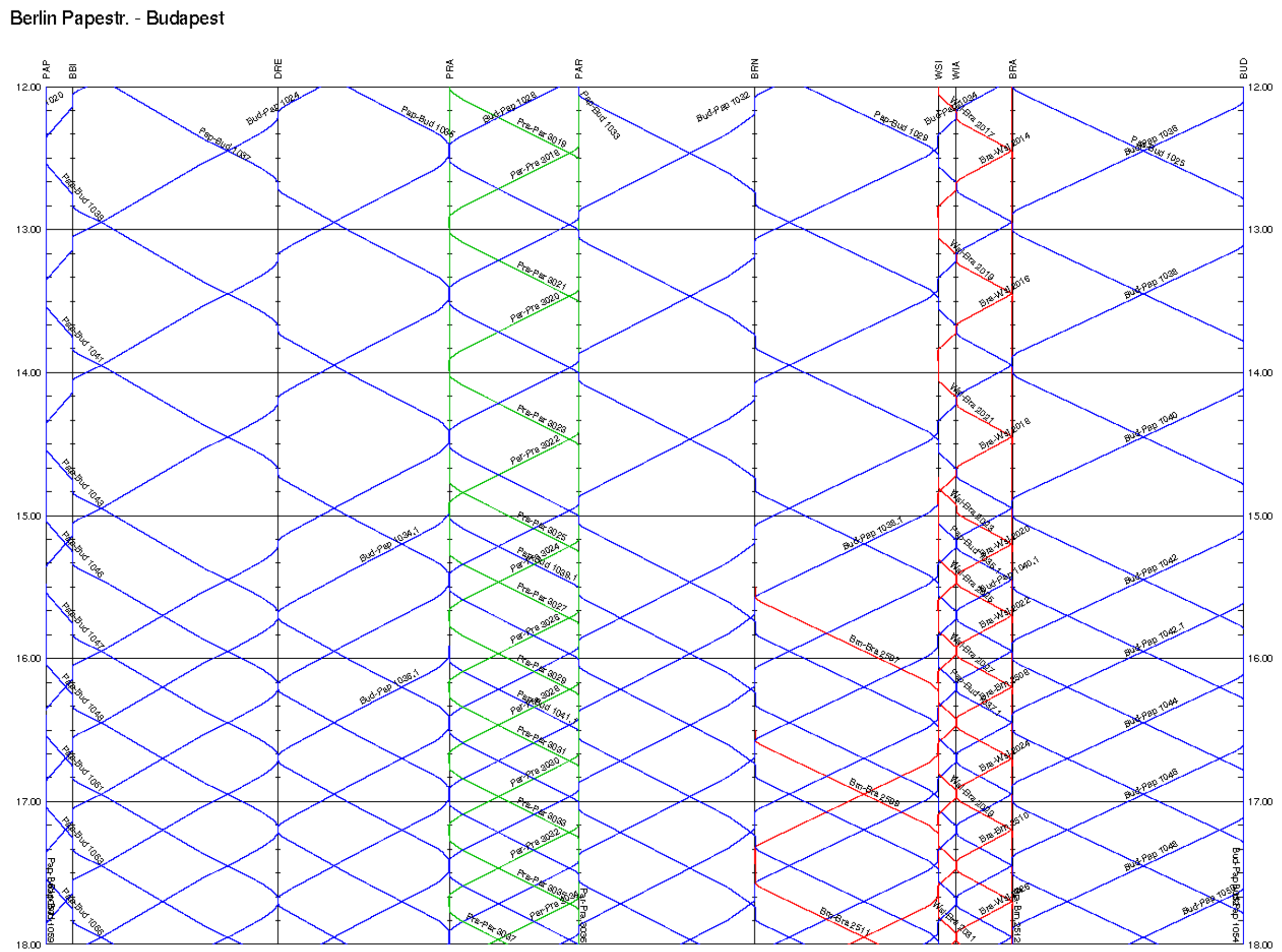
OpenPowerNet


OPEN TRACK
Input
Simulation
Output
Rolling Stock
Infrastructure
Timetable
Interactivity Disturbances
Animation
Diagrams
Train Graphs
Occupations
Statistics

Source: ETHZ

OPEN TRACK



Source: IFB

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Railway Operation Simulation

Railway Operation Simulation

Propulsion Technology

Railway Operation Simulation


Propulsion Technology


Power Supply System

Railway Operation Simulation

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Propulsion Technology

Power Supply System

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Railway Operation Simulation

OPENTRACK

ATM
Advanced Train Module

Propulsion Technology

Power Supply System

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Railway Operation Simulation

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ATM
Advanced Train Module

PSC
Power Supply Calculation

Propulsion Technology

Power Supply System

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Railway Operation Simulation

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Advanced Train Module

⟷ **Interaction**

PSC
Power Supply Calculation

Propulsion Technology

Power Supply System

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Railway Operation Simulation

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PSC
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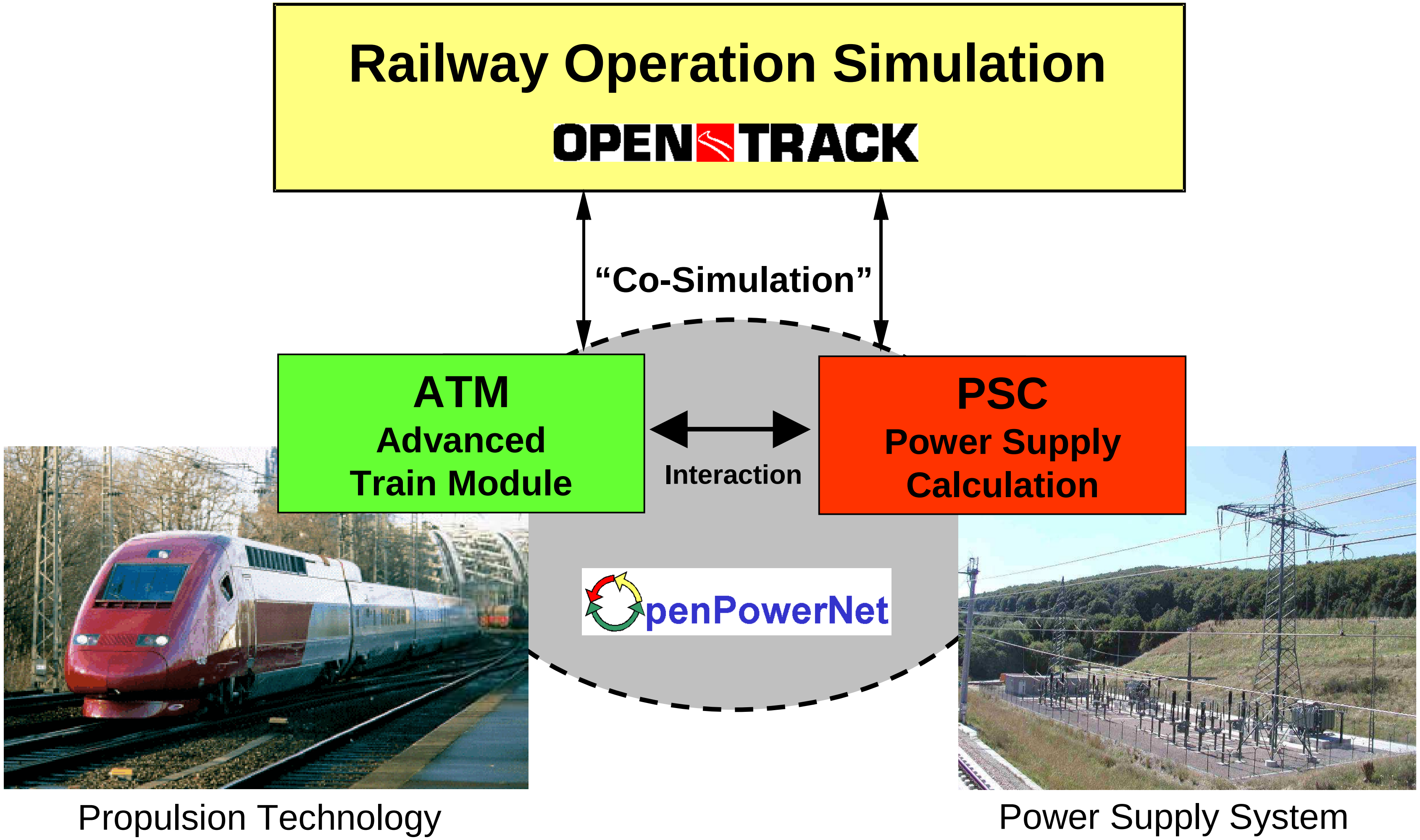
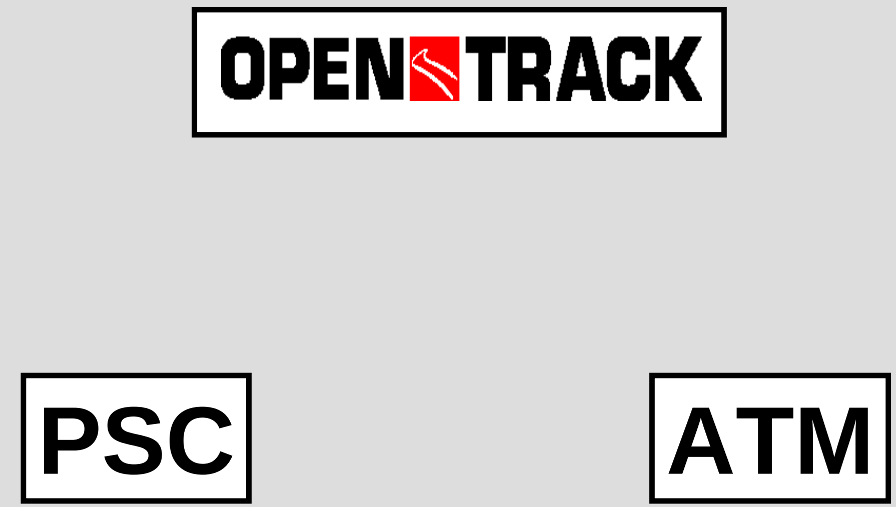
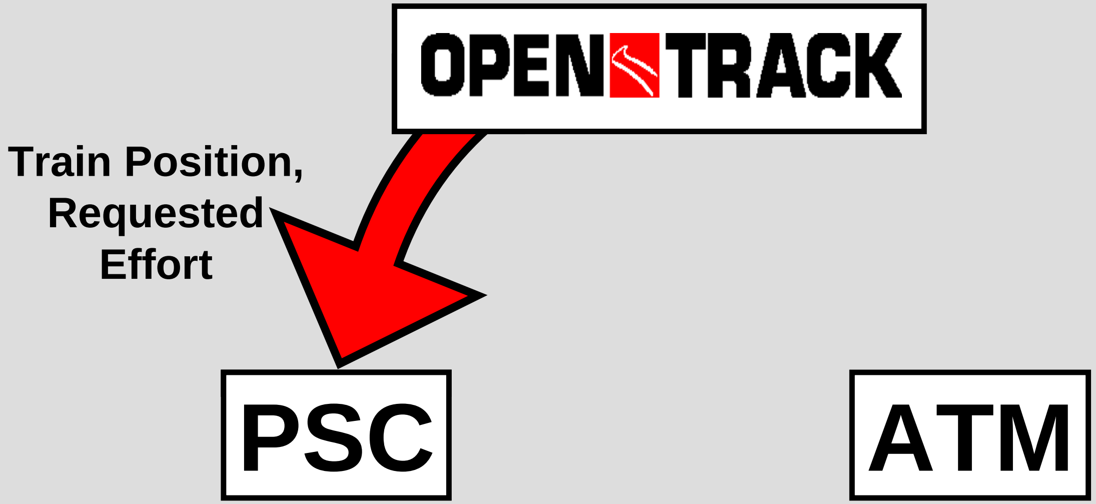
Power Supply System


Railway Operation Simulation
OPEN TRACK
"Co-Simulation"
ATM
Advanced
Train Module
Interaction
PSC
Power Supply
Calculation
OpenPowerNet
Propulsion Technology
Power Supply System

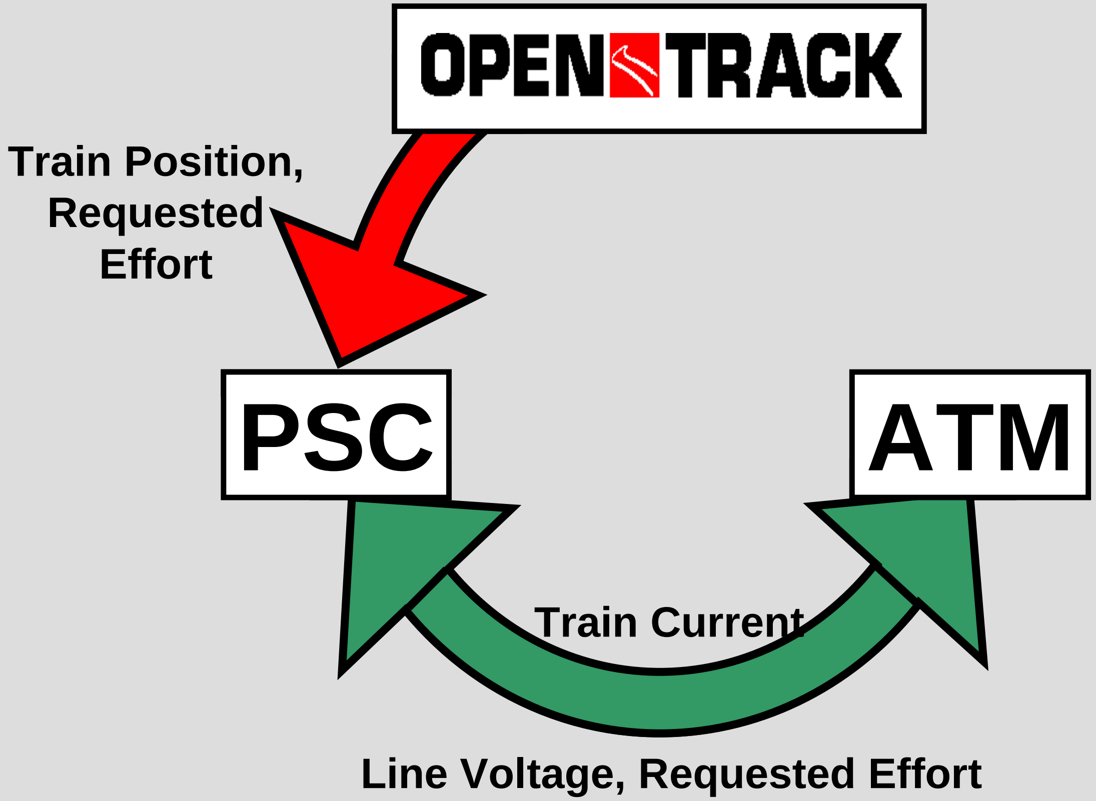
Simulation Sequence per Time Step

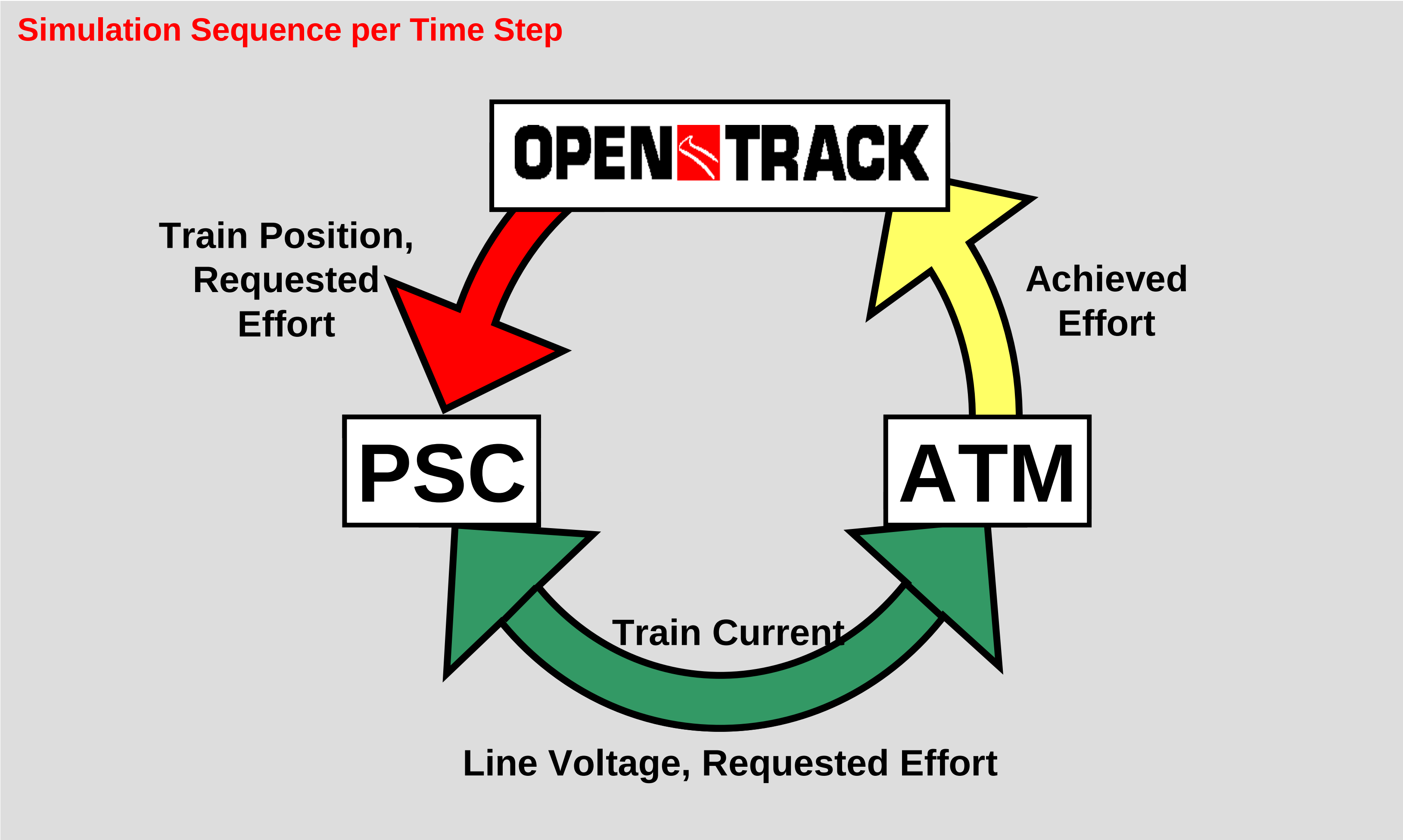


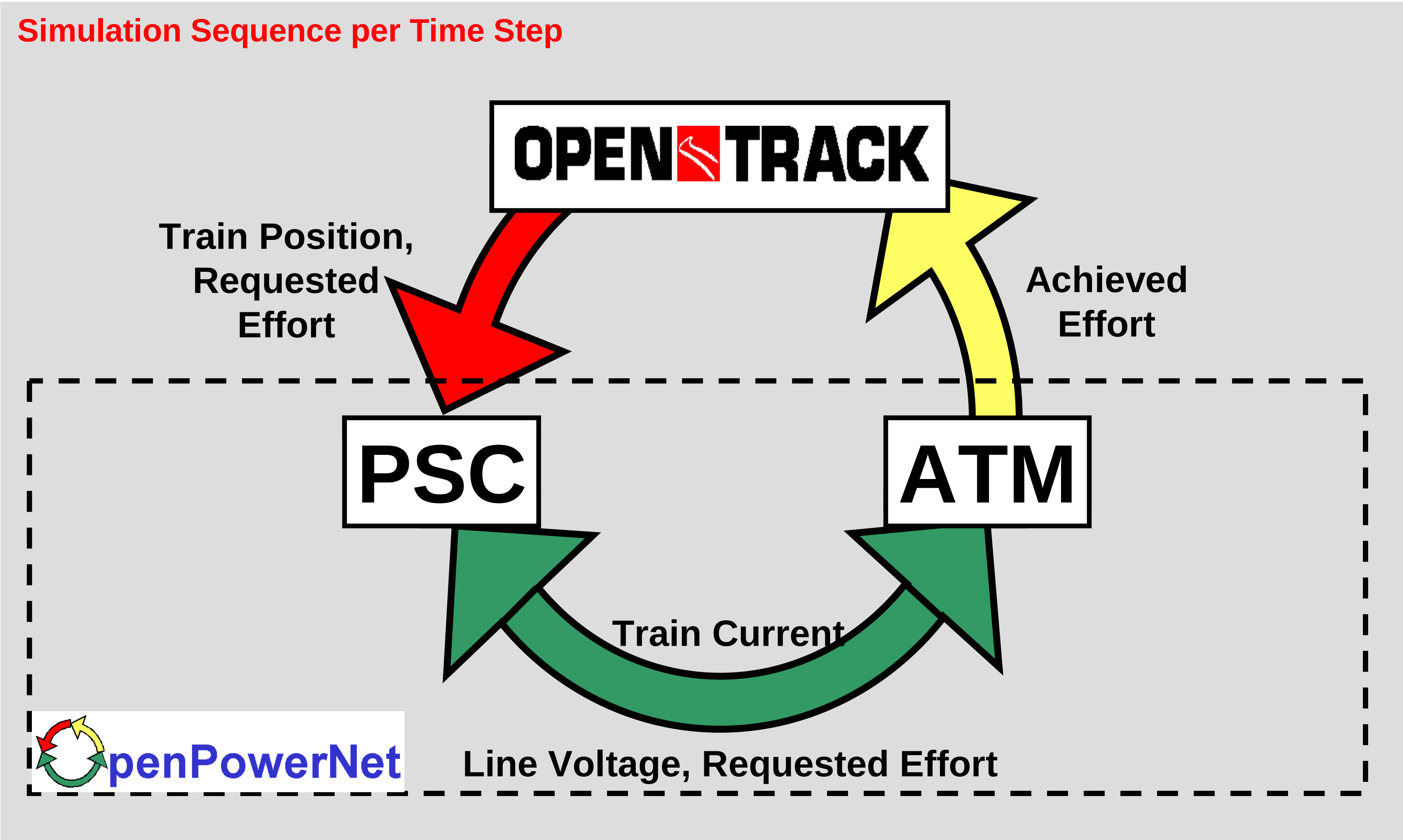
Simulation Sequence per Time Step

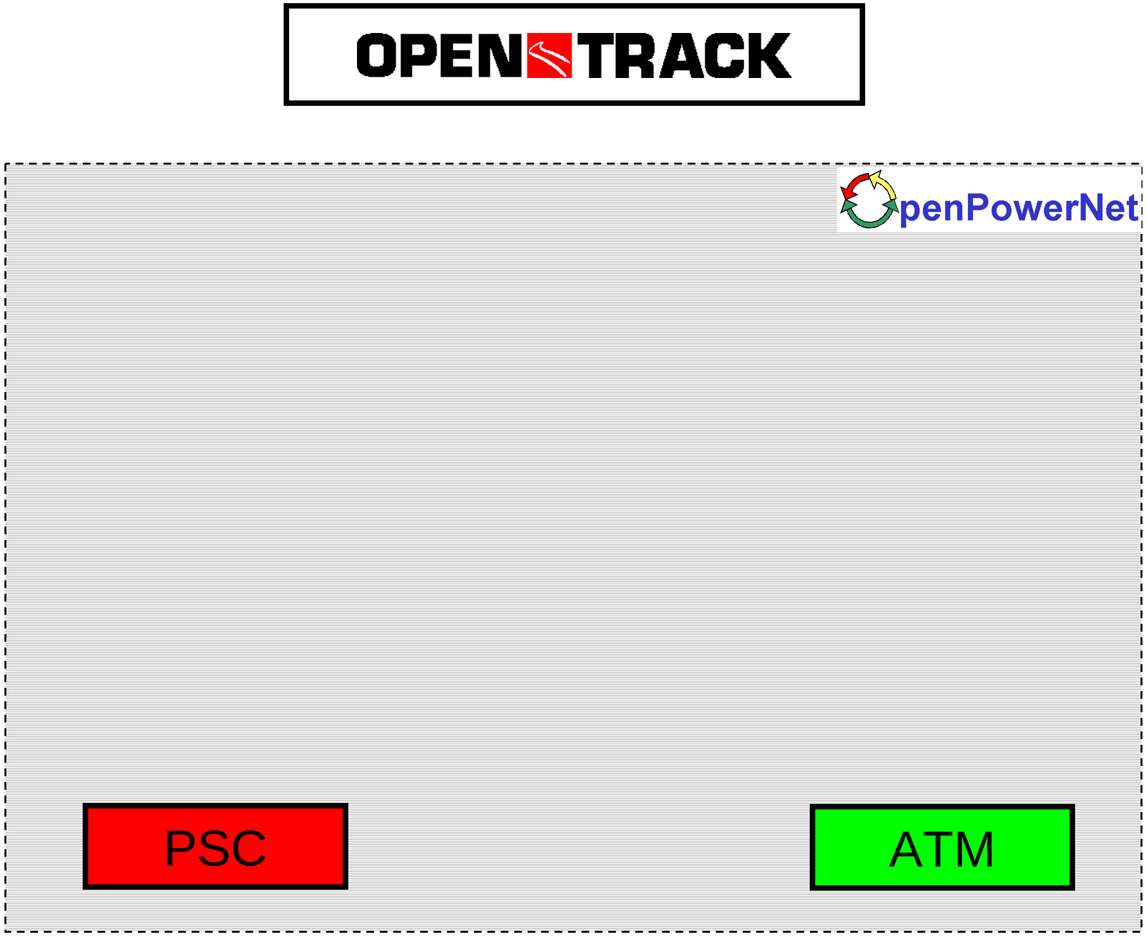


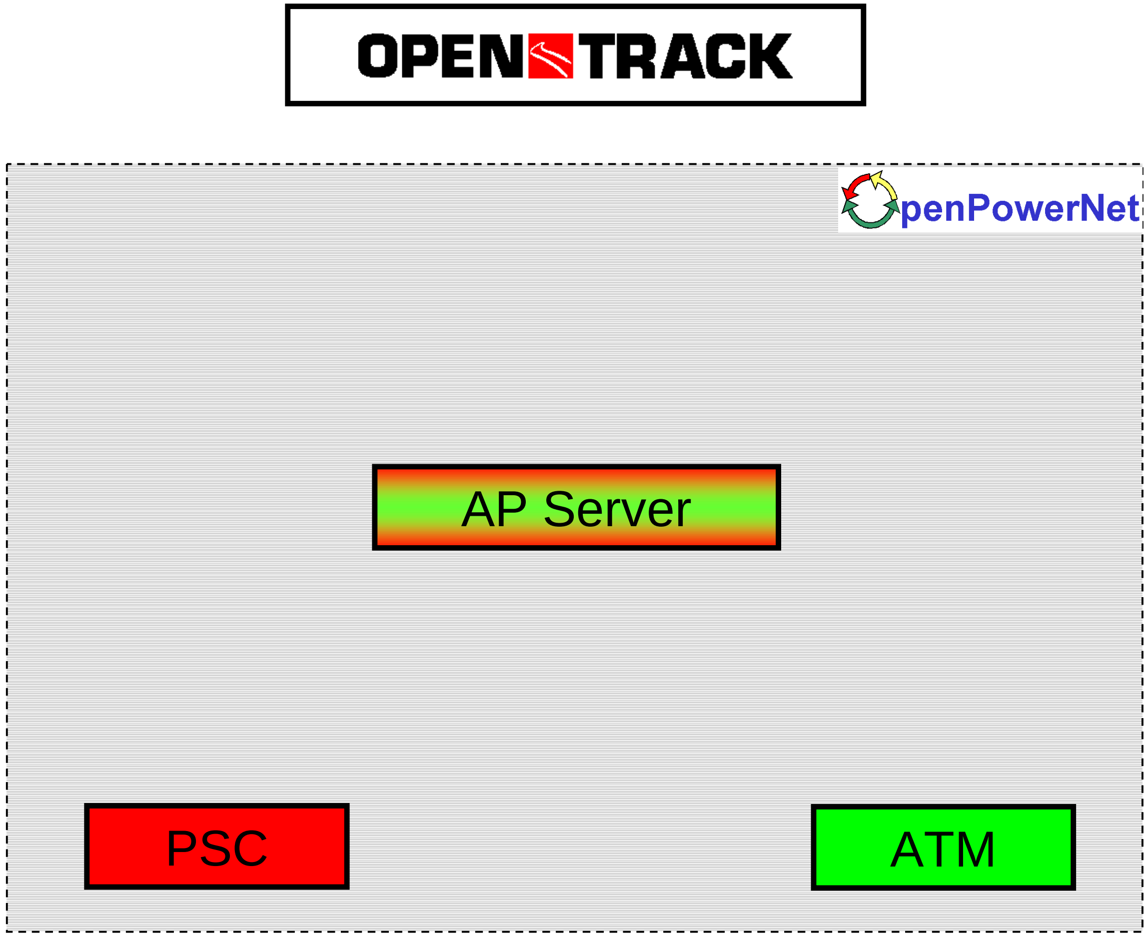
Simulation Sequence per Time Step

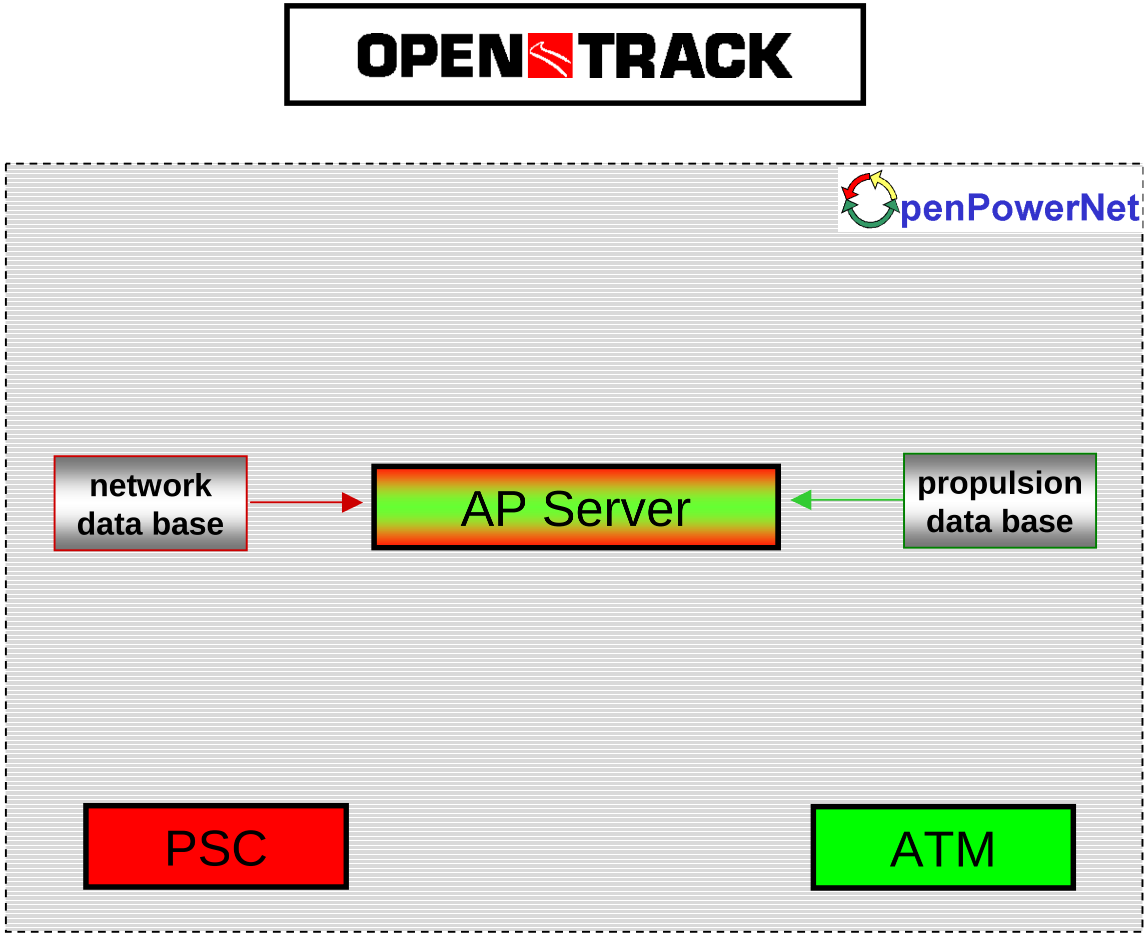


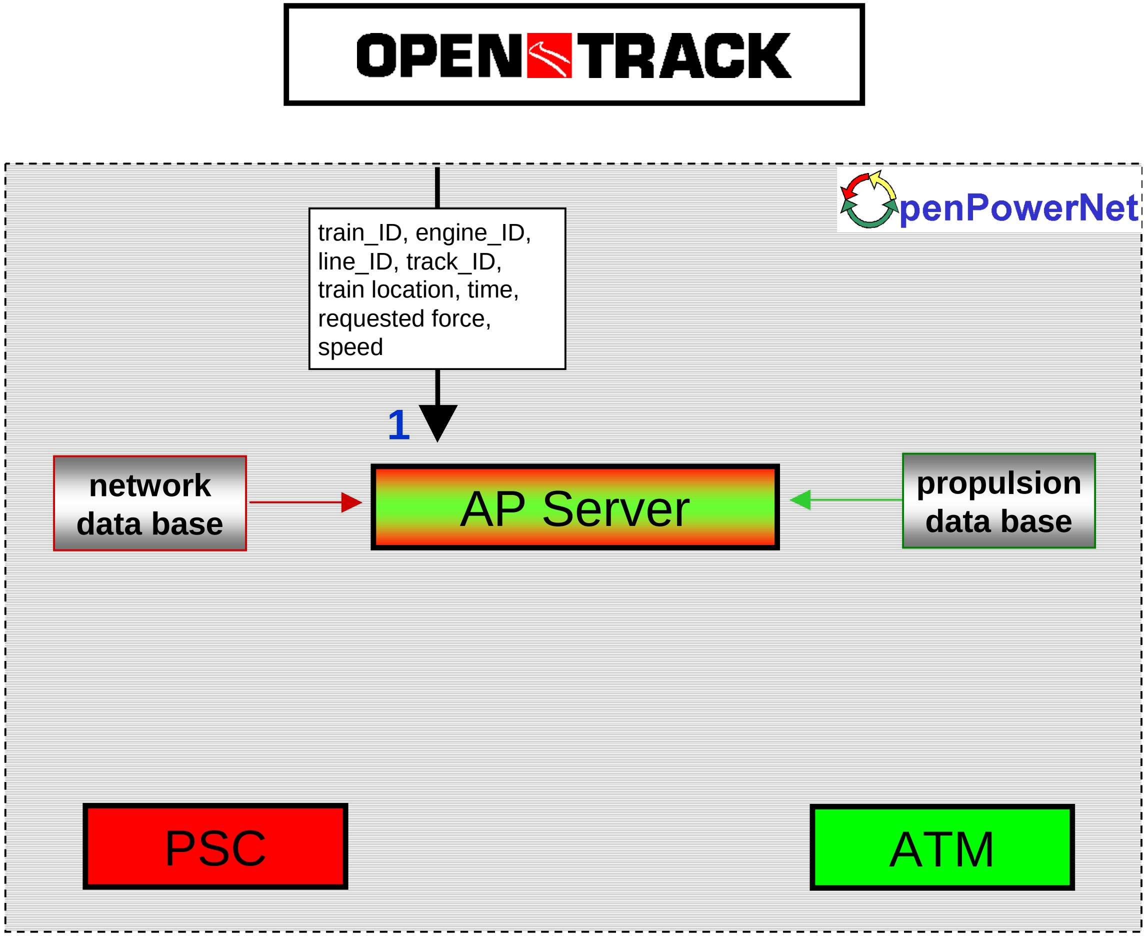

Simulation Sequence per Time Step
OPEN TRACK
Train Position,
Requested
Effort
Achieved
Effort
PSC
ATM
Train Current
Line Voltage, Requested Effort

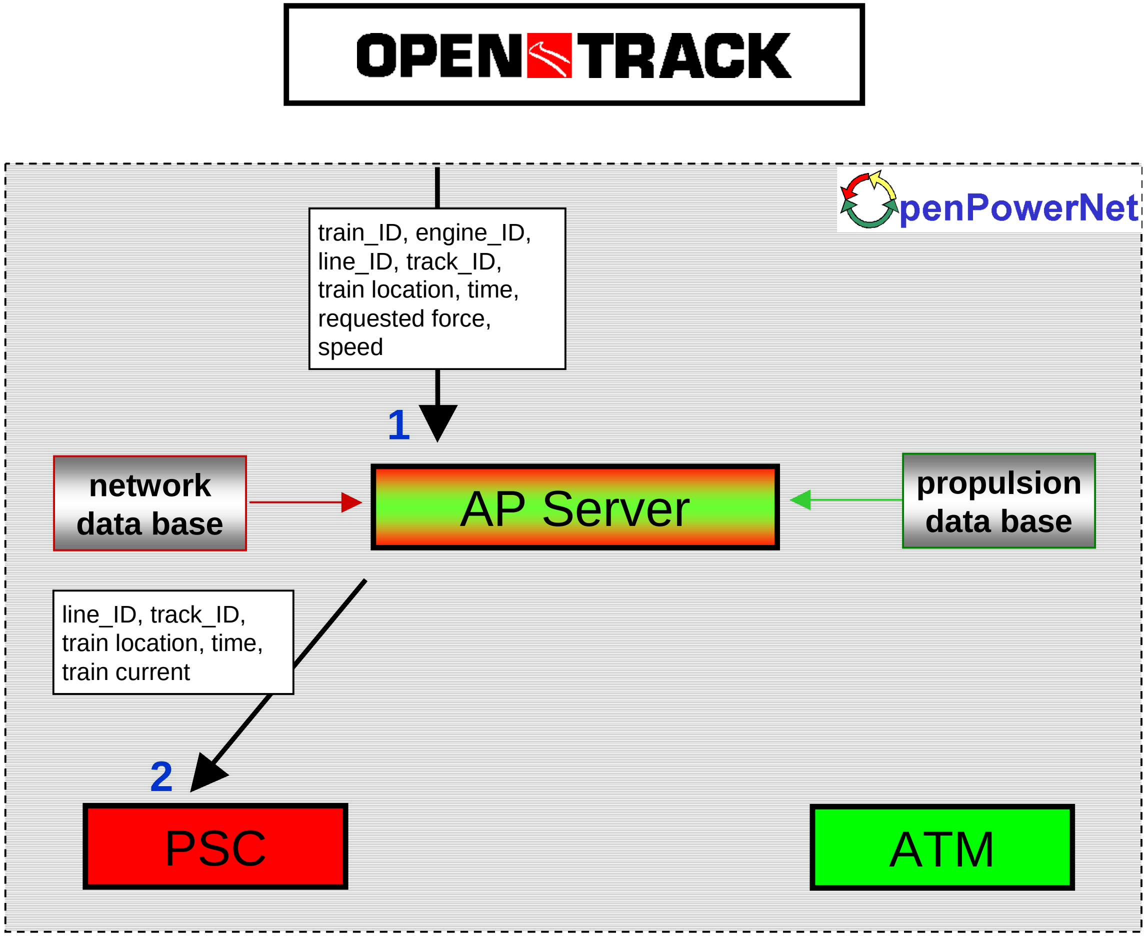

Simulation Sequence per Time Step
OPEN TRACK
Train Position, Requested Effort
Achieved Effort
PSC
ATM
Train Current
OpenPowerNet
Line Voltage, Requested Effort


OPEN TRACK
OpenPowerNet
PSC
ATM


OPEN TRACK
OpenPowerNet
AP Server
PSC
ATM


OPEN TRACK
OpenPowerNet
network data base
AP Server
propulsion data base
PSC
ATM


OPEN TRACK
OpenPowerNet
train_ID, engine_ID, line_ID, track_ID, train location, time, requested force, speed
1
network data base
AP Server
propulsion data base
PSC
ATM



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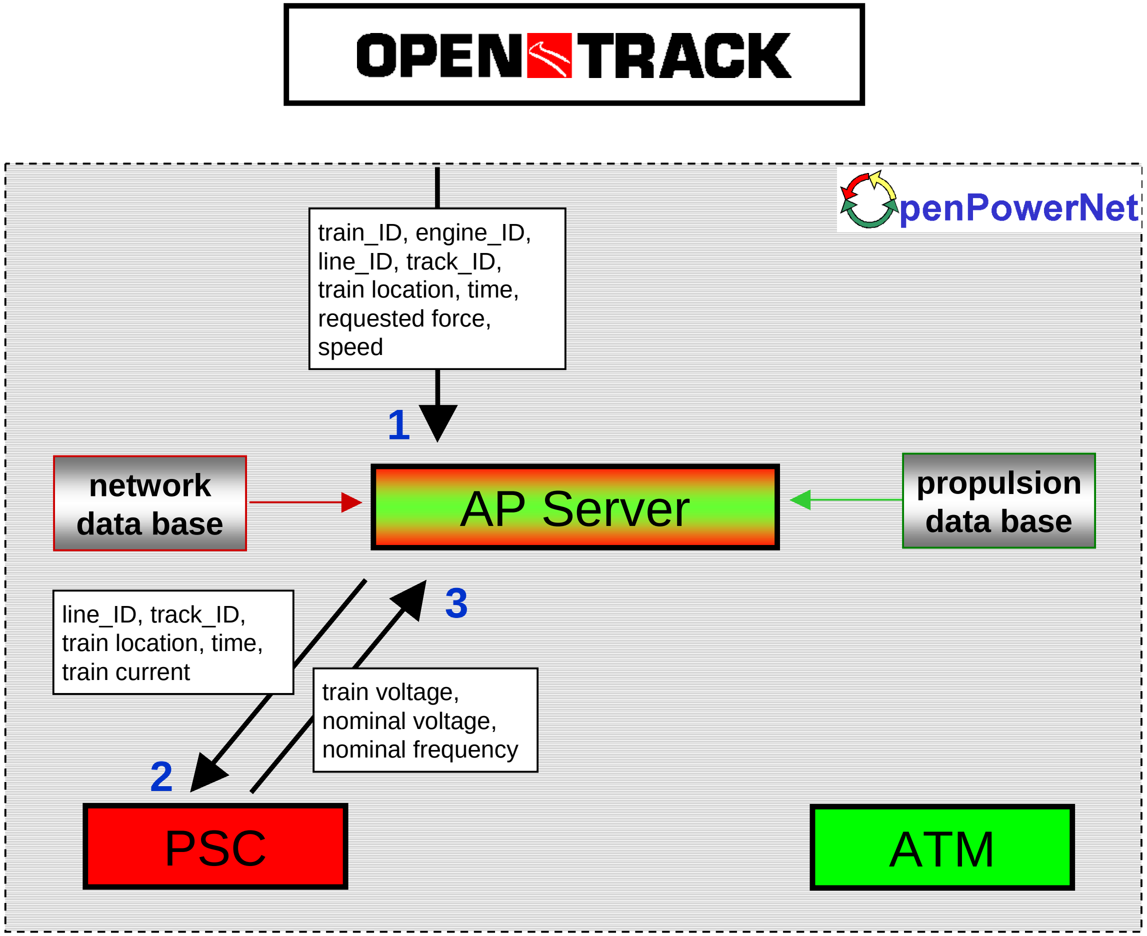
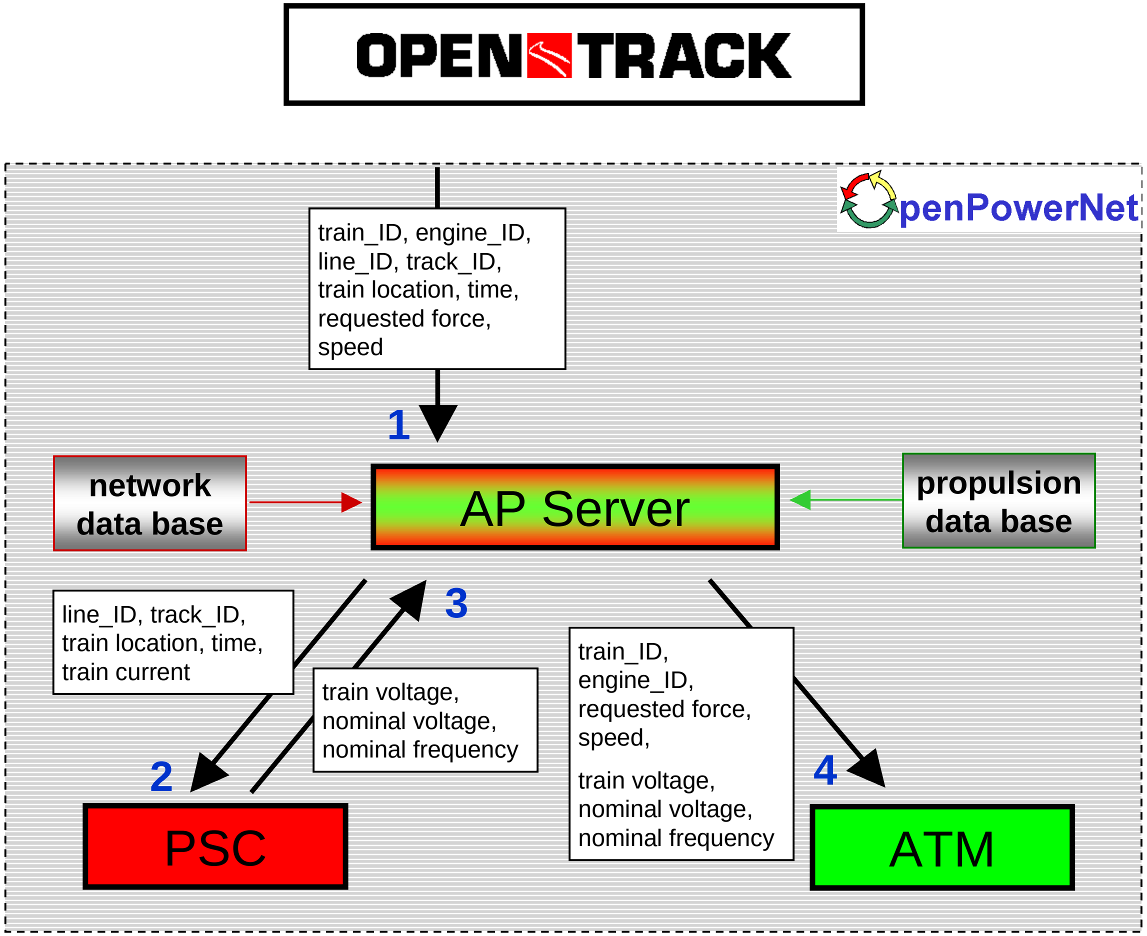

OPEN TRACK
OpenPowerNet
train_ID, engine_ID, line_ID, track_ID, train location, time, requested force, speed
1
network data base
AP Server
propulsion data base
line_ID, track_ID, train location, time, train current
3
train voltage, nominal voltage, nominal frequency
2
PSC
ATM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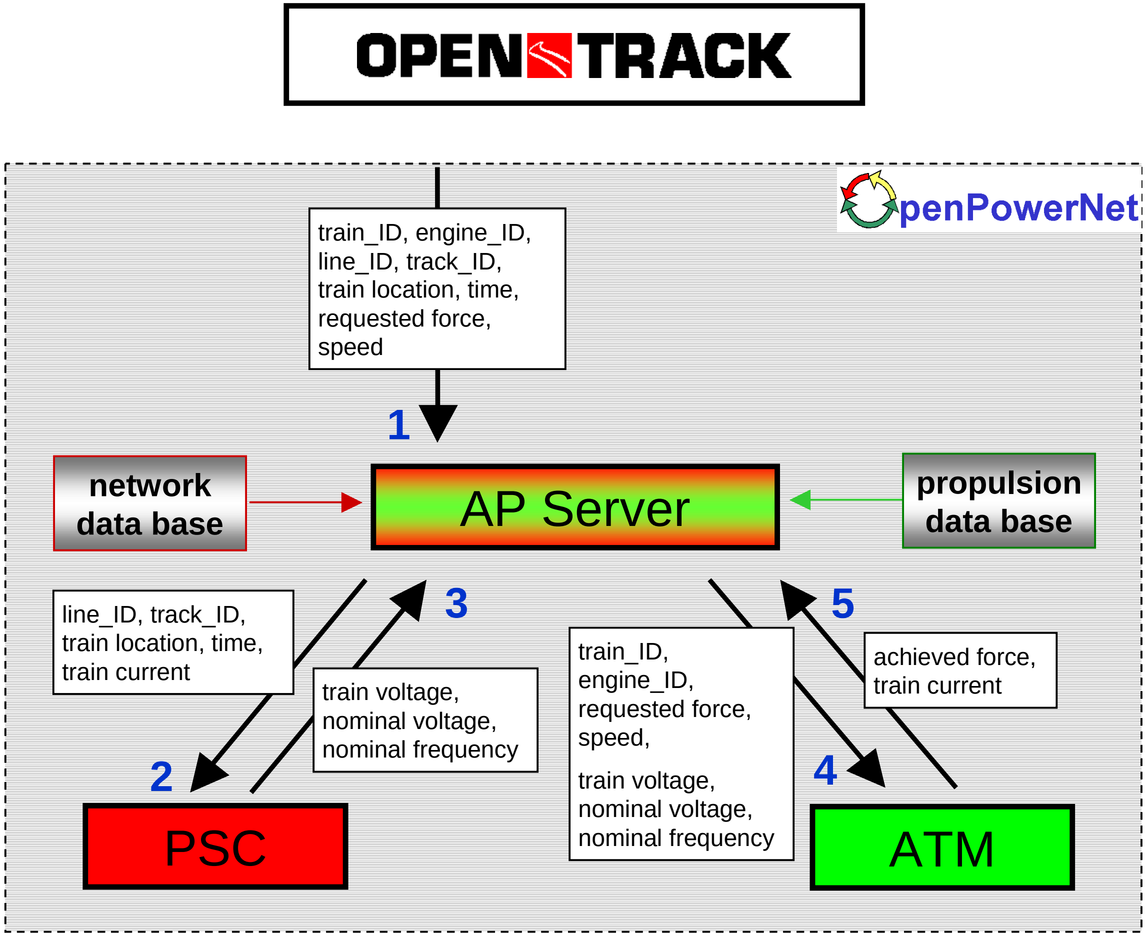
3
train voltage, nominal voltage, nominal frequency
train_ID, engine_ID, requested force, speed,
train voltage, nominal voltage, nominal frequency
2
4
PSC
ATM



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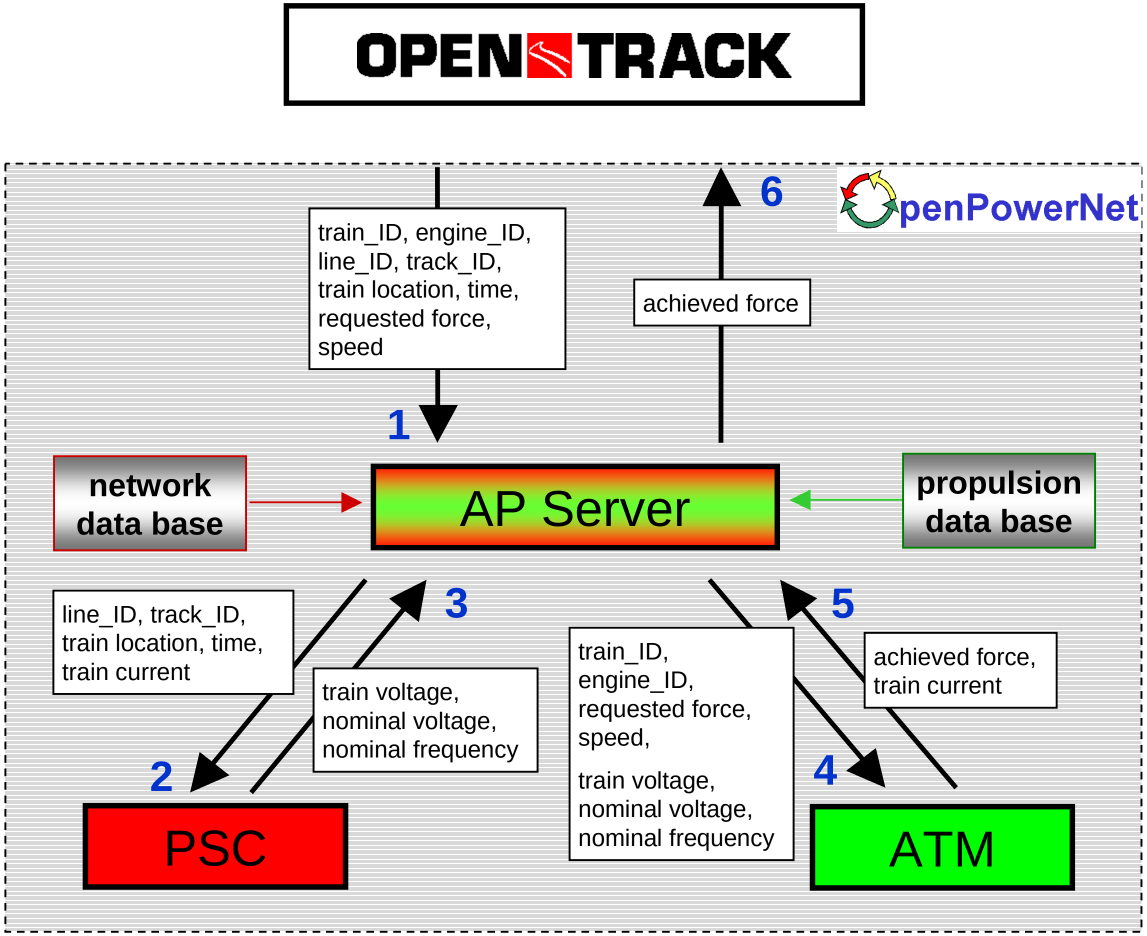
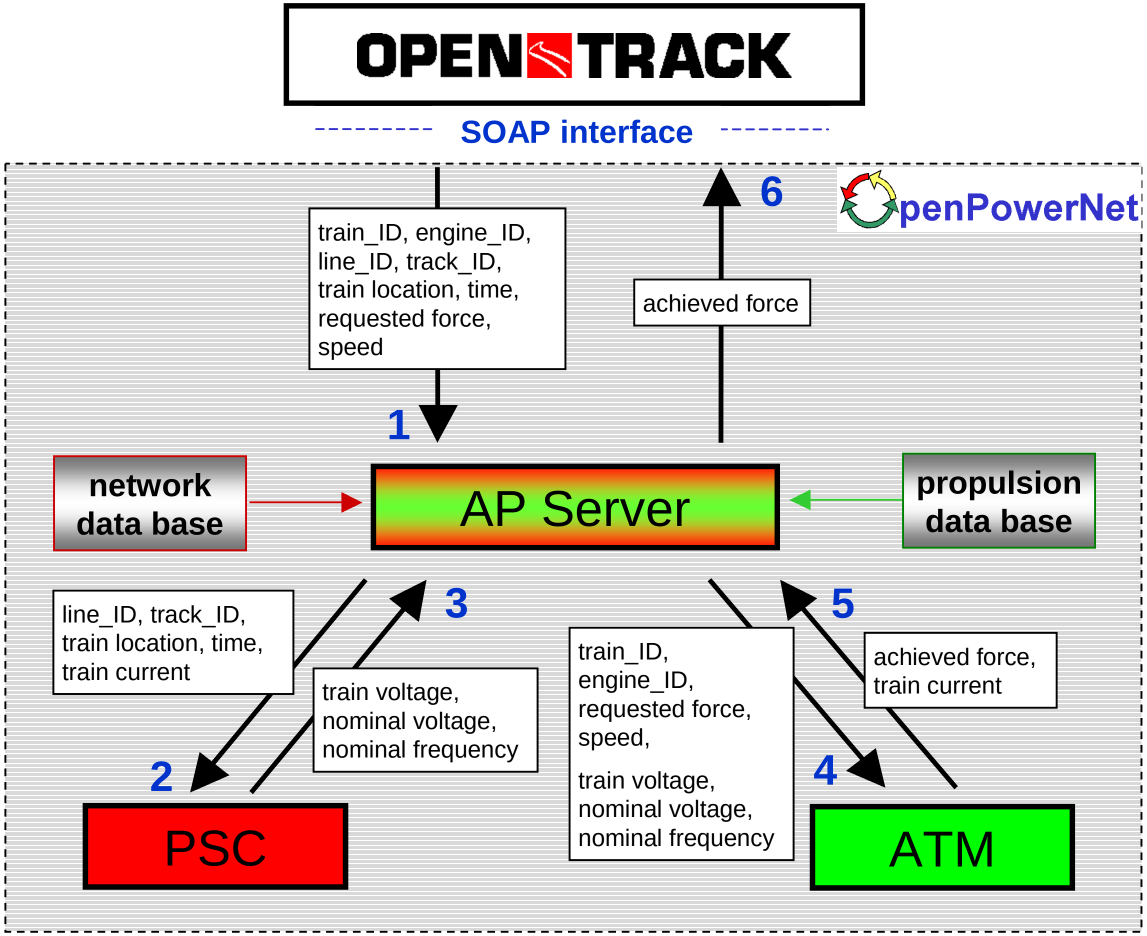

OPEN TRACK
OpenPowerNet
train_ID, engine_ID, line_ID, track_ID, train location, time, requested force, speed
achieved force
6
1
network data base
AP Server
propulsion data base
line_ID, track_ID, train location, time, train current
3
5
train voltage, nominal voltage, nominal frequency
train_ID, engine_ID, requested force, speed,
train voltage, nominal voltage, nominal frequency
achieved force, train current
2
4
PSC
ATM



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Modelling levels available for propulsion simulation

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a) constant efficiency factors for propulsion equipment

Modelling levels available for propulsion simulation

a) **constant efficiency factors for propulsion equipment**

b) **driving state related efficiency factors**

Modelling levels available for propulsion simulation

a) constant efficiency factors for propulsion equipment

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c) load depending efficiency factors of components

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a) constant efficiency factors for propulsion equipment

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d) detailed engine models of components

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**

Modelling levels available for propulsion simulation

a) constant efficiency factors for propulsion equipment

b) driving state related efficiency factors

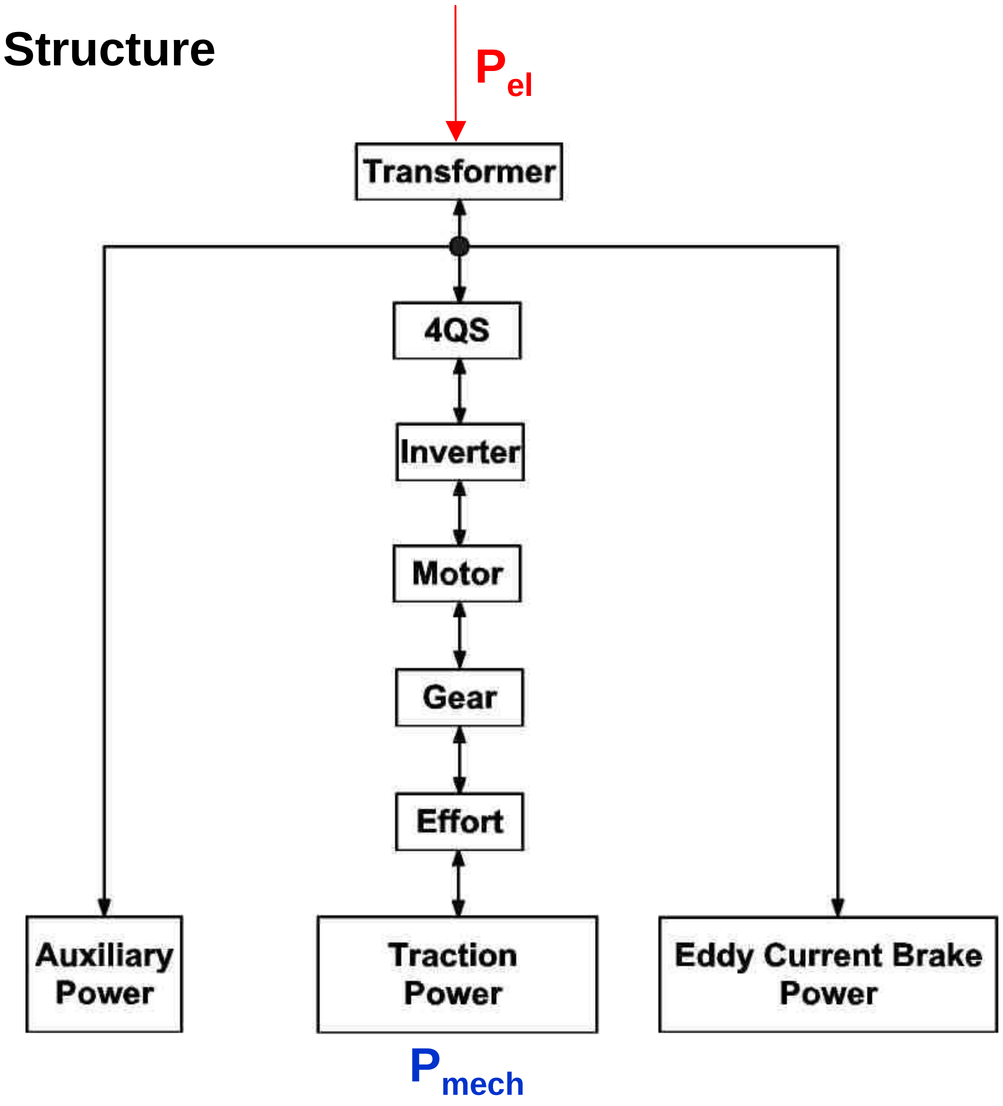
c) load depending efficiency factors of components

d) detailed engine models of components

\+ auxiliary power and eddy current break

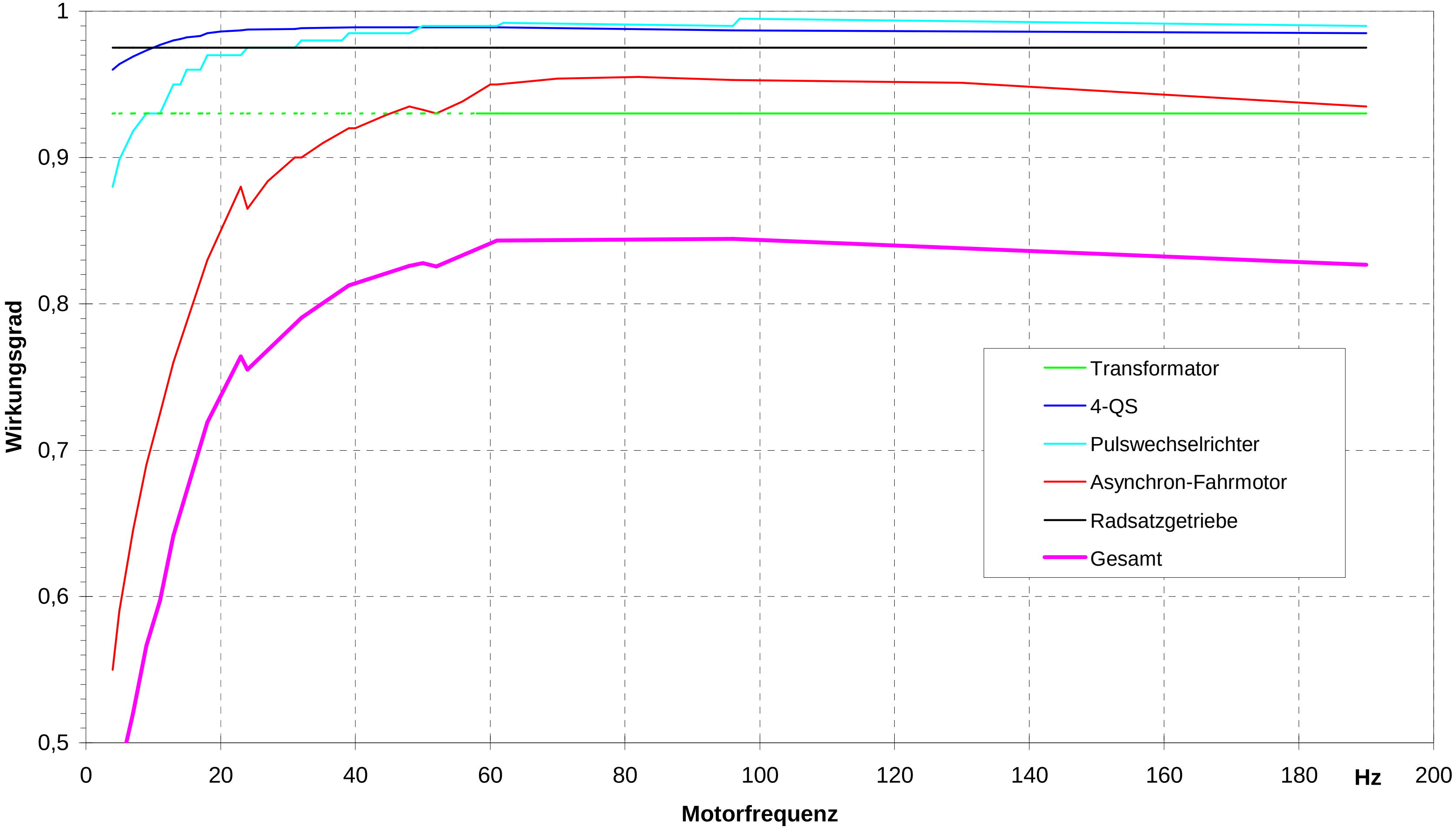
\+ additionally: limiting values of propulsion control
(e.g. voltage related current limitation)

Propulsion Structure

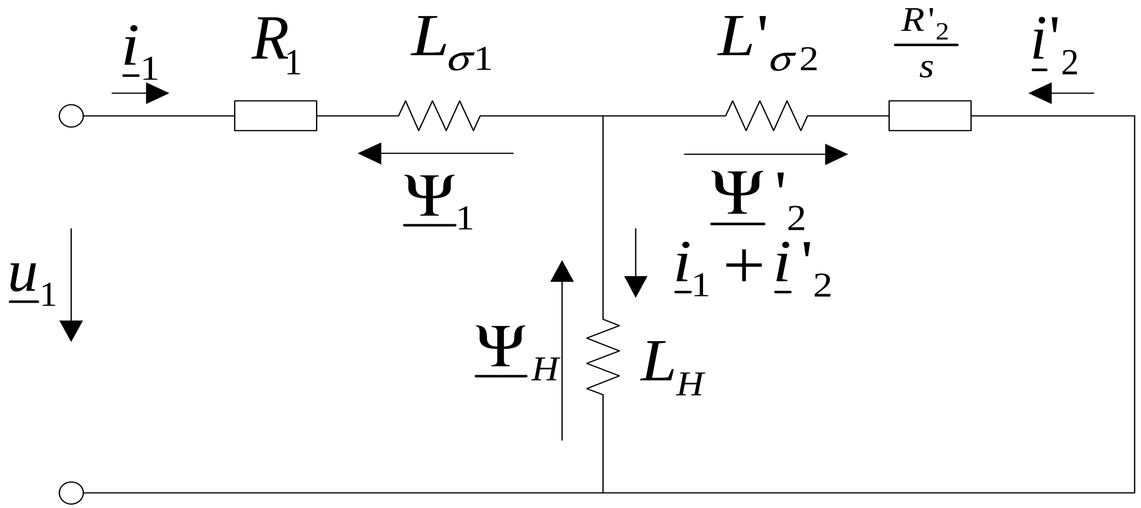


Efficiency Characteristics of ICE3 train

1 AC 15 kV 16,7 Hz



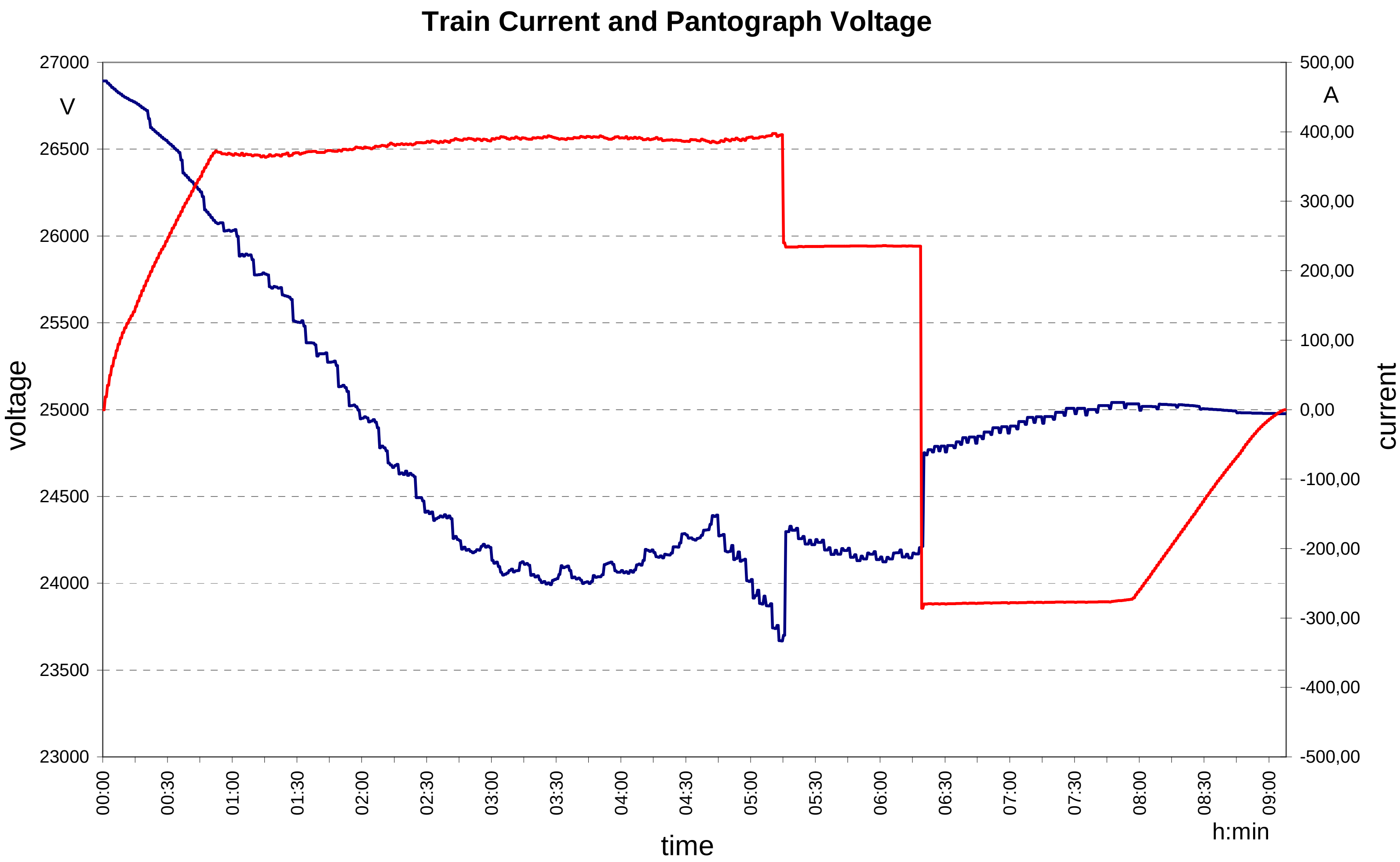
Propulsion Component Modelling (example for traction motor)



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

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

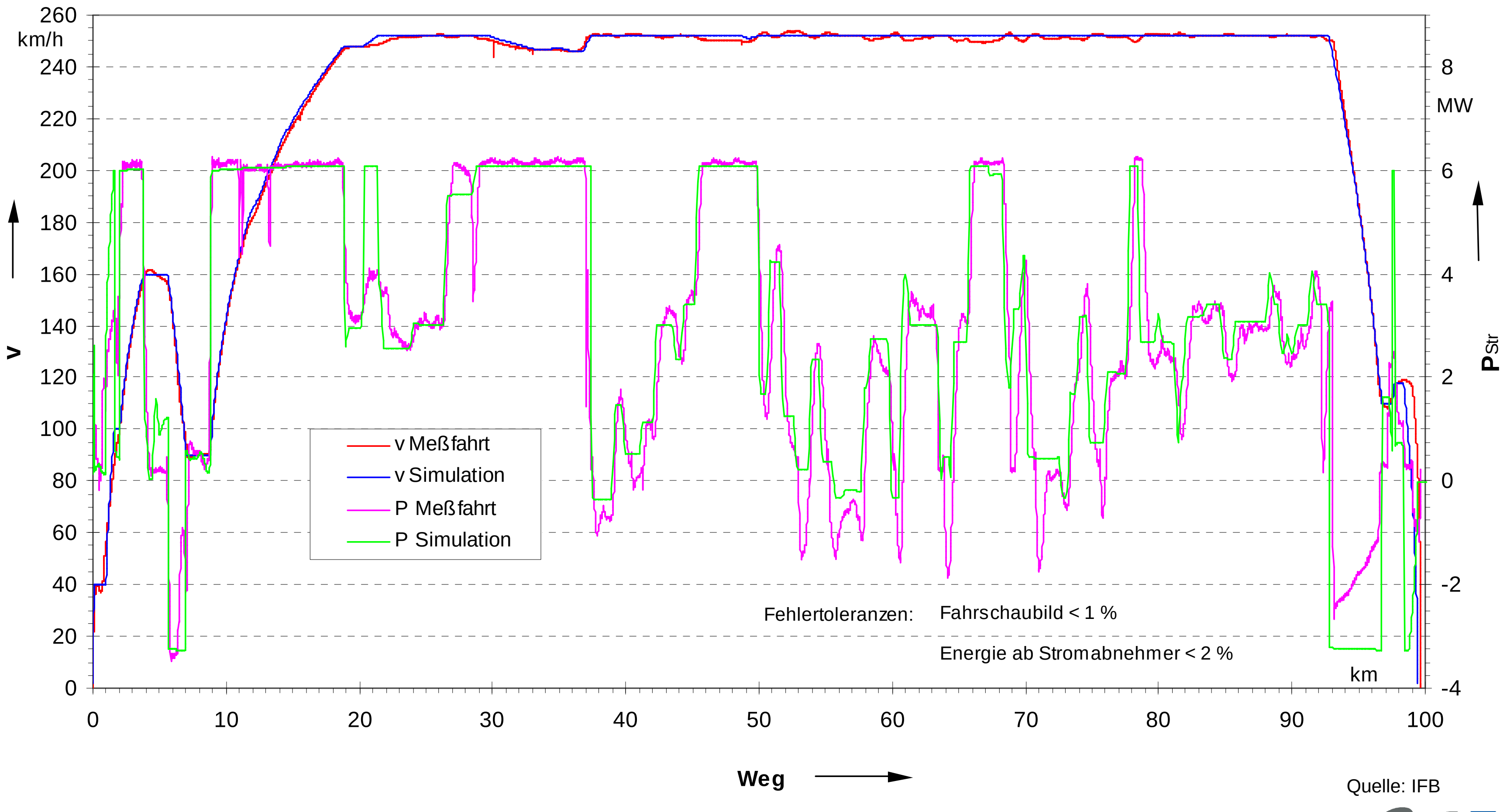
Propulsion Model Verification



Train Speed and Power Characteristics

Measurement and Simulation Results

ICE1 Hannover – Göttingen



Quelle: IFB

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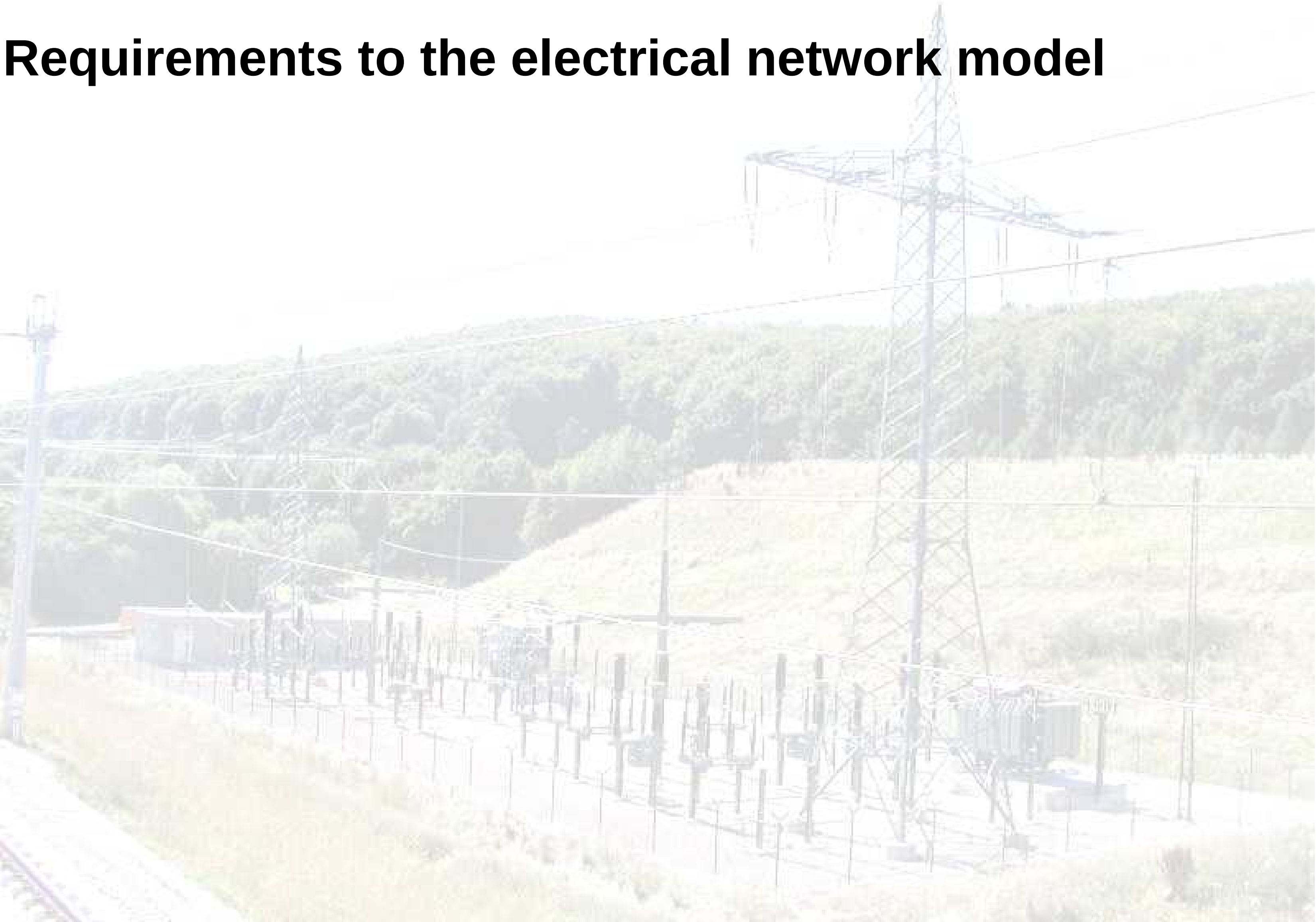
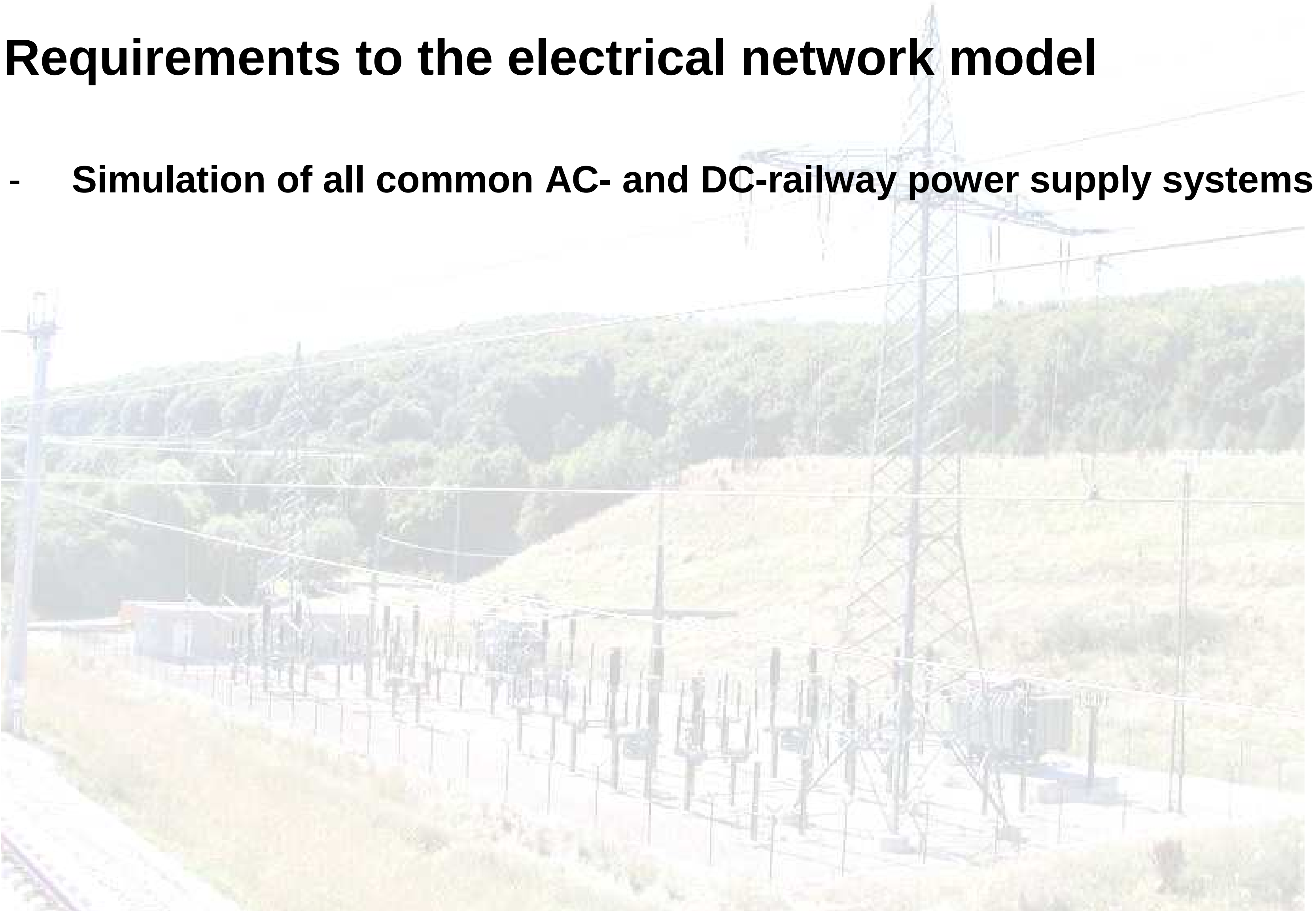
Requirements to the electrical network model



Requirements to the electrical network model

- **Simulation of all common AC- and DC-railway power supply systems**



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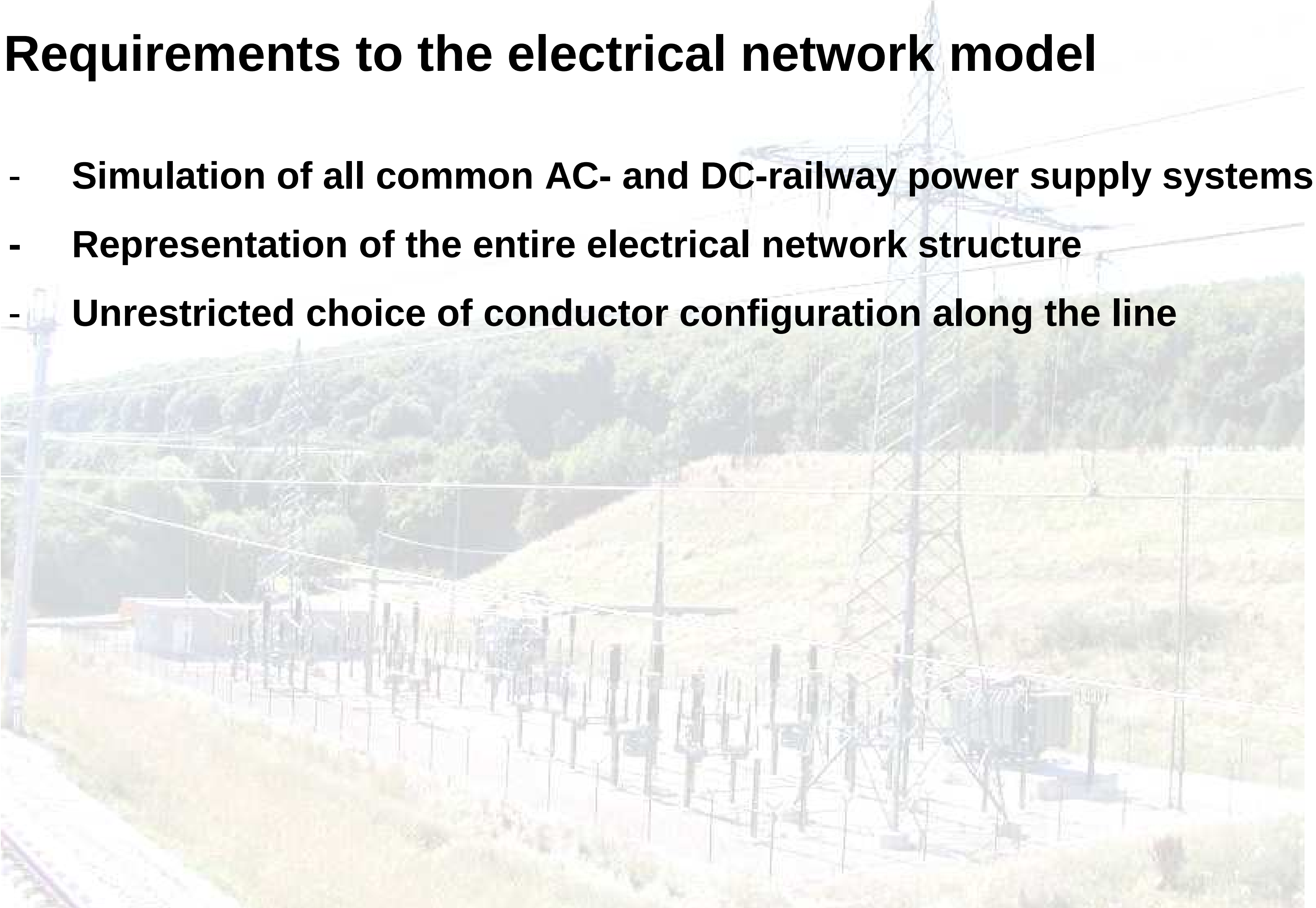
Requirements to the electrical network model

- Simulation of all common AC- and DC-railway power supply systems
- Representation of the entire electrical network structure

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

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

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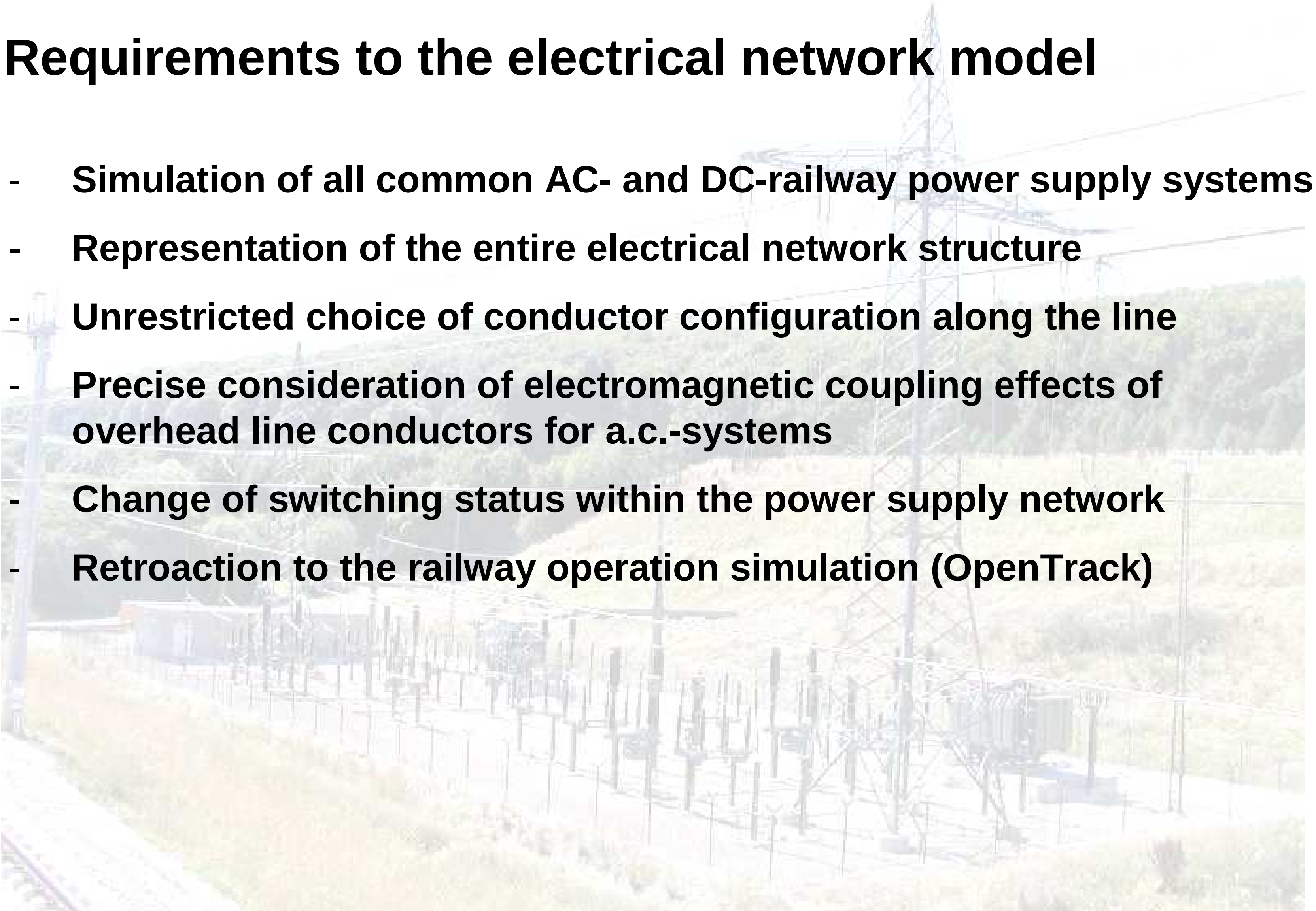
Requirements to the electrical network model

- **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**

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)

Requirements to the electrical network model

- Simulation of all common AC- and DC-railway power supply systems
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- Iterative communication with the propulsion simulation (ATM)

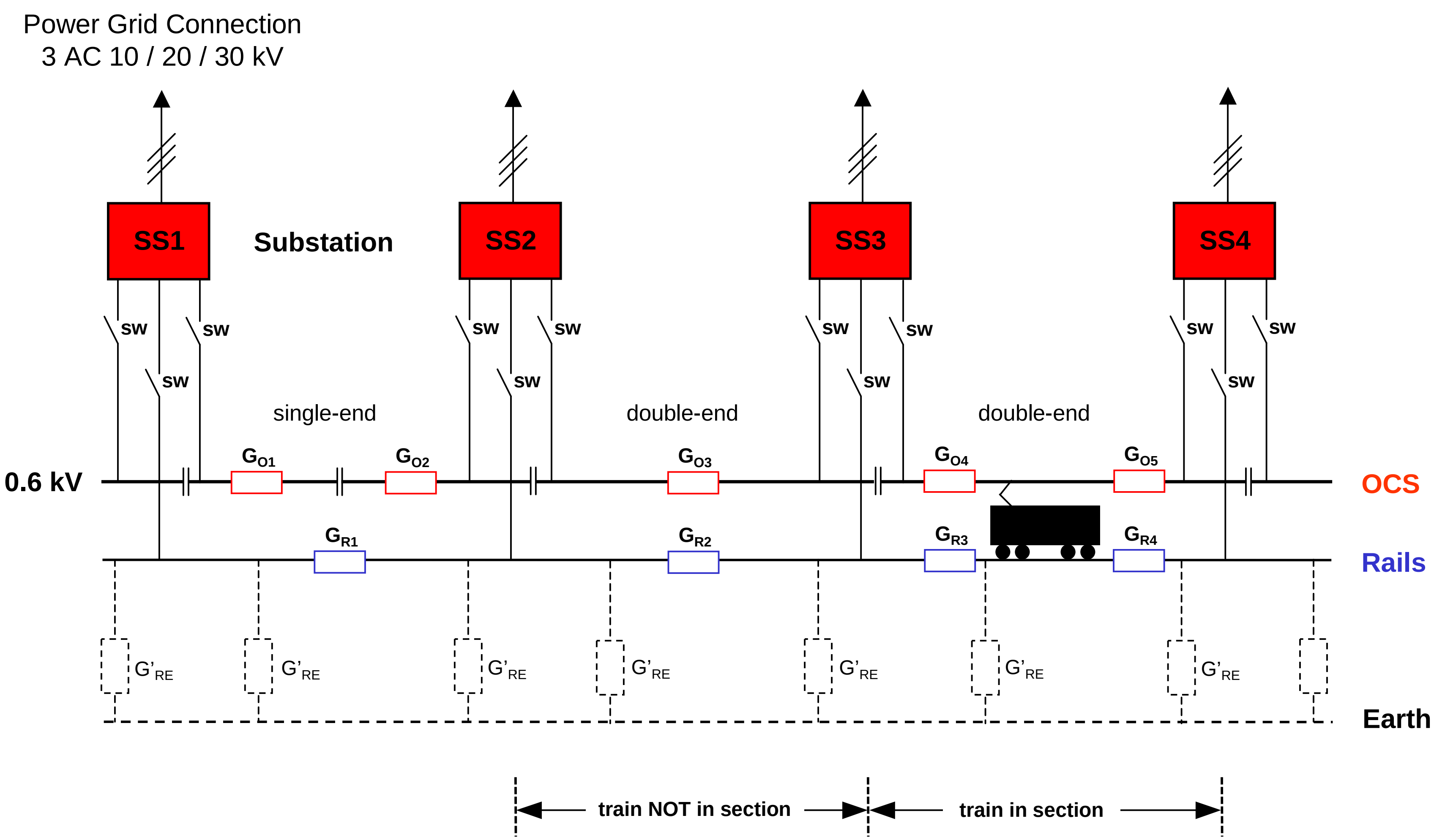
Requirements to the electrical network model

- **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**

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)



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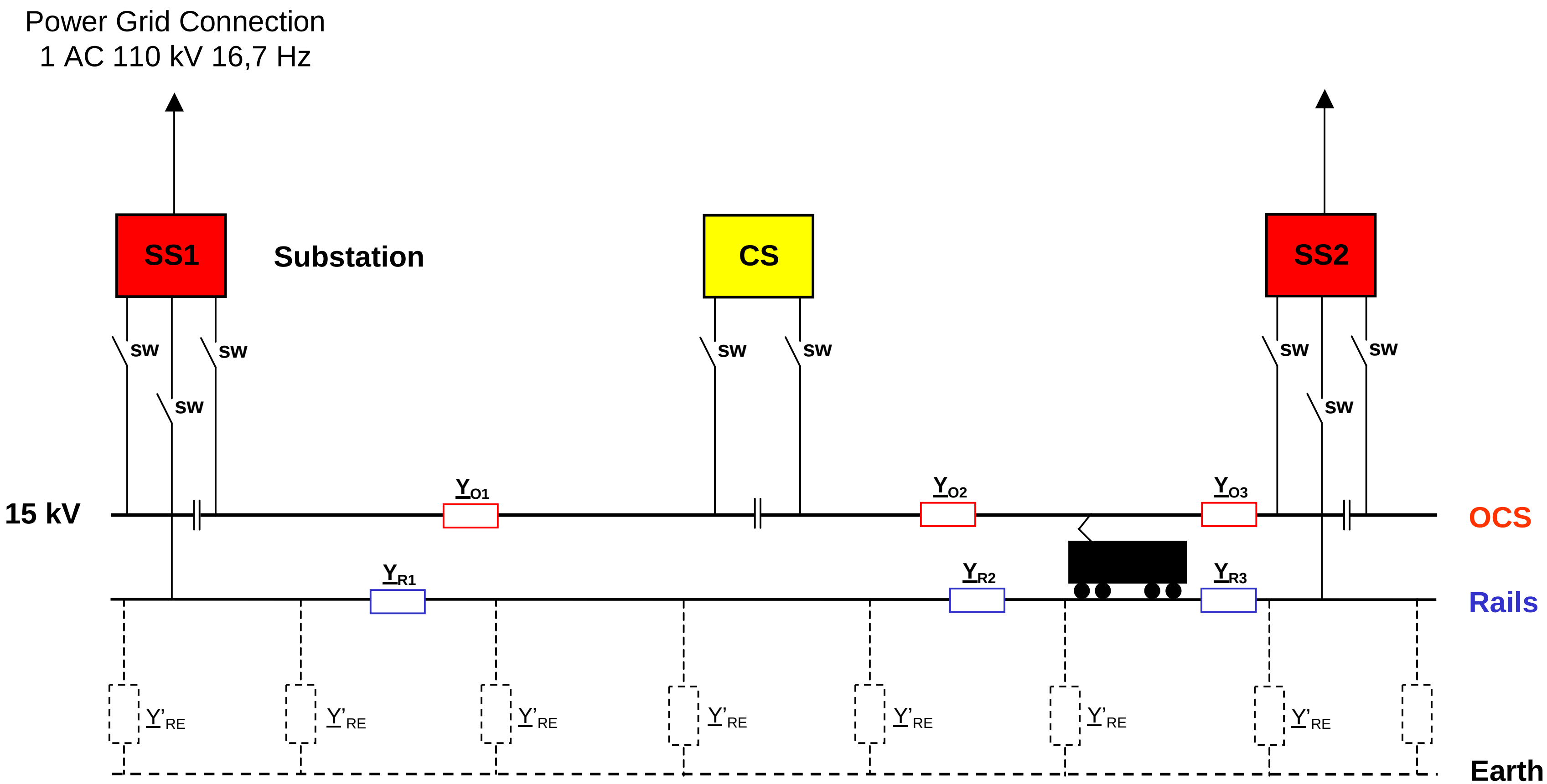
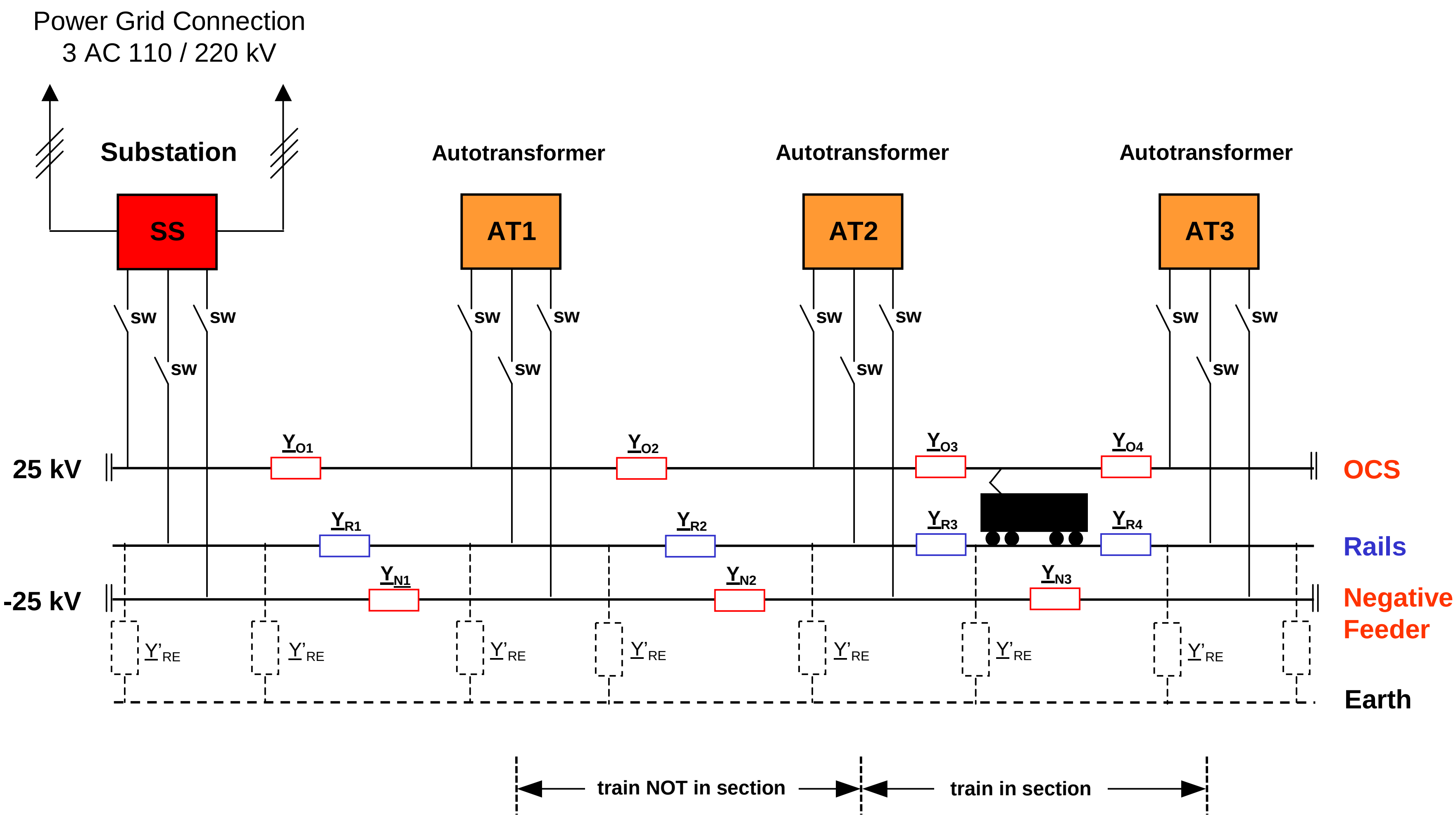
Power Supply Network Structure (1 AC 15 kV 16,7 Hz)



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



Modelling of infrastructure

Catenary arrangement and switch status

Modelling of the Railway Power Supply System

Modelling of the Railway Power Supply System

- **Electrical network structure (feeding sections, feeding points, switching status) in congruence to the track topology**

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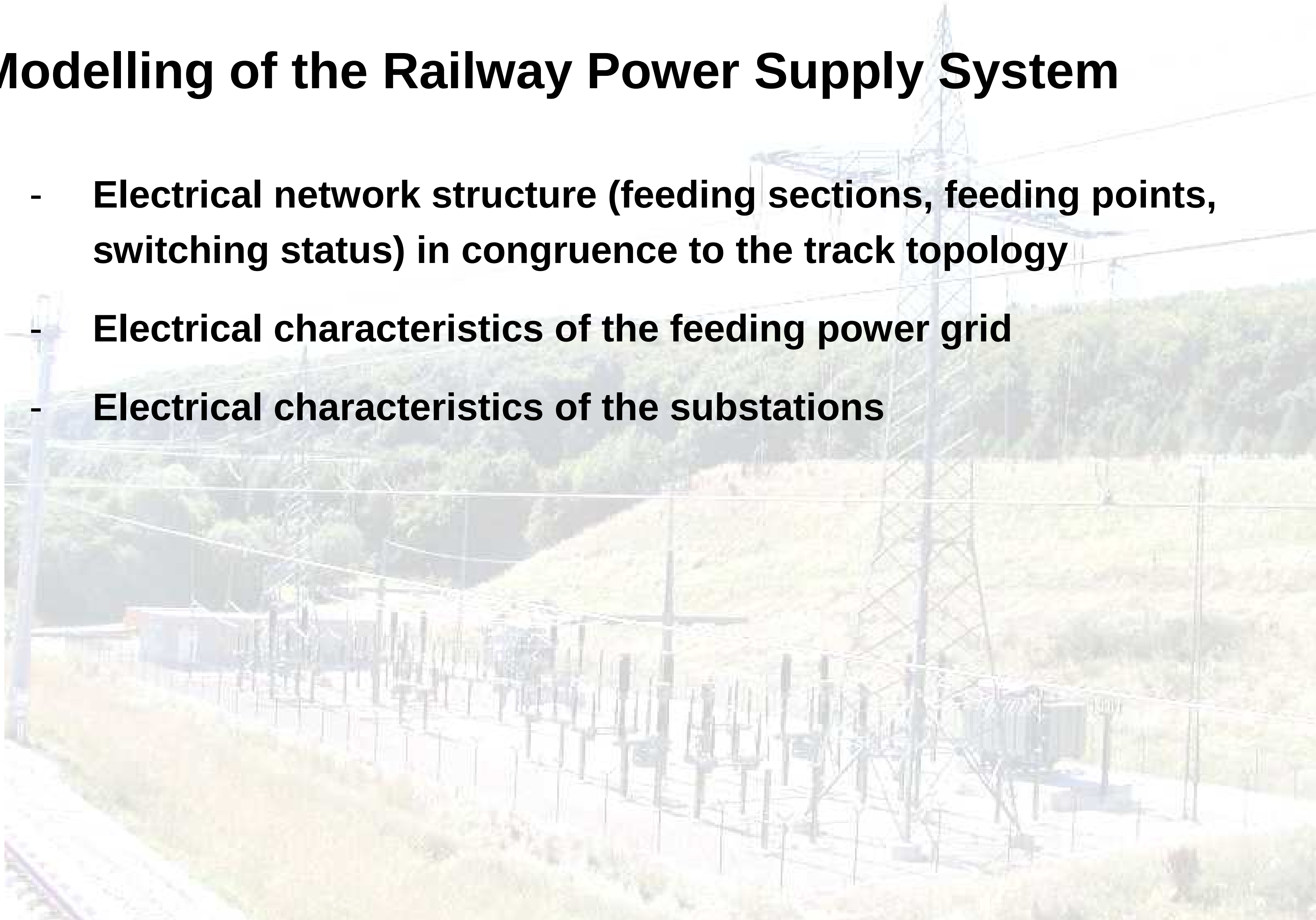
Modelling of the Railway Power Supply System

- Electrical network structure (feeding sections, feeding points, switching status) in congruence to the track topology
- Electrical characteristics of the feeding power grid

Modelling of the Railway Power Supply System

- Electrical network structure (feeding sections, feeding points, switching status) in congruence to the track topology
- Electrical characteristics of the feeding power grid
- Electrical characteristics of the substations



Modelling of the Railway Power Supply System

- **Electrical network structure (feeding sections, feeding points, switching status) 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)**

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Modelling of the Railway Power Supply System

- Electrical network structure (feeding sections, feeding points, switching status) 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 the Railway Power Supply System

- Electrical network structure (feeding sections, feeding points, switching status) in congruence to the track topology
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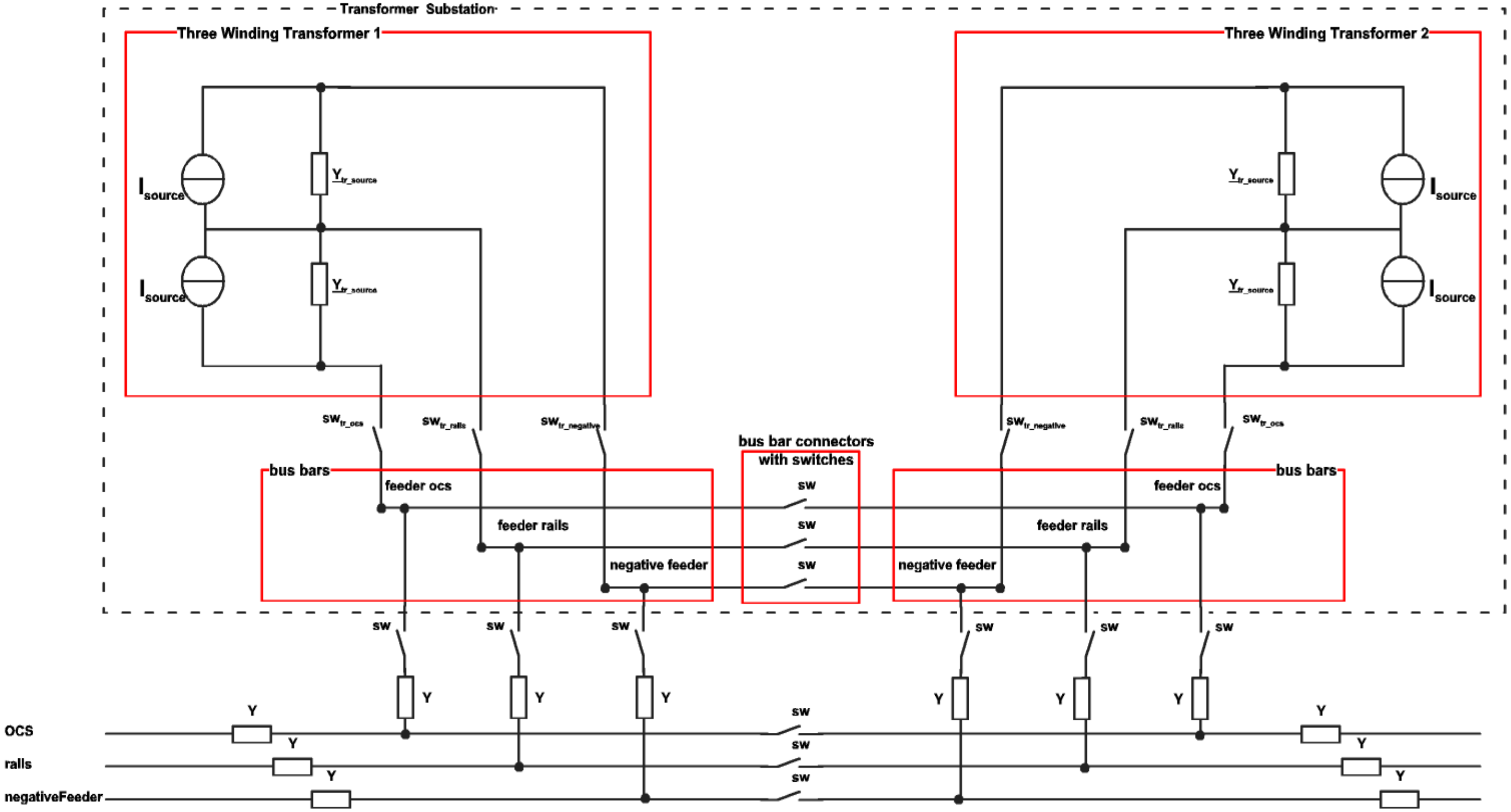
- **Loading capacity (conductors, converters, transformers)**
- **Protection settings**

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



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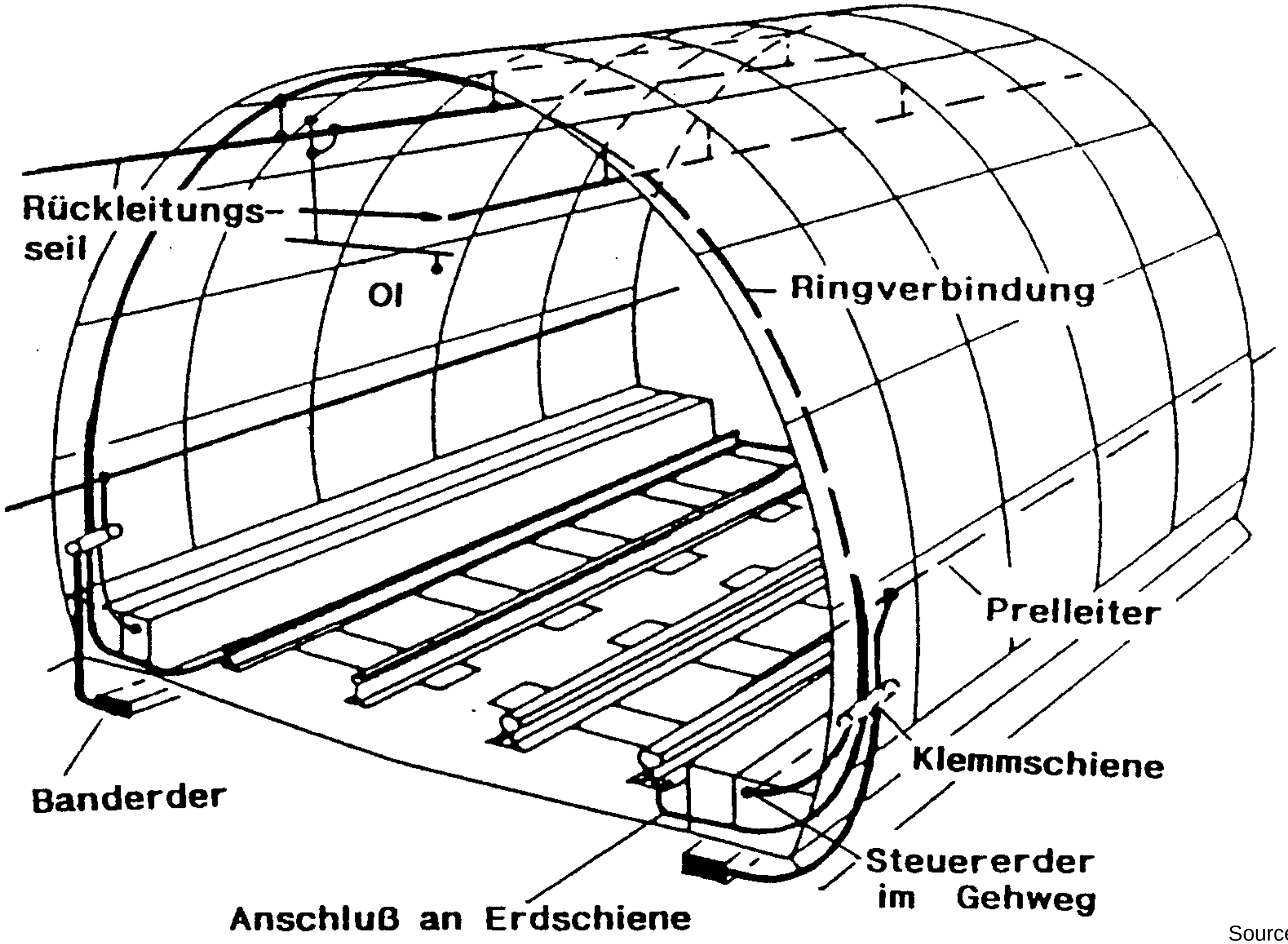
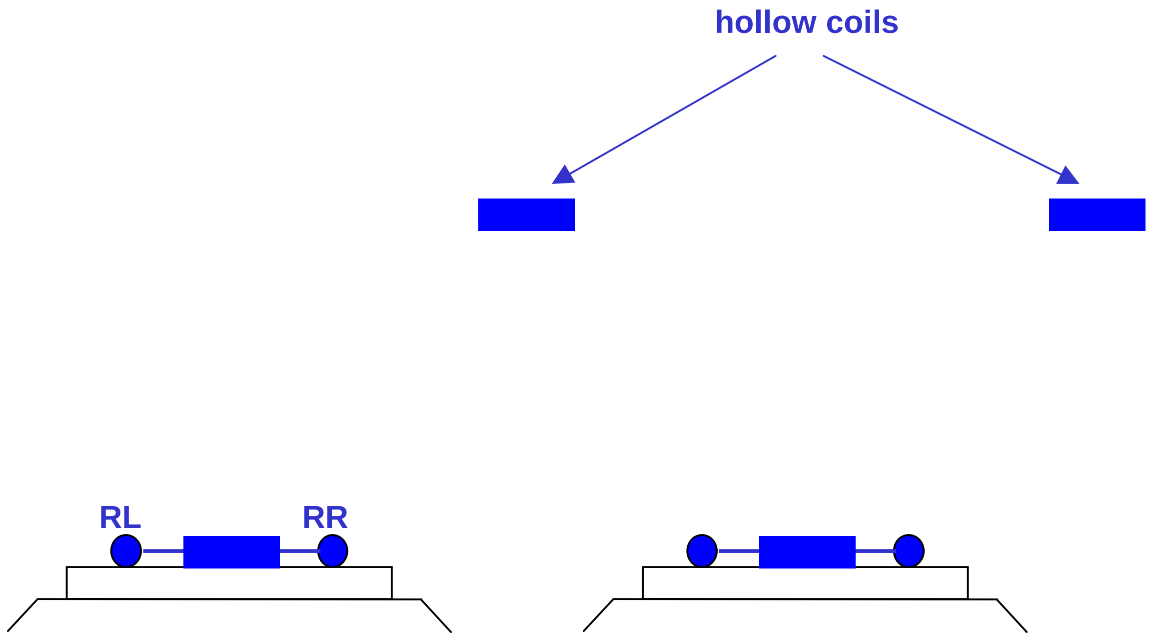
Trackside Arrangement of Conductors



Source: DB KoRiL 997

Trackside Arrangement of Conductors



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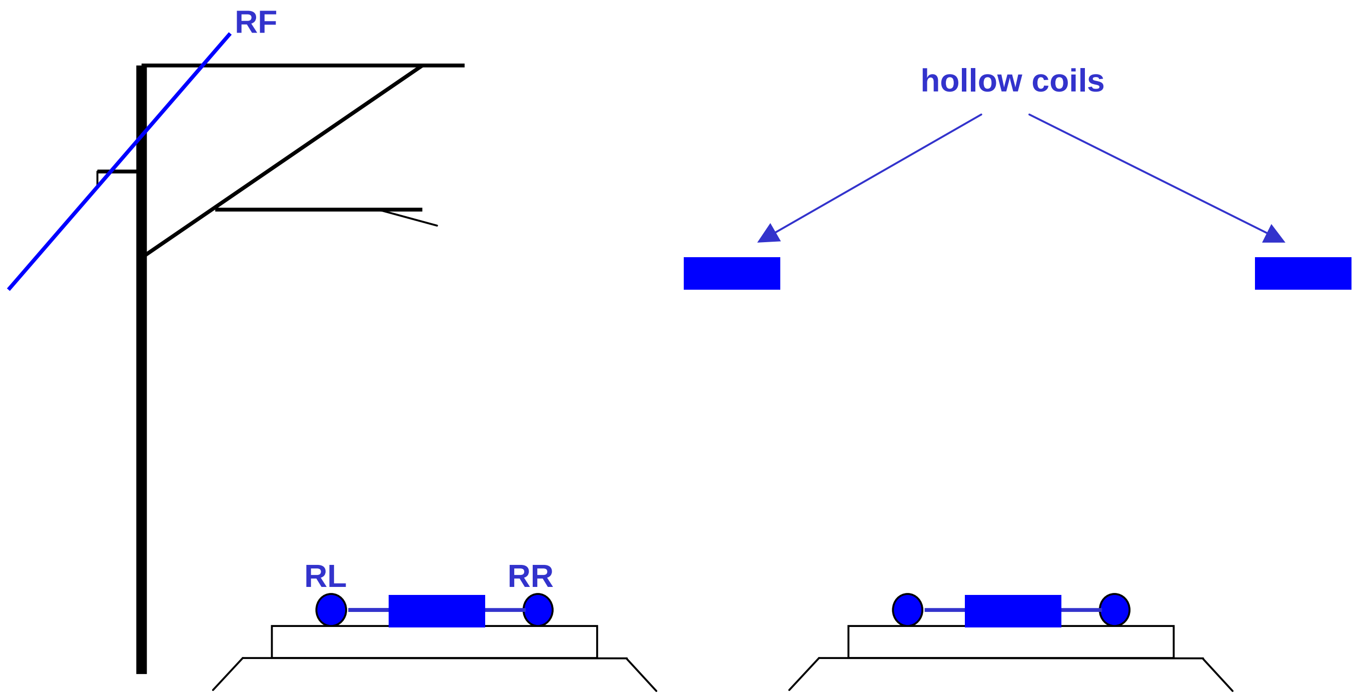

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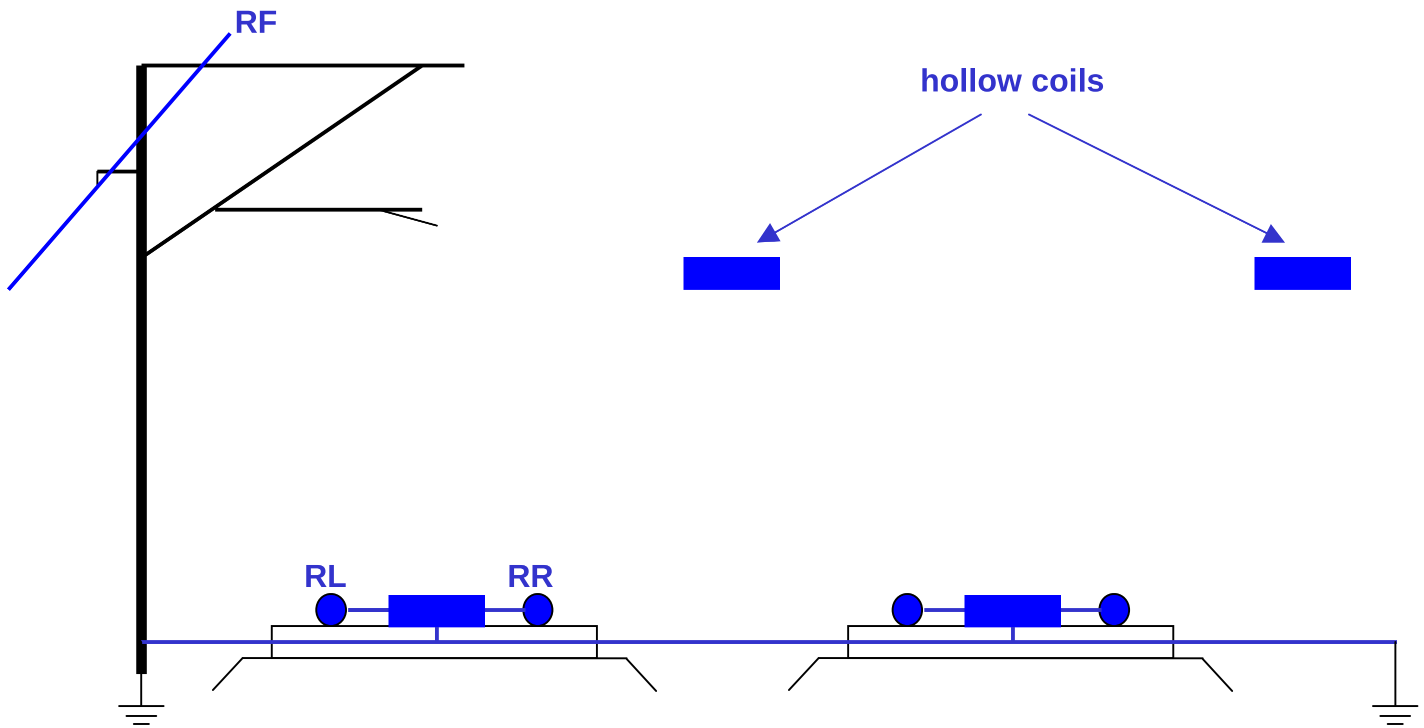

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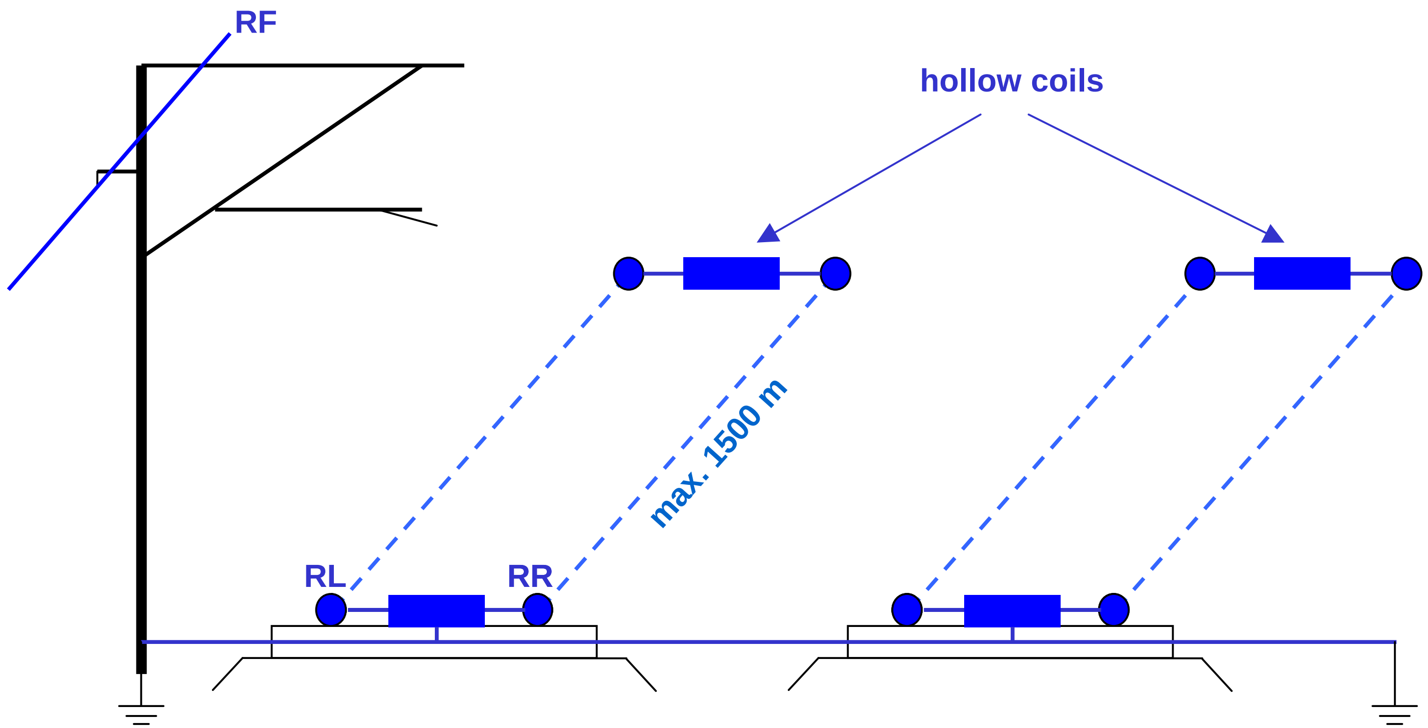

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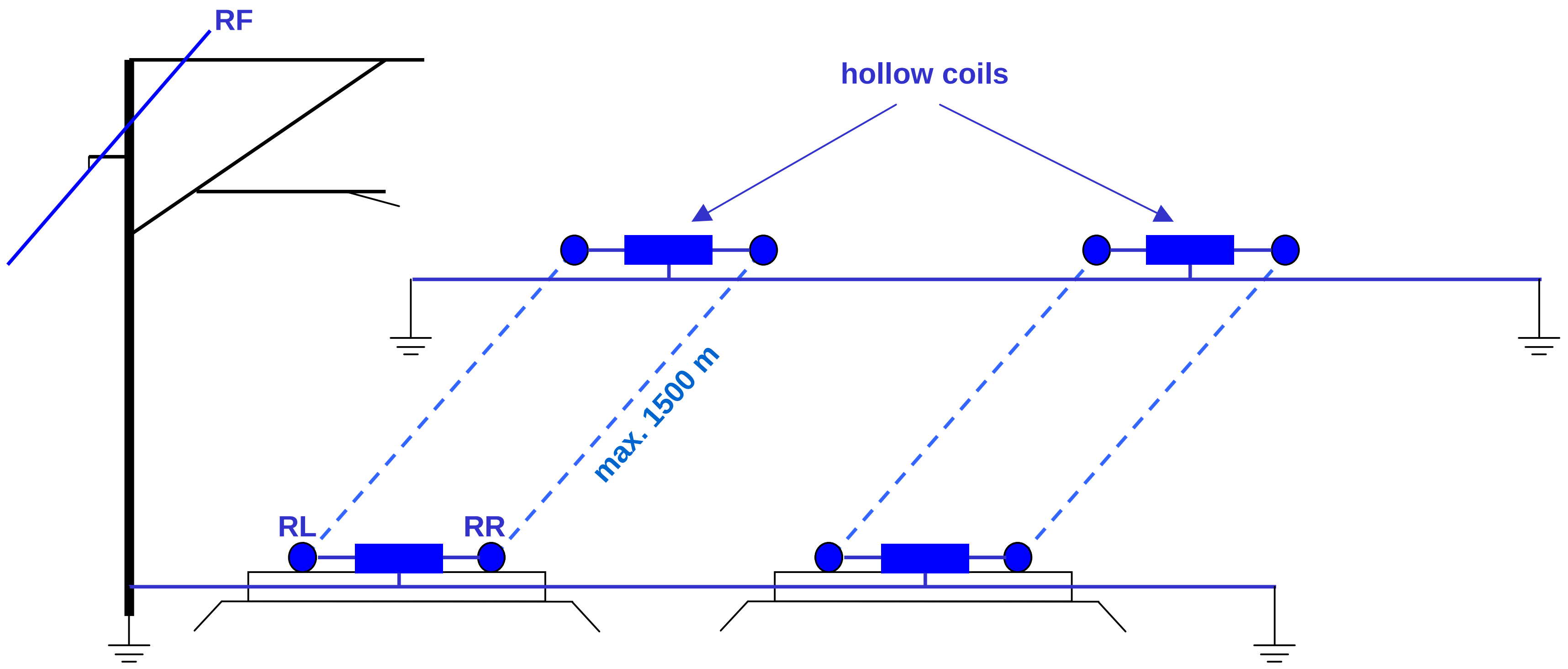

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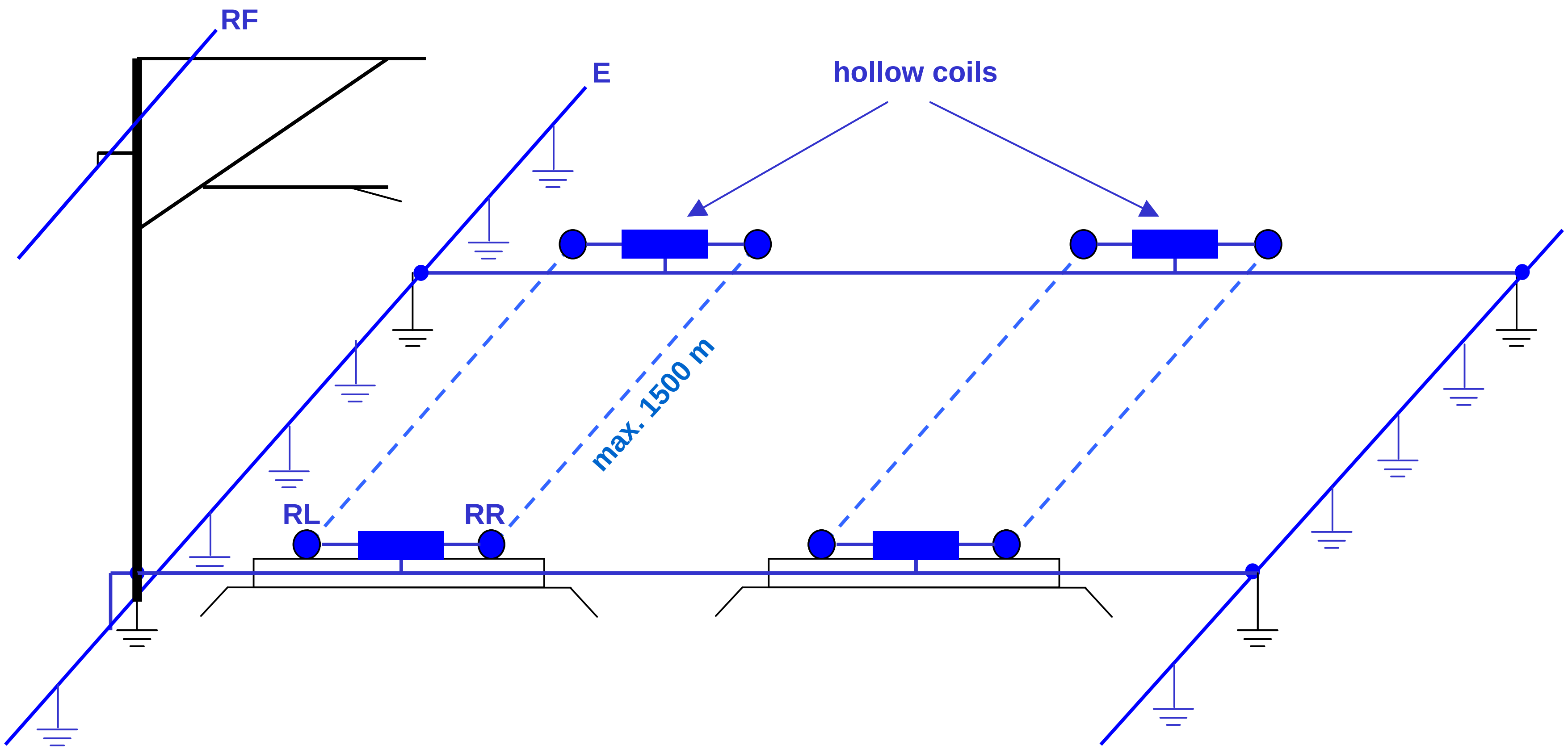

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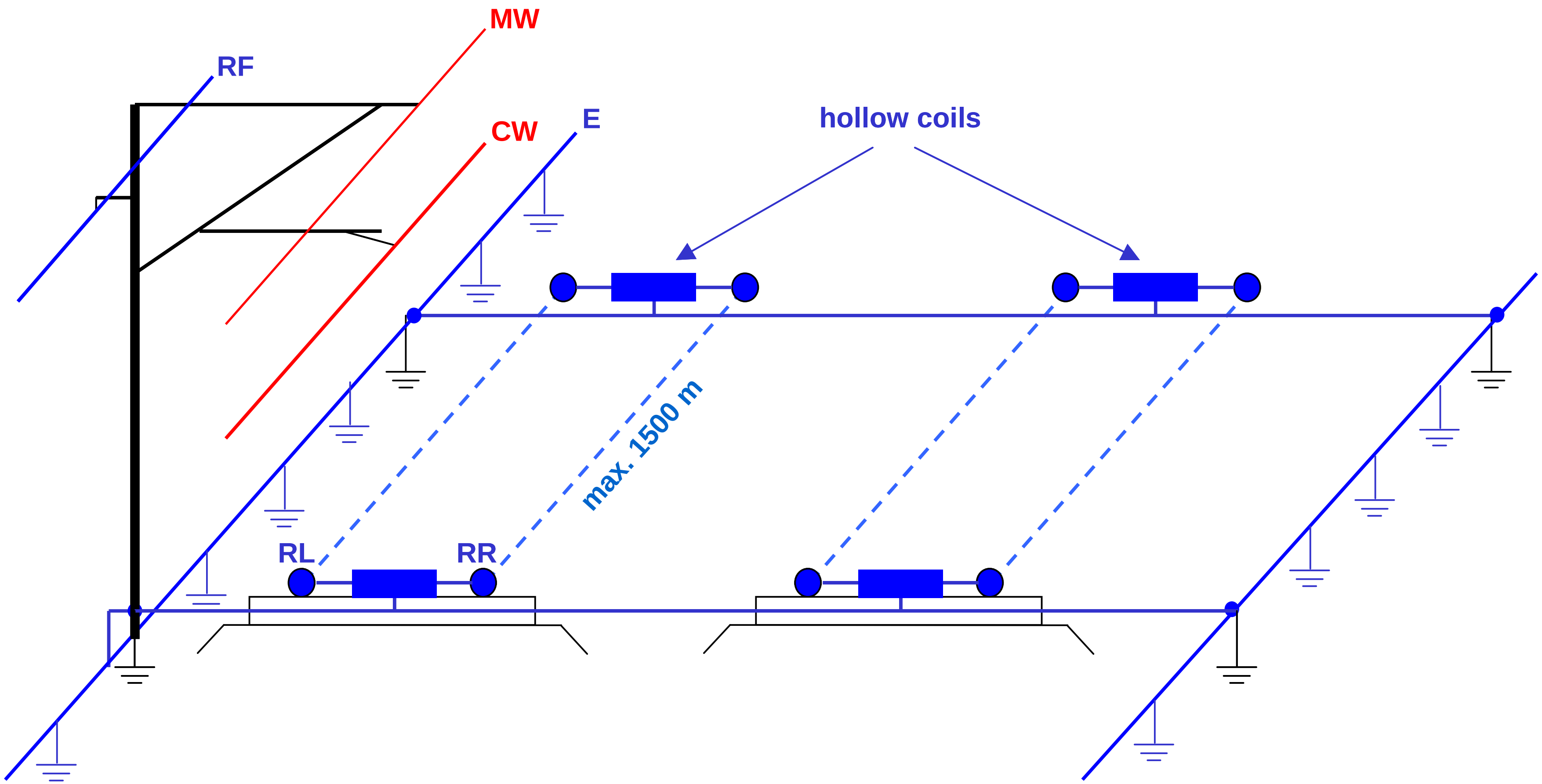
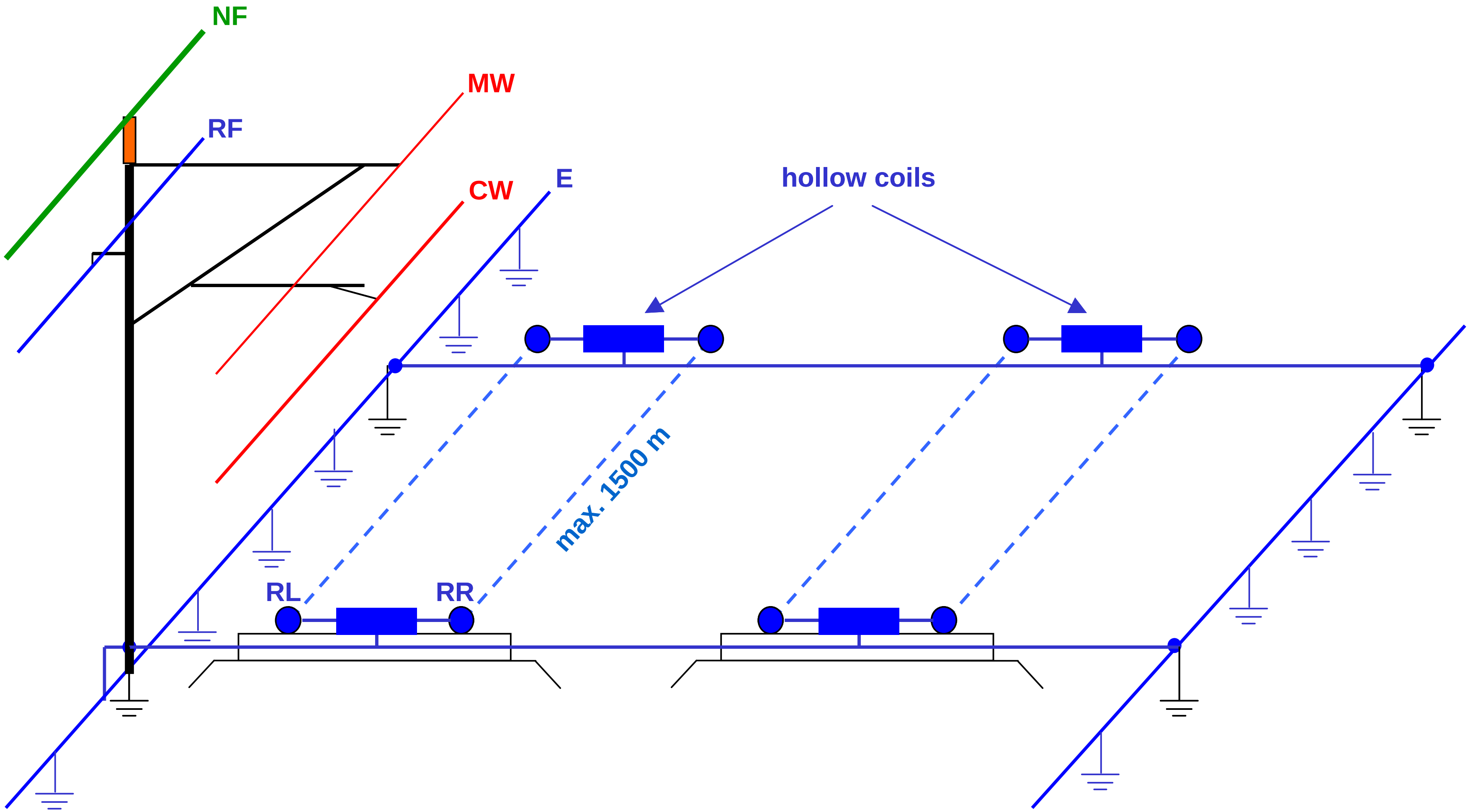
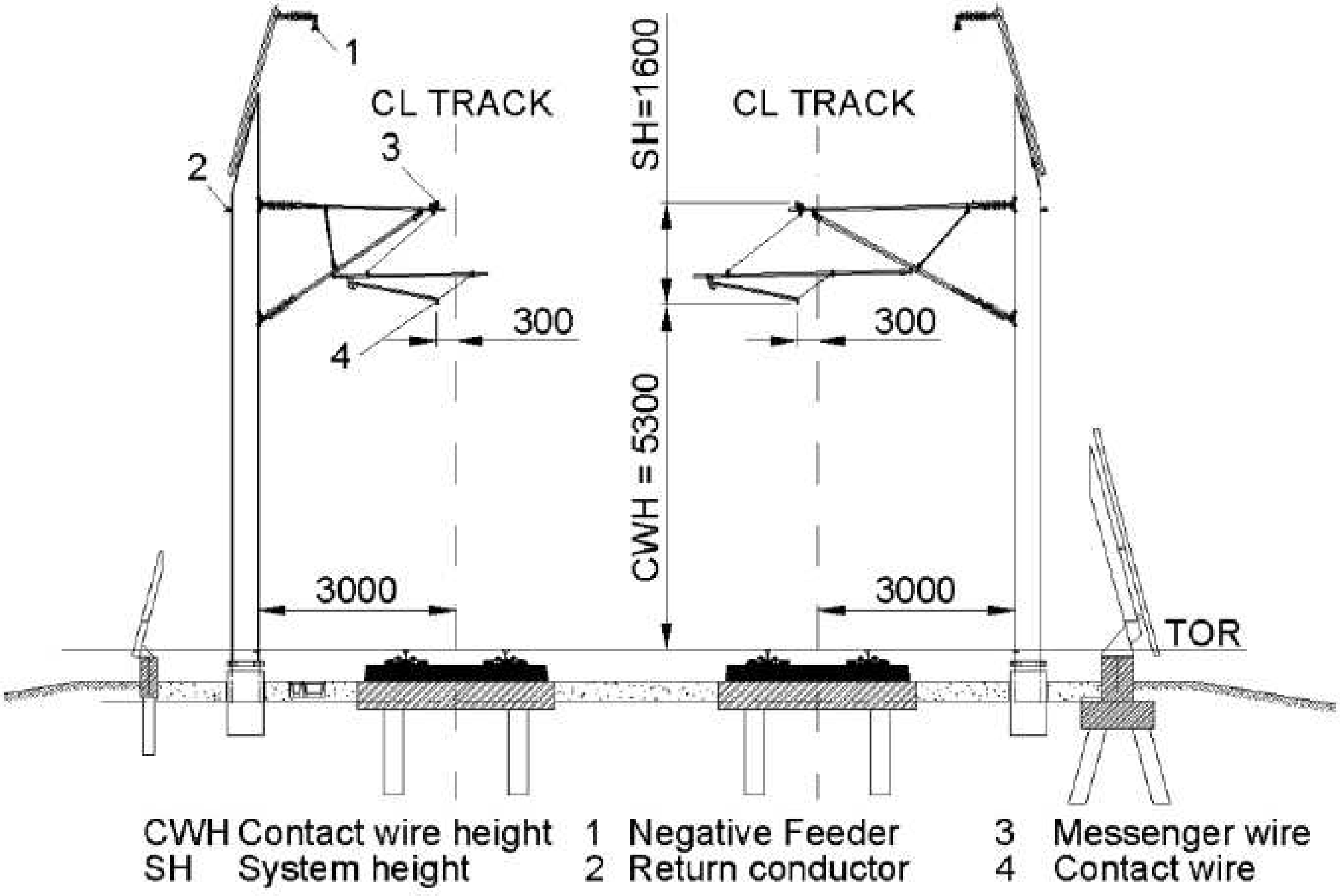


Trackside Arrangement of Conductors



Catenary Arrangement and Conductor Model



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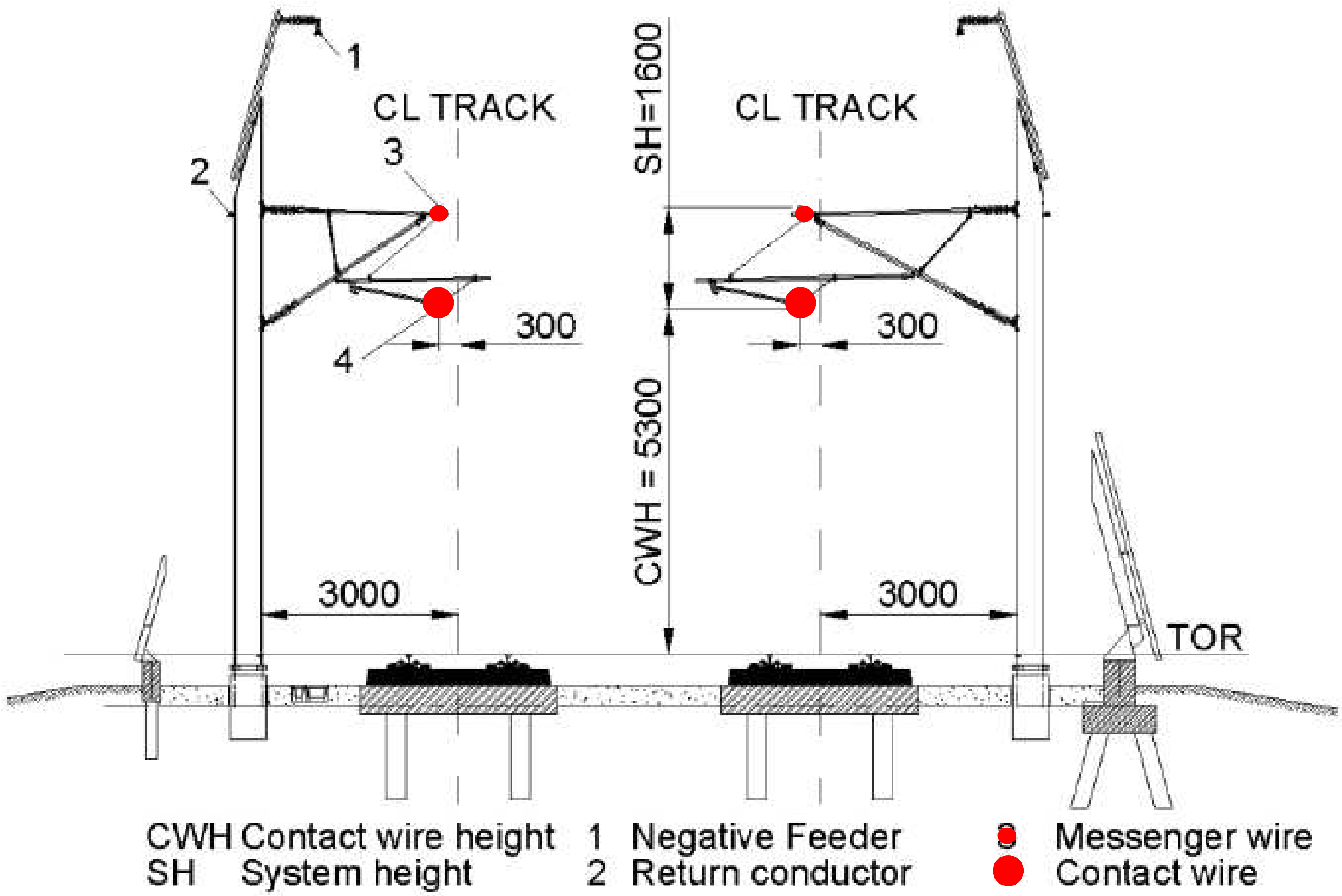

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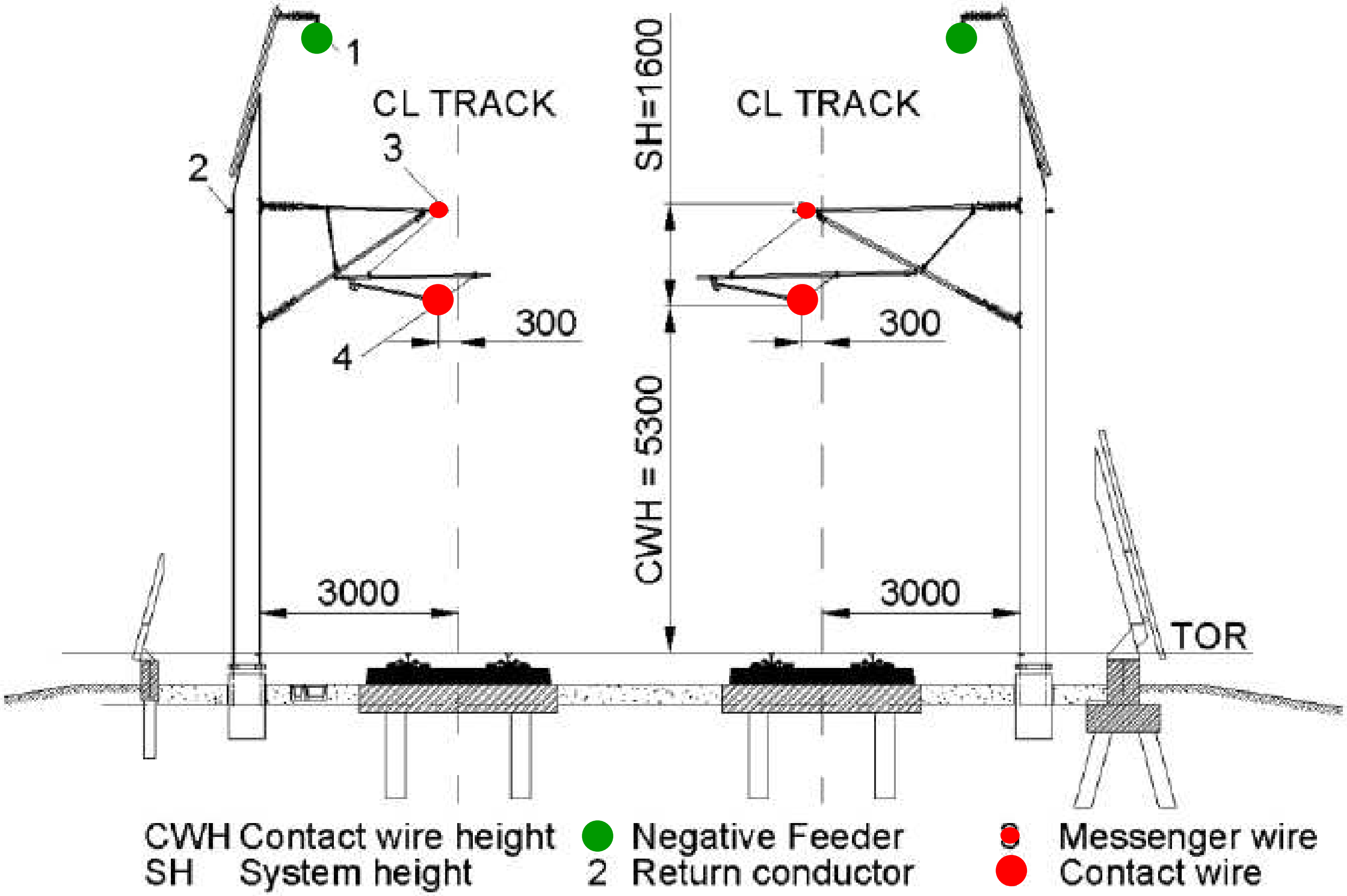

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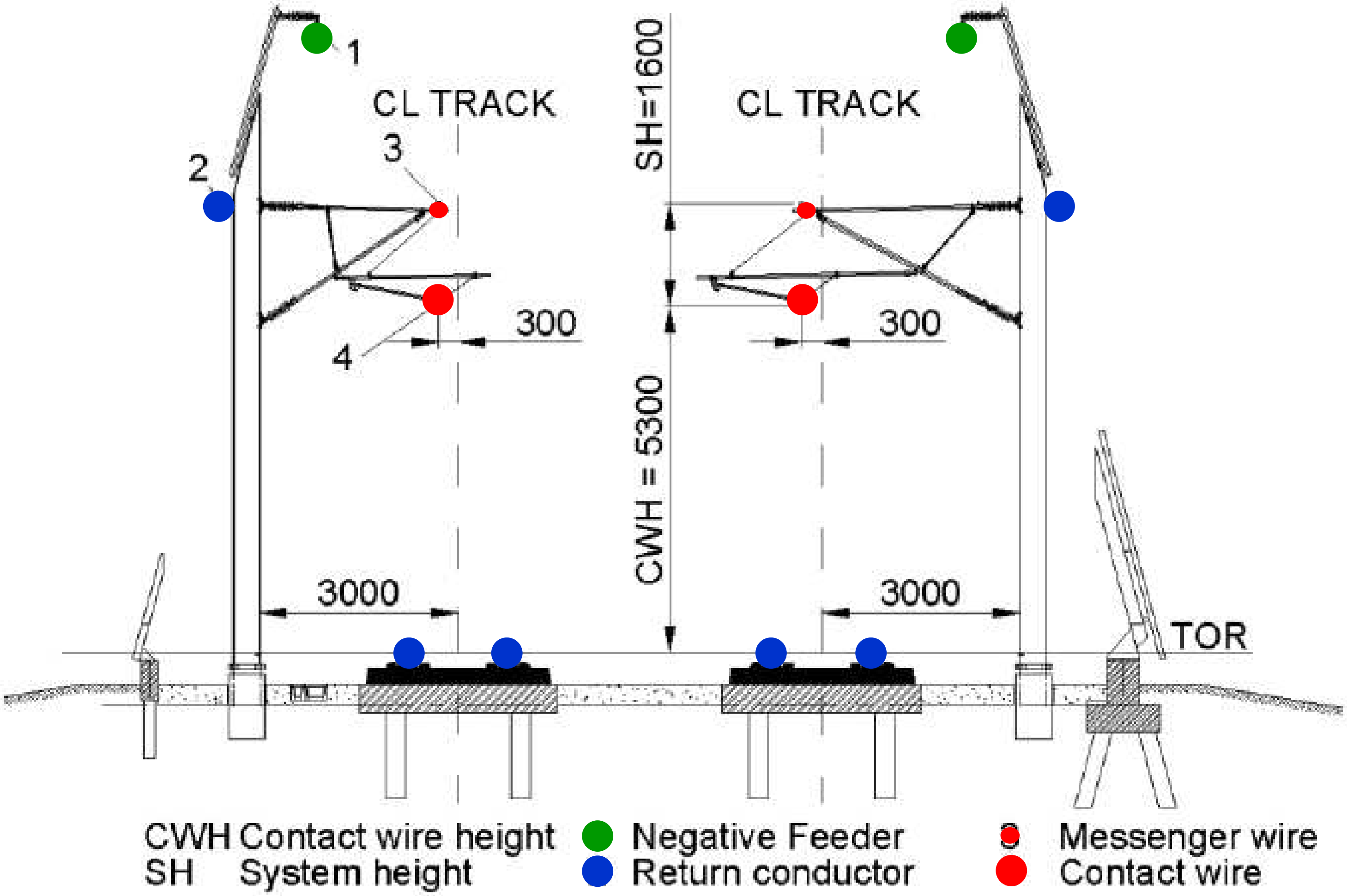
Catenary Arrangement and Conductor Model



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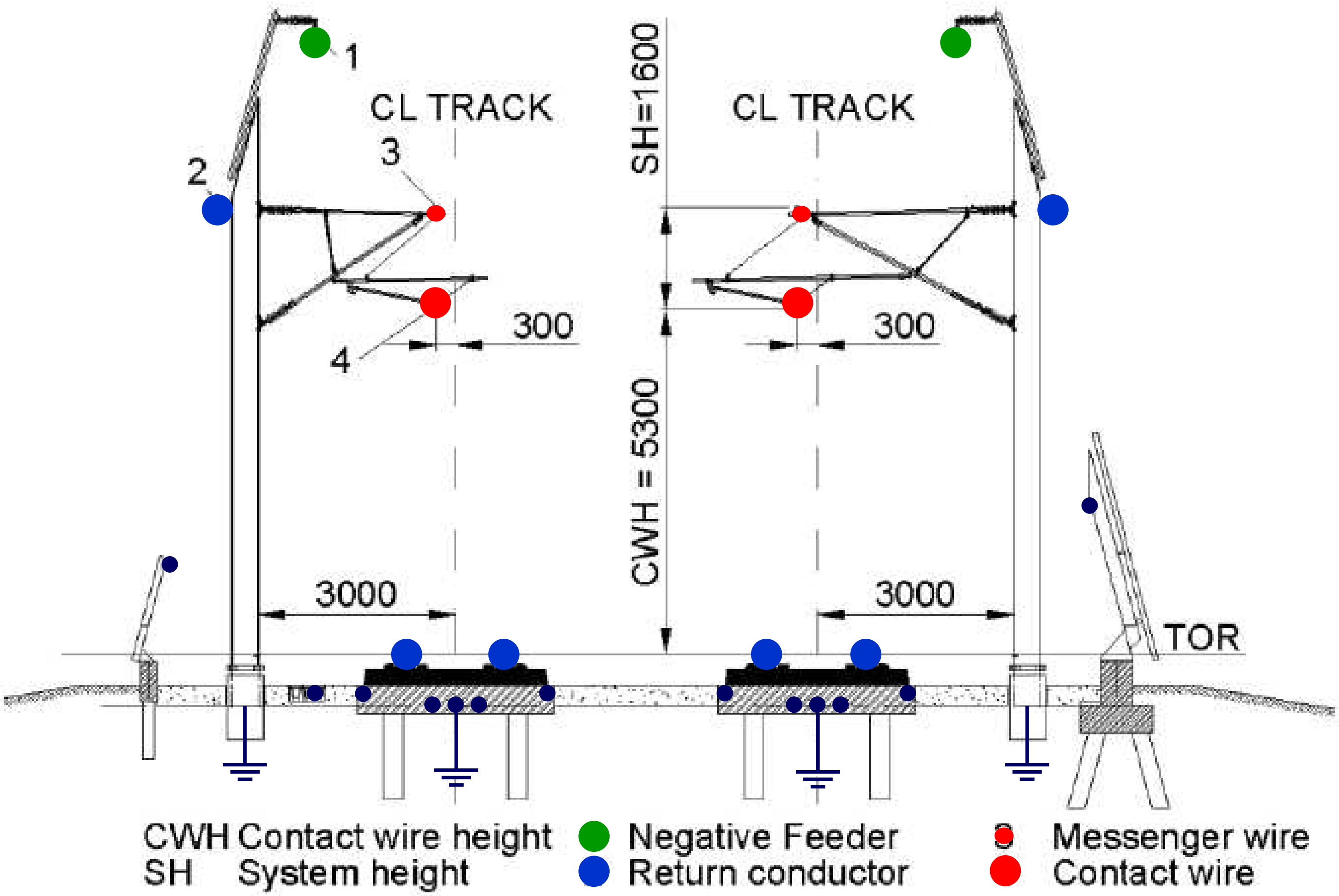

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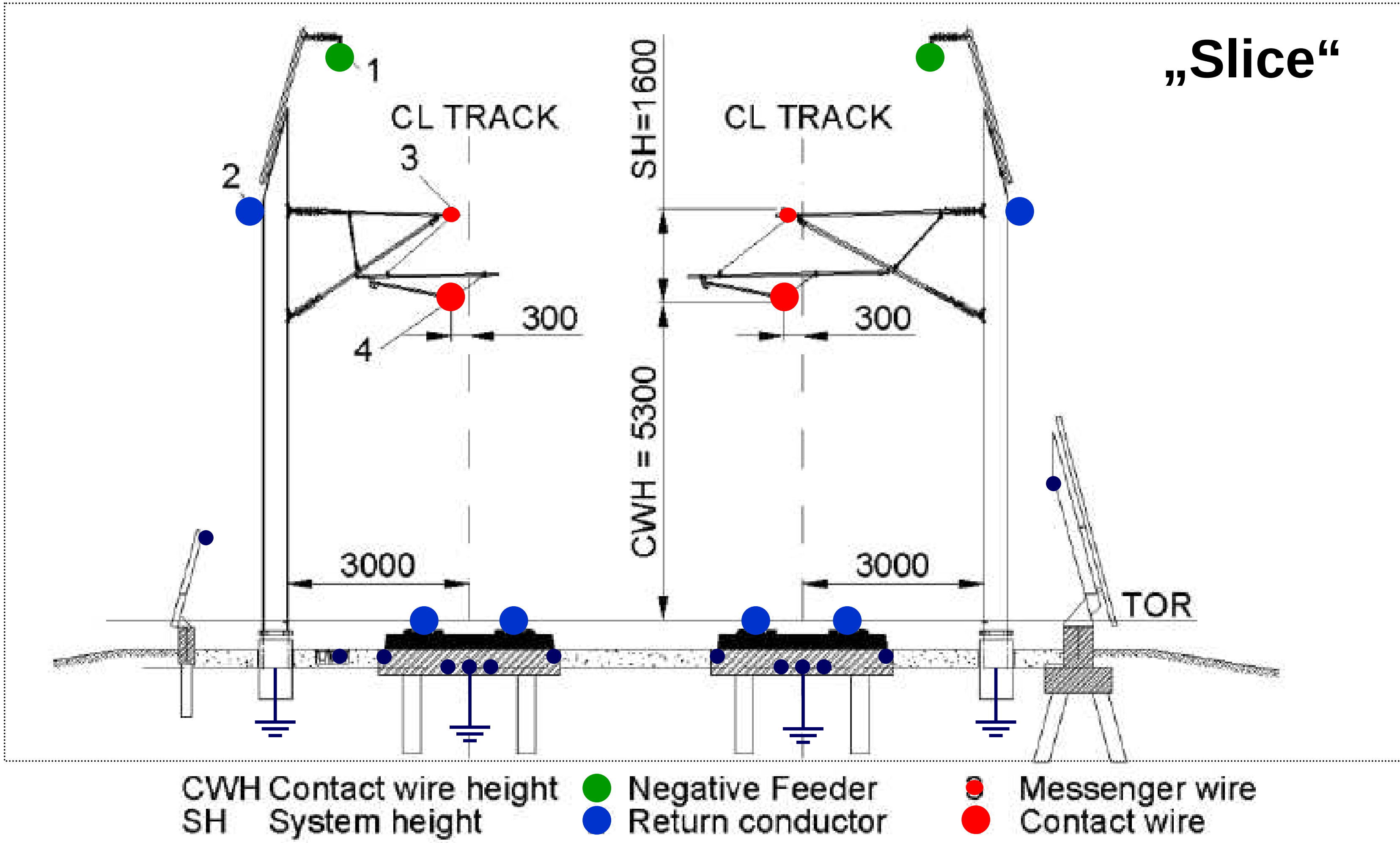
Catenary Arrangement and Conductor Model



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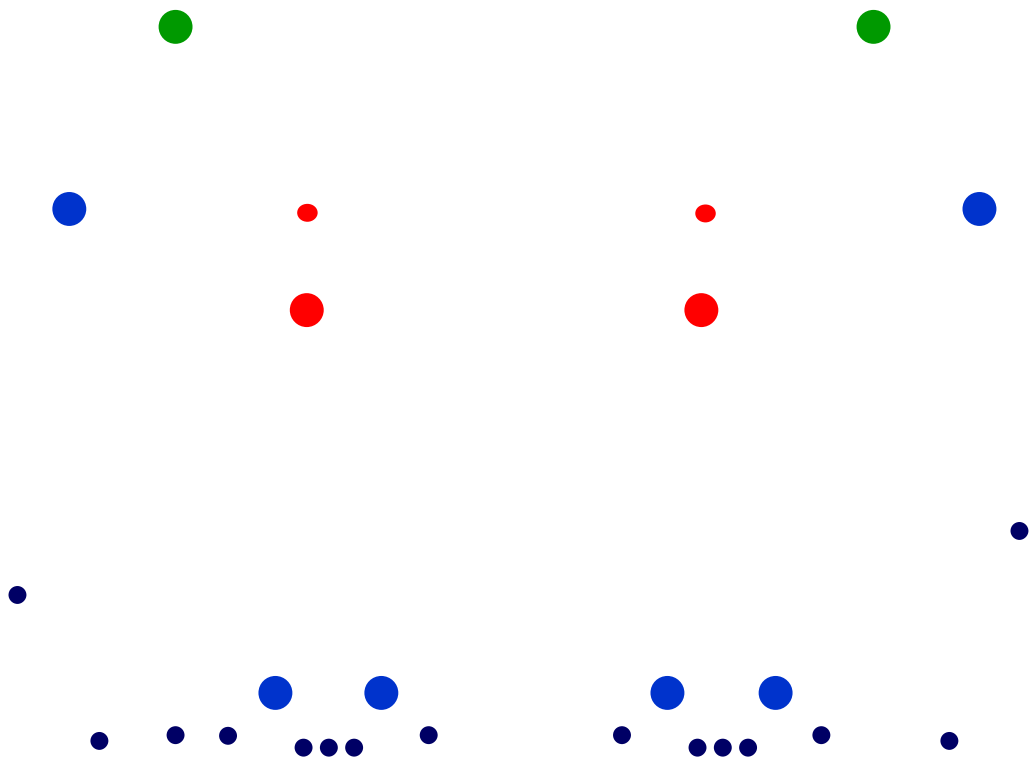

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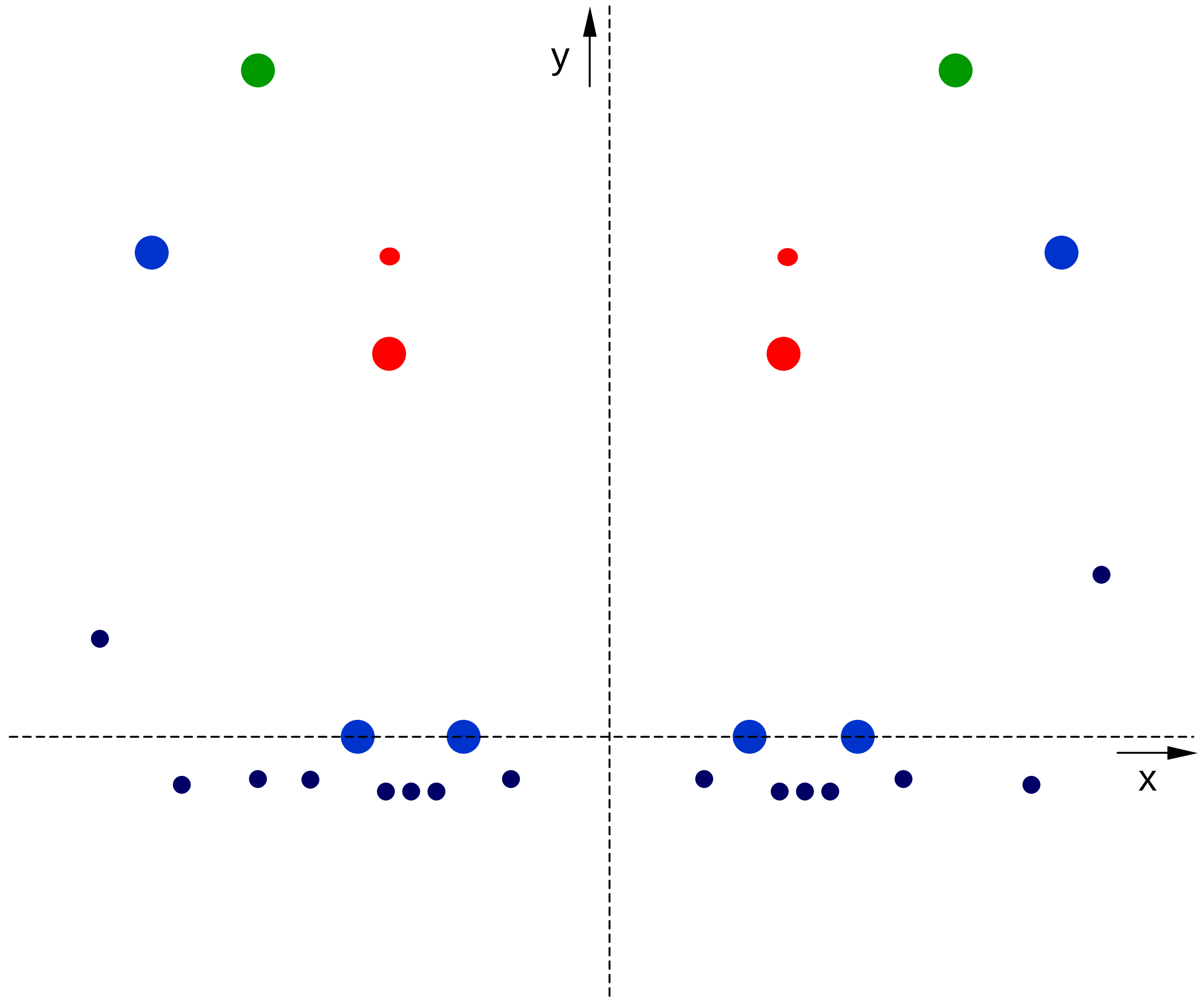

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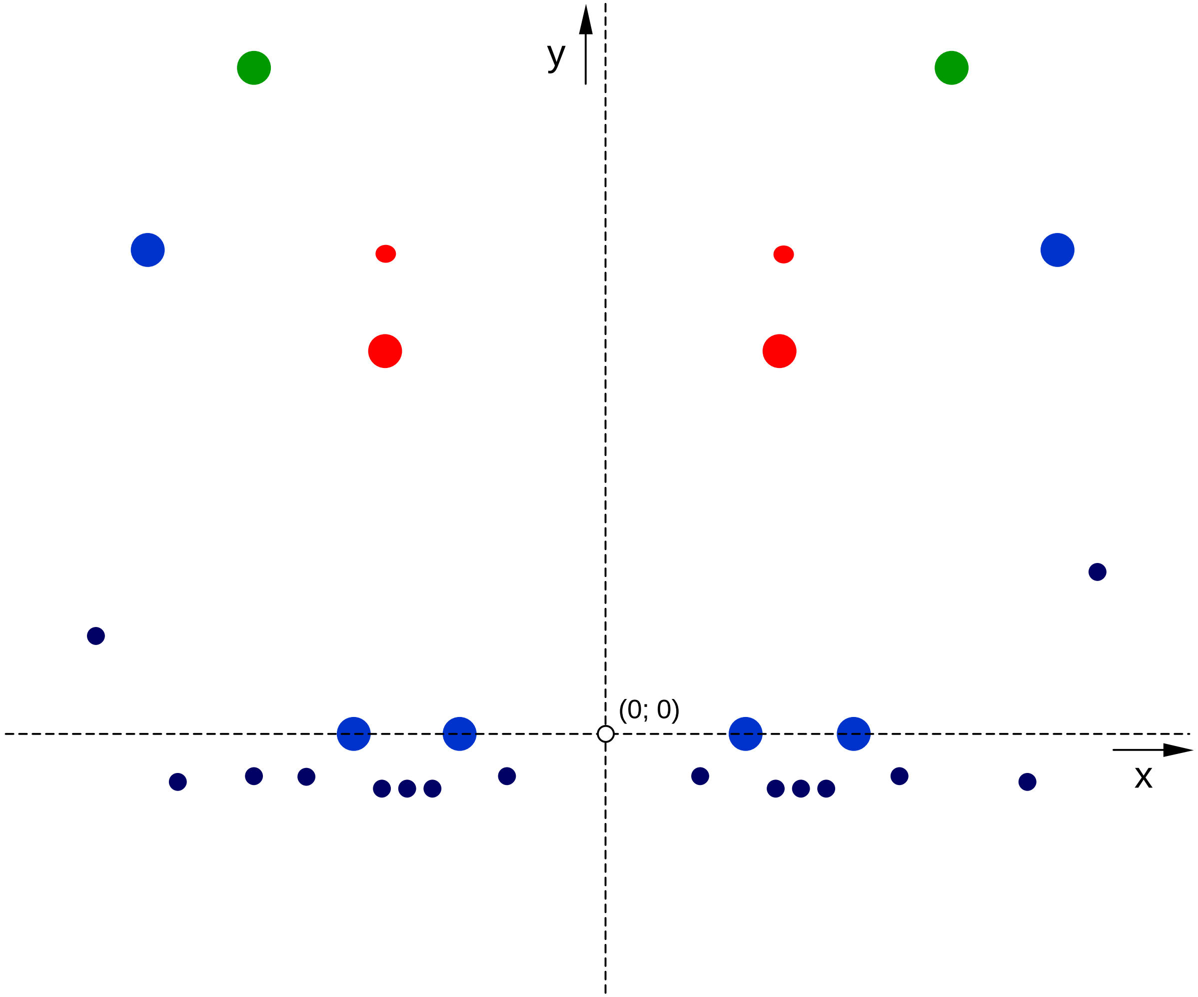

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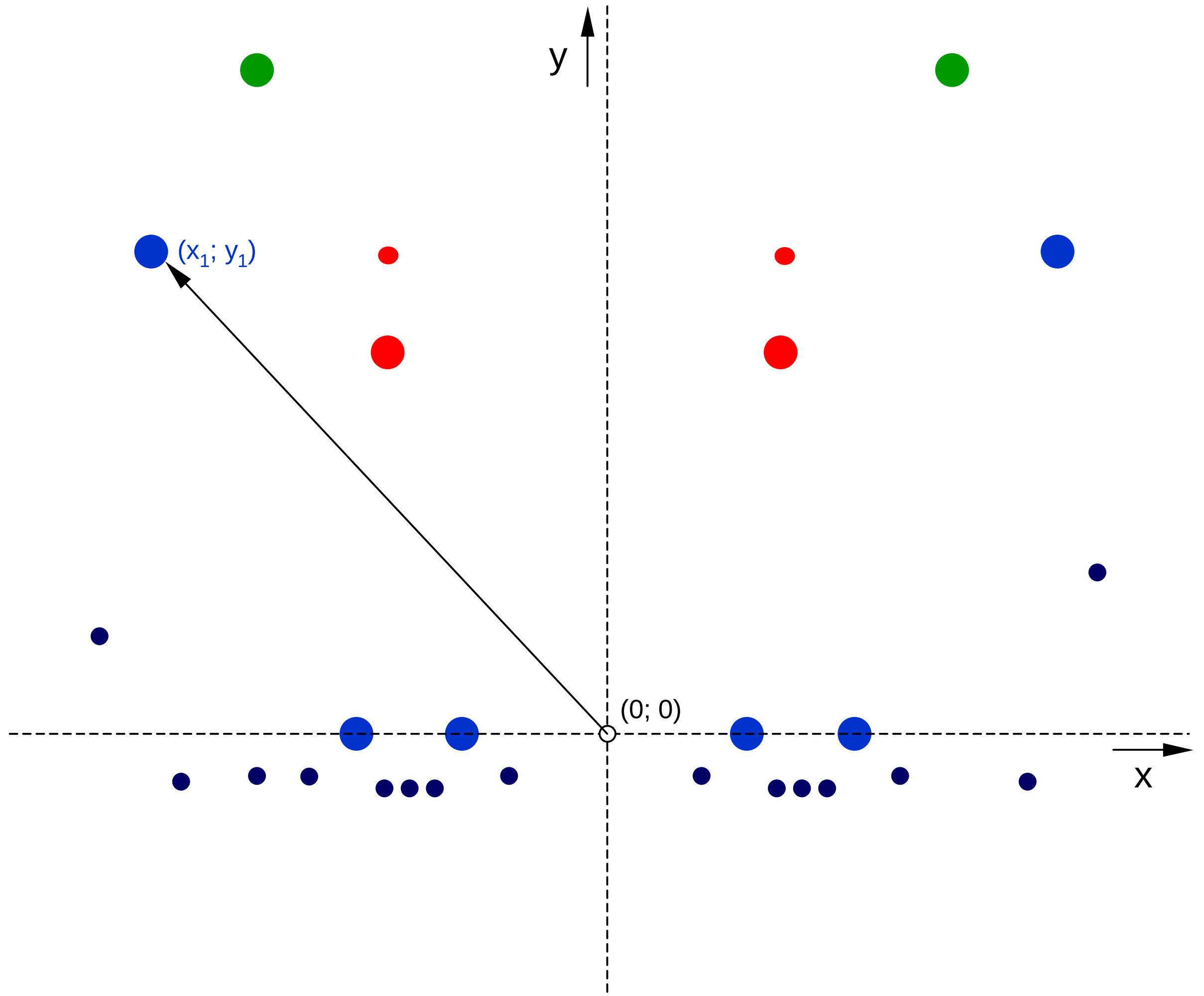

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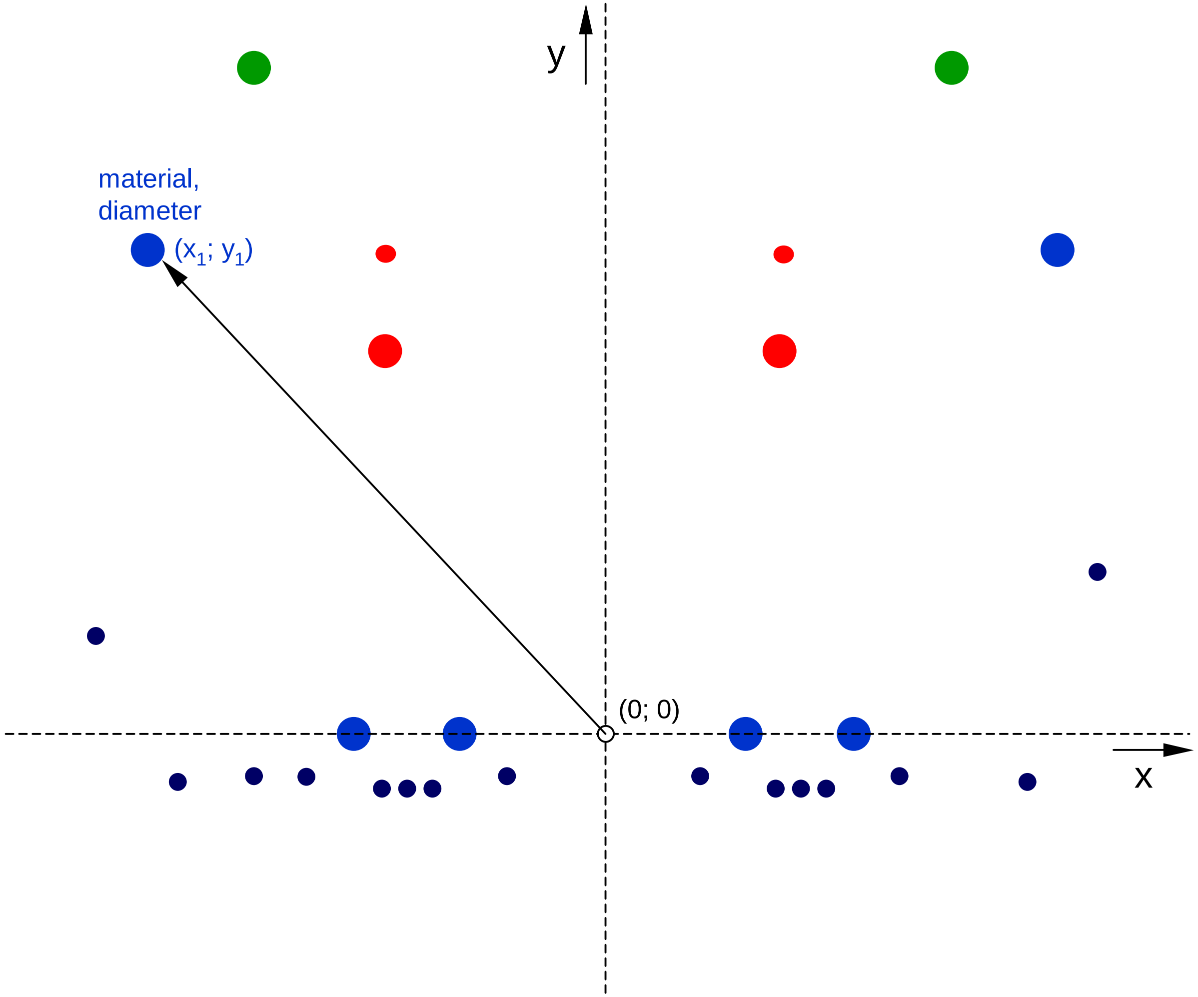

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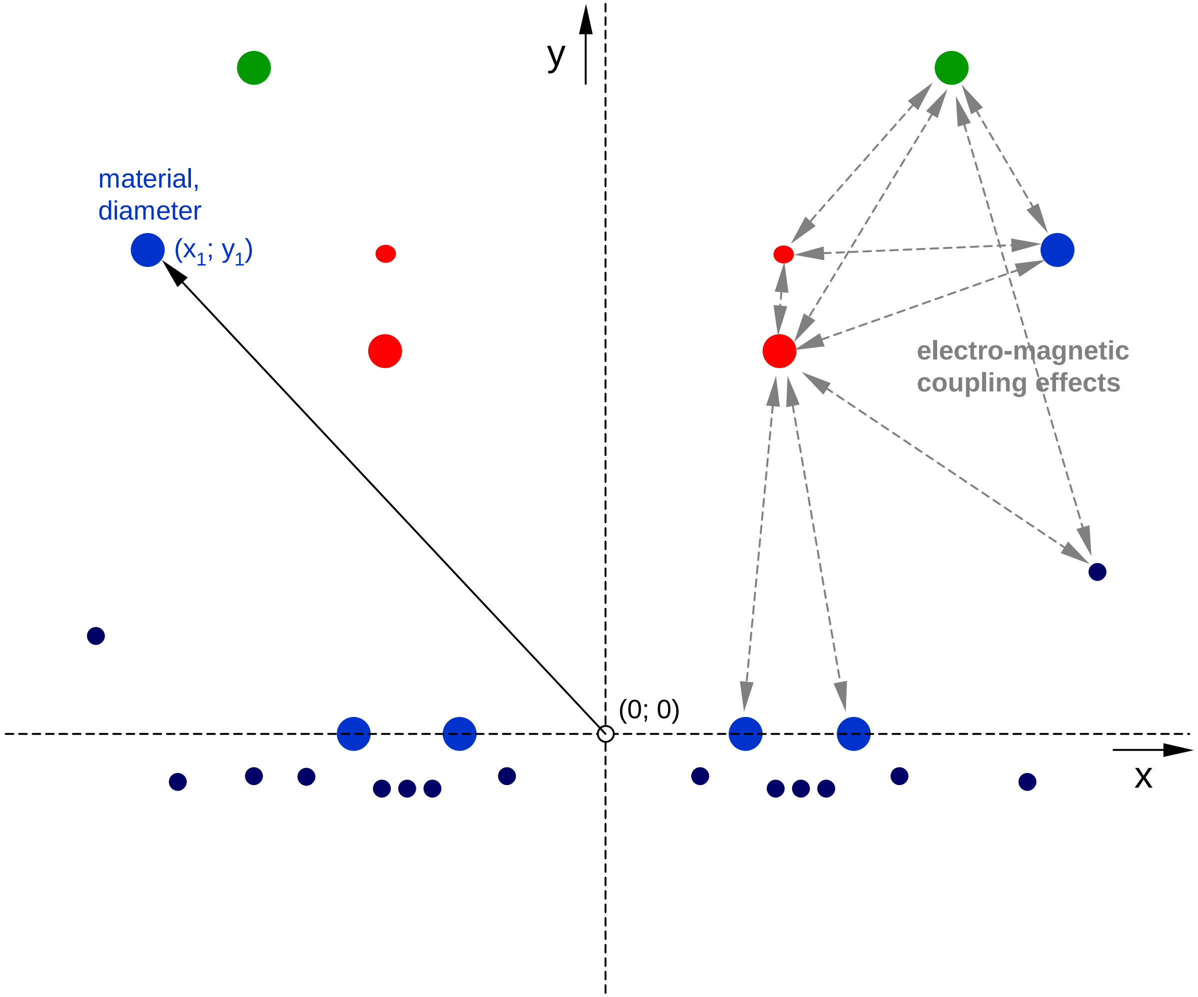

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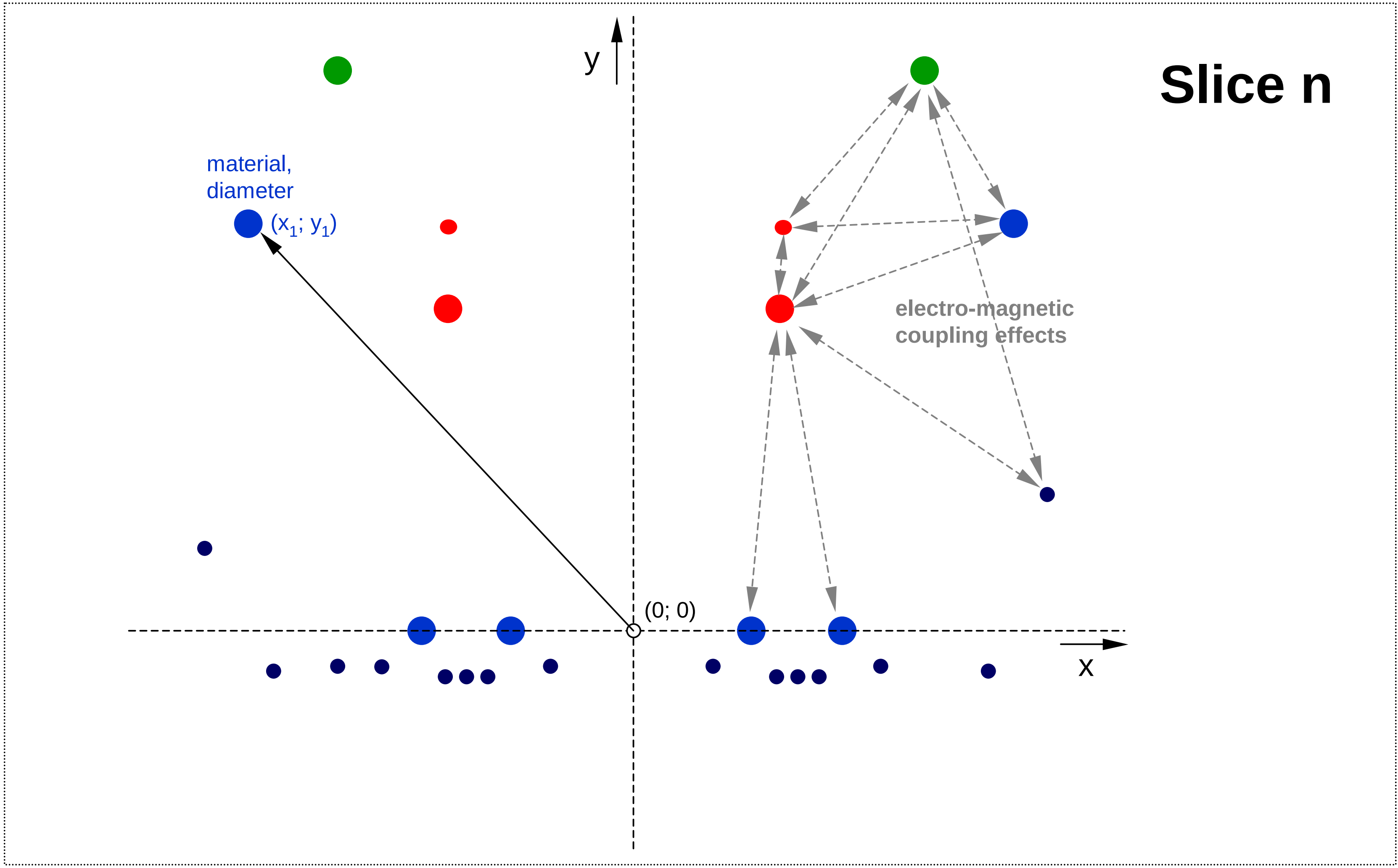
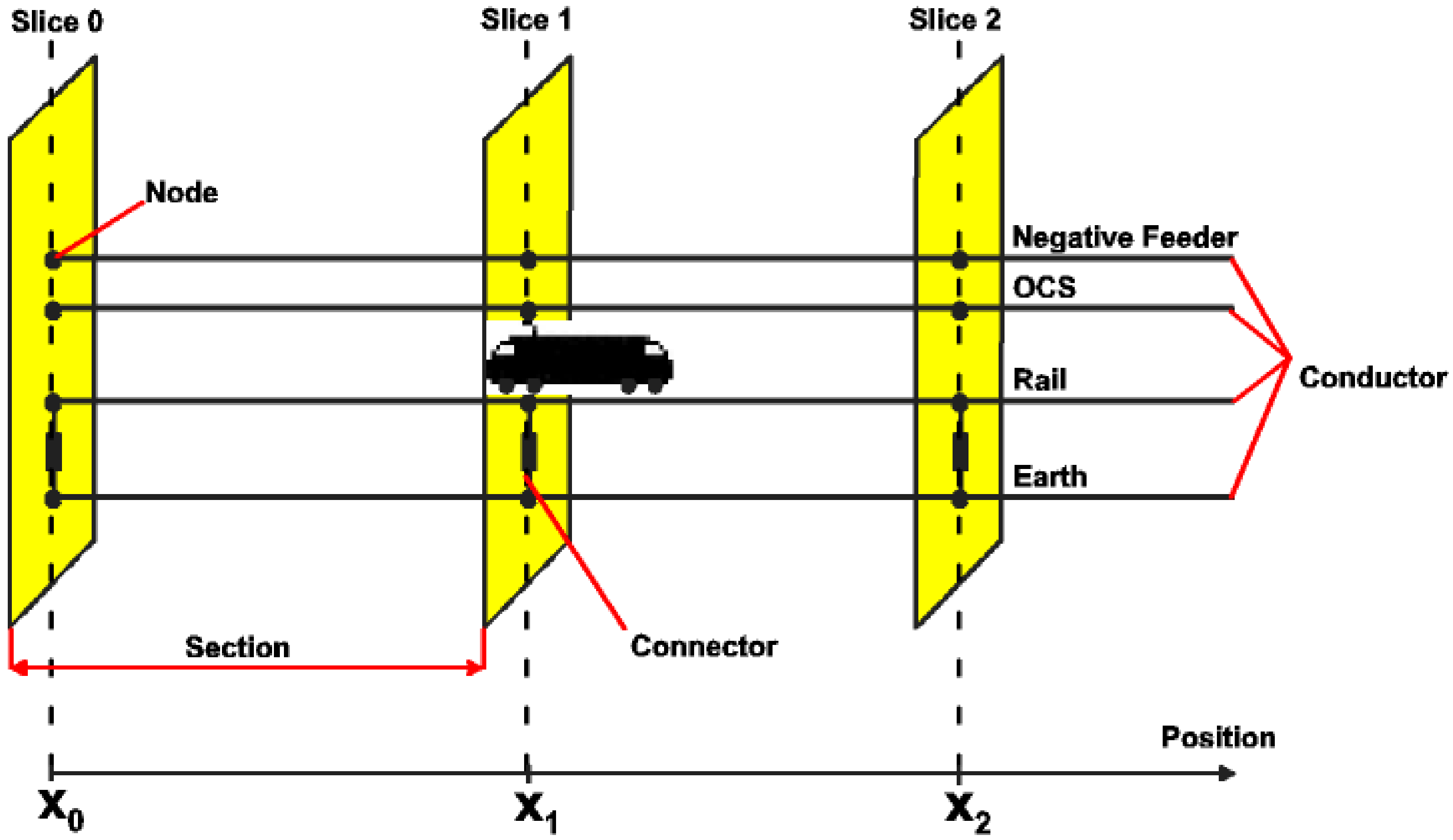
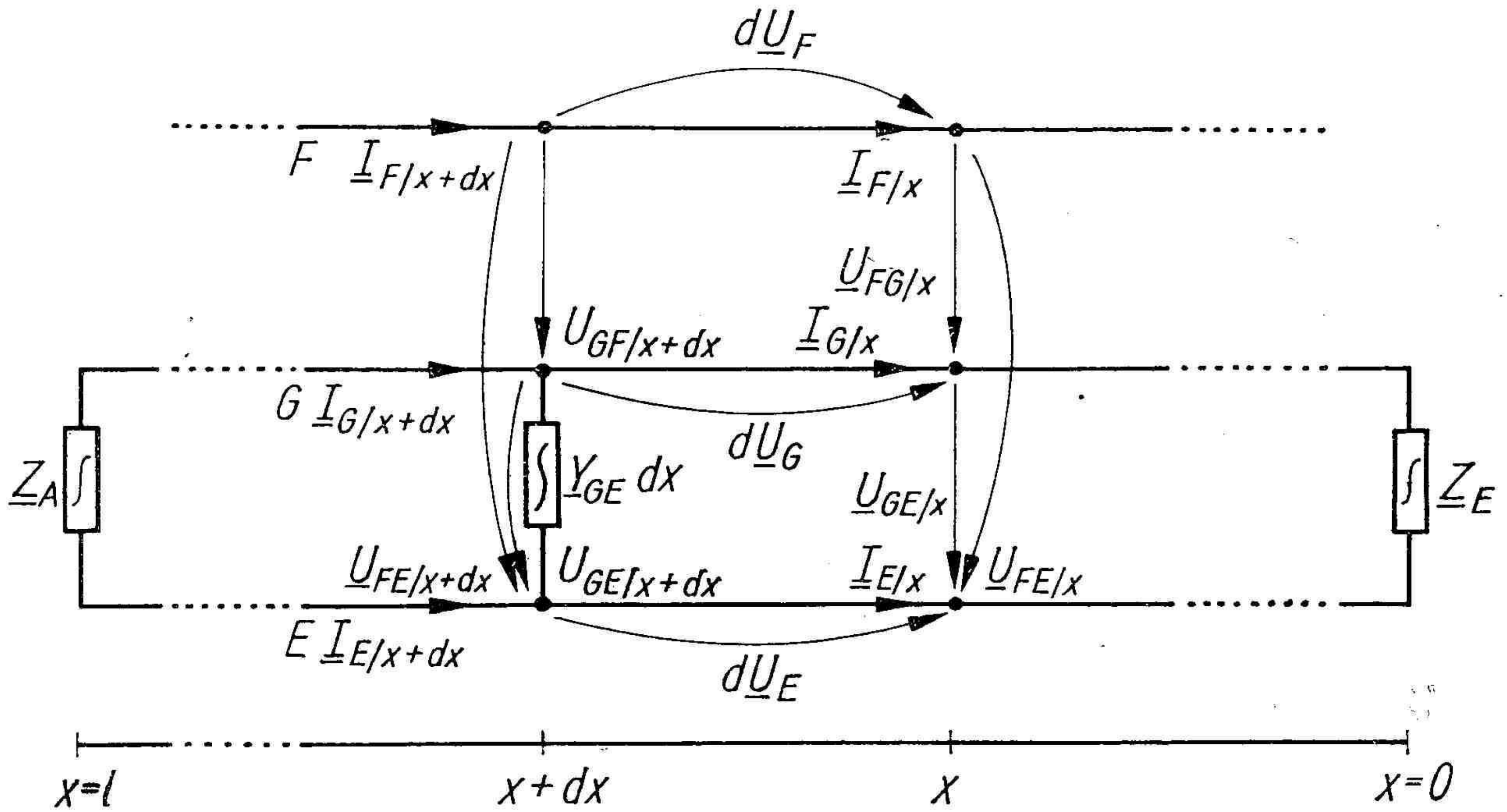


Sequence of Slices



Mathematical Network Model



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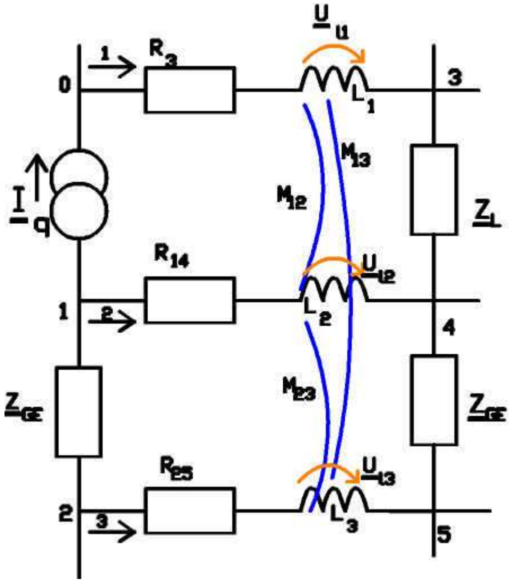

Electrical network calculation using the advanced method of nodes

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

	node voltages					inductive voltages			currents
nodes	$\underline{U}_{10}$	$\underline{U}_{20}$	$\underline{U}_{30}$	$\underline{U}_{40}$	$\underline{U}_{50}$	$\underline{U}_{l1}$	$\underline{U}_{l2}$	$\underline{U}_{l3}$	$\underline{I}_q$
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

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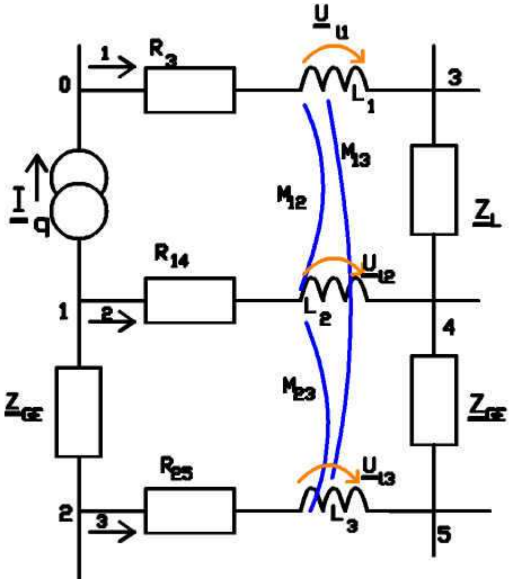

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Voltage drops caused by self- and mutual induction

	node voltages					inductive voltages			currents
nodes	$\underline{U}_{10}$	$\underline{U}_{20}$	$\underline{U}_{30}$	$\underline{U}_{40}$	$\underline{U}_{50}$	$\underline{U}_{l1}$	$\underline{U}_{l2}$	$\underline{U}_{l3}$	$\underline{I}_q$
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

Verification of the simulation

- **Punctual theoretical evaluation**

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  - **current sum cero for network slices**

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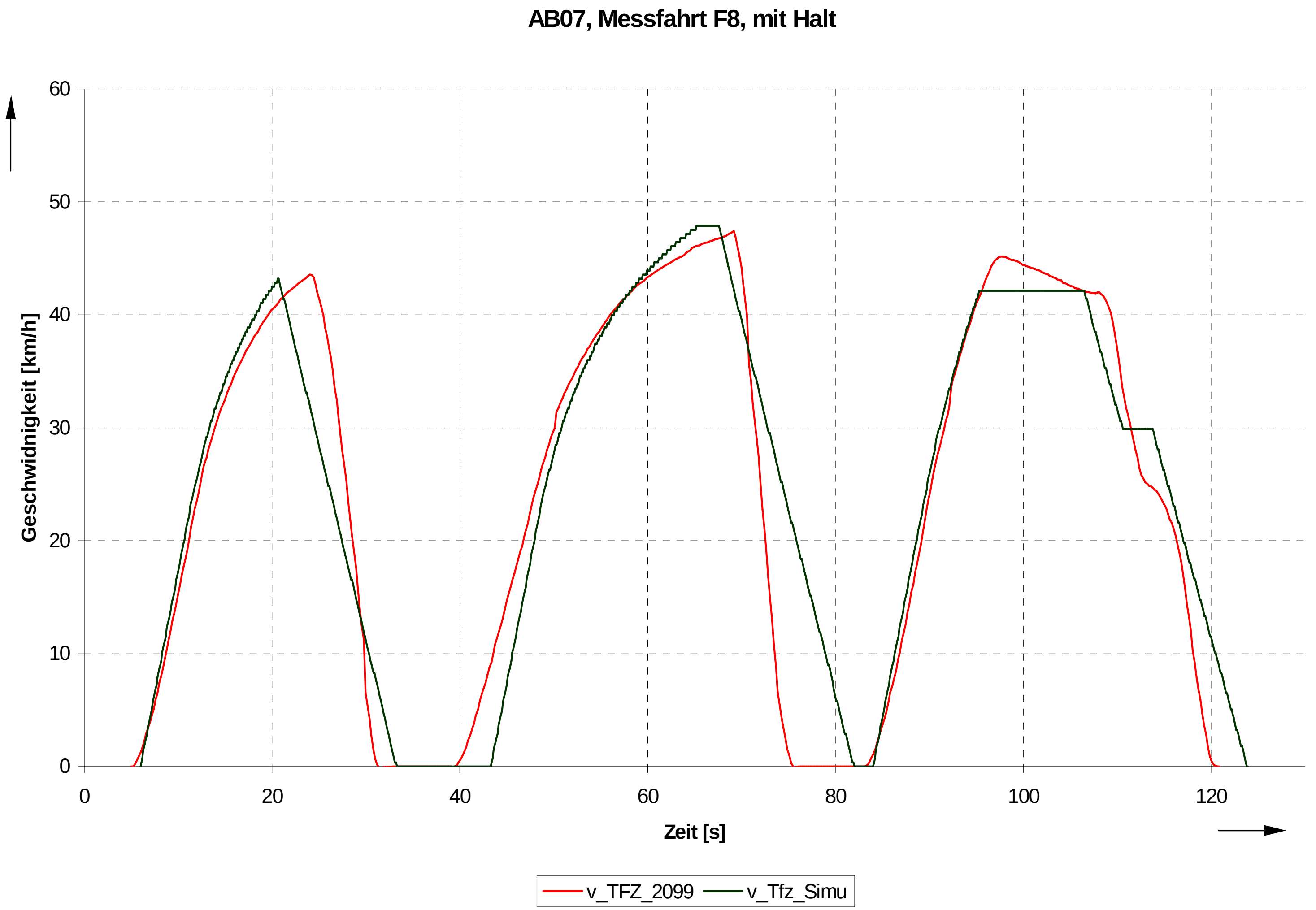
  - current-, voltage- and power characteristics

Verification: Measurement and Simulation



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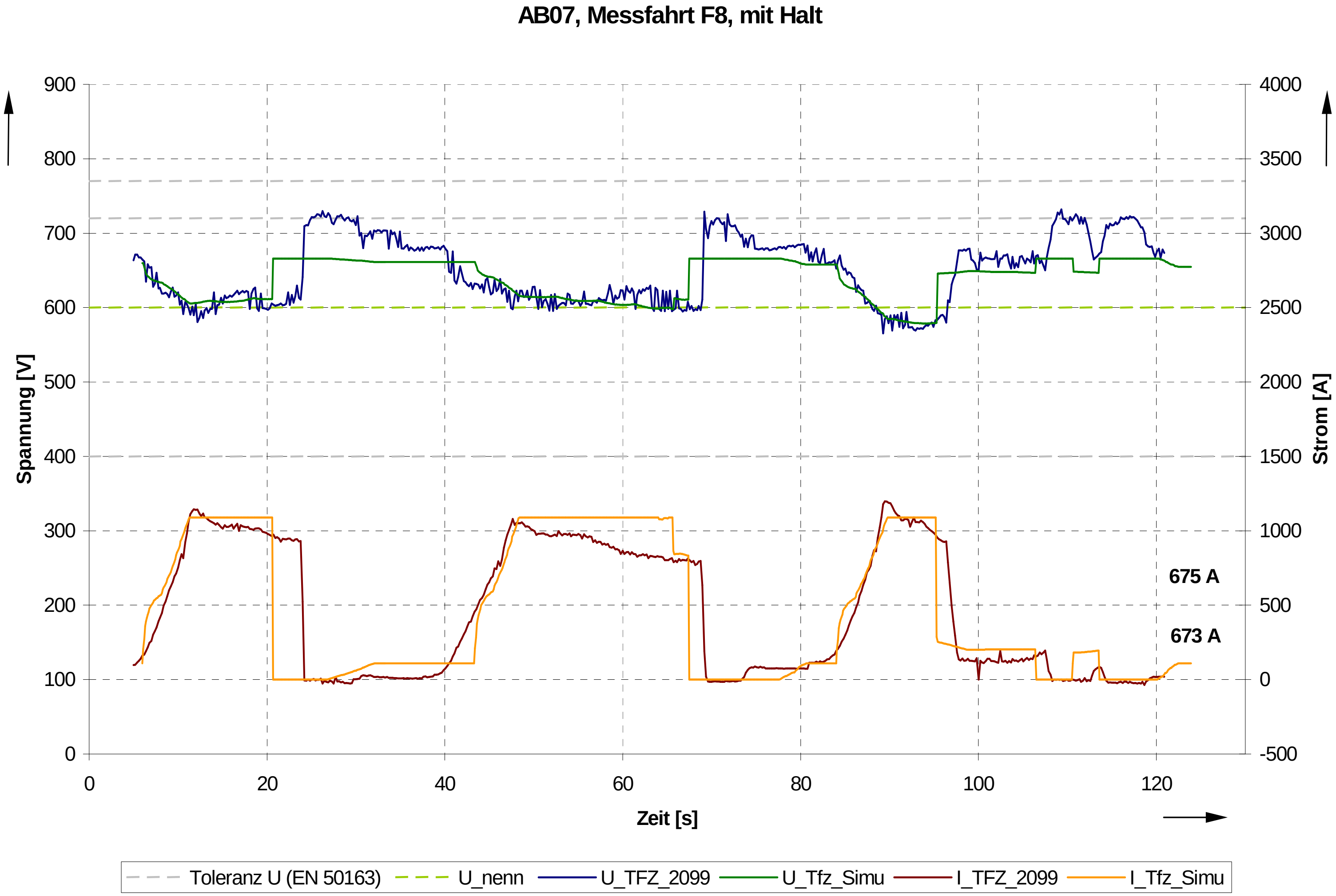
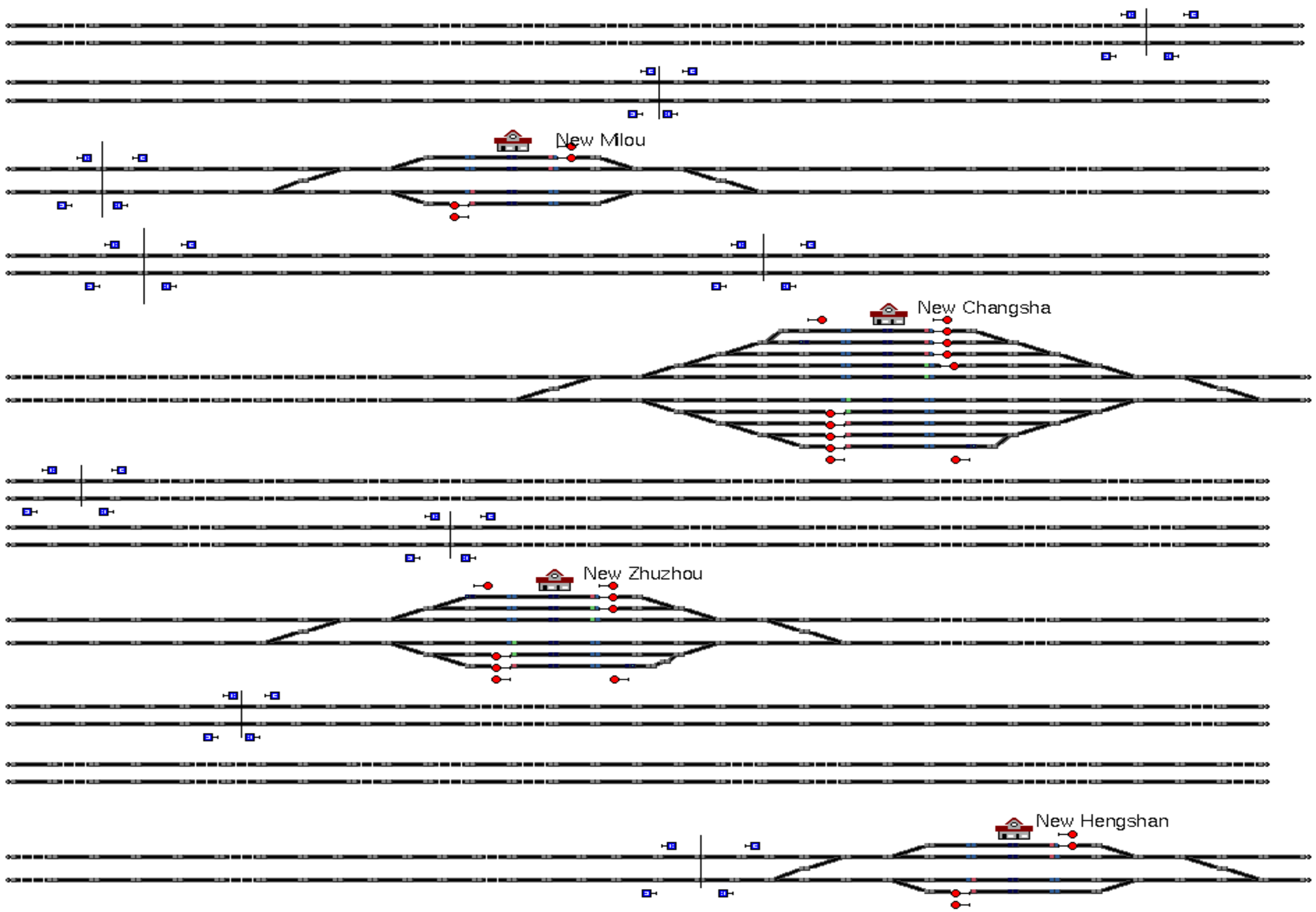
Verification: Measurement and Simulation

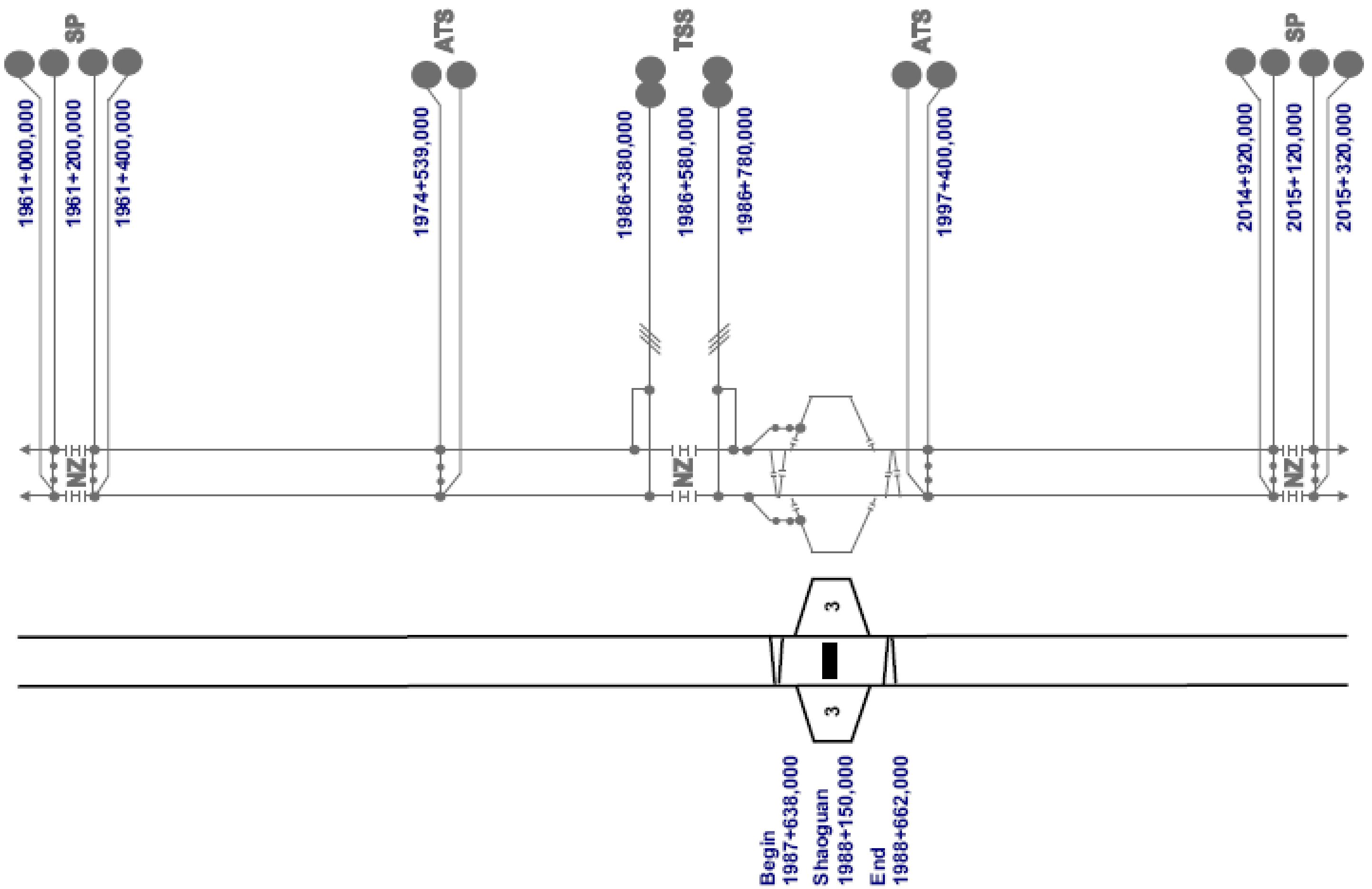



High Speed Railway
350 km/h
966 km Double Track
2AC 25 kV 50 Hz

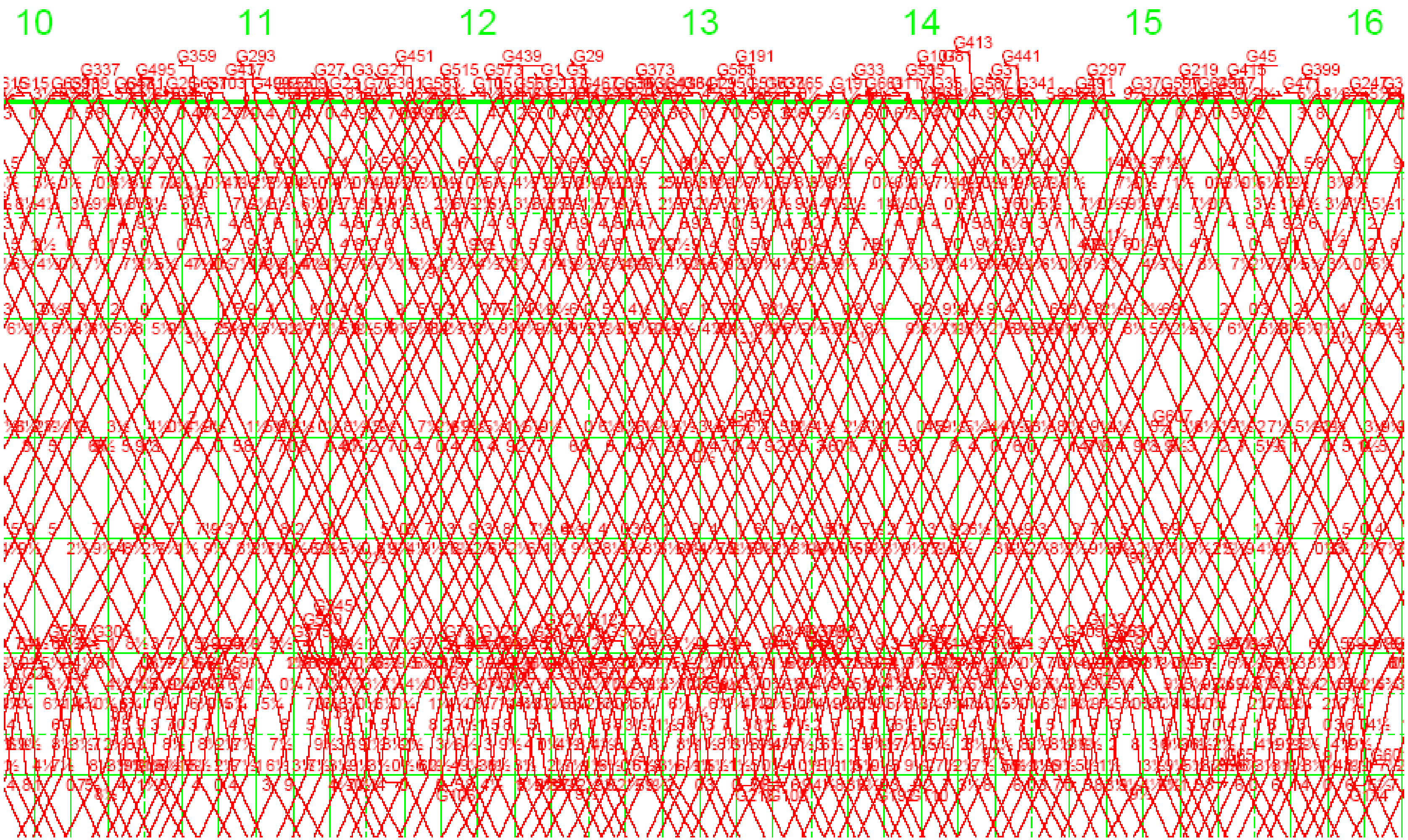
Simulation Example: High Speed Railway 966 km, Track Alignment (Detail)



Simulation Example: High Speed Railway 966 km, OCS Infeed (Detail)



Simulation Example: High Speed Railway 966 km, Timetable Draft (Detail)



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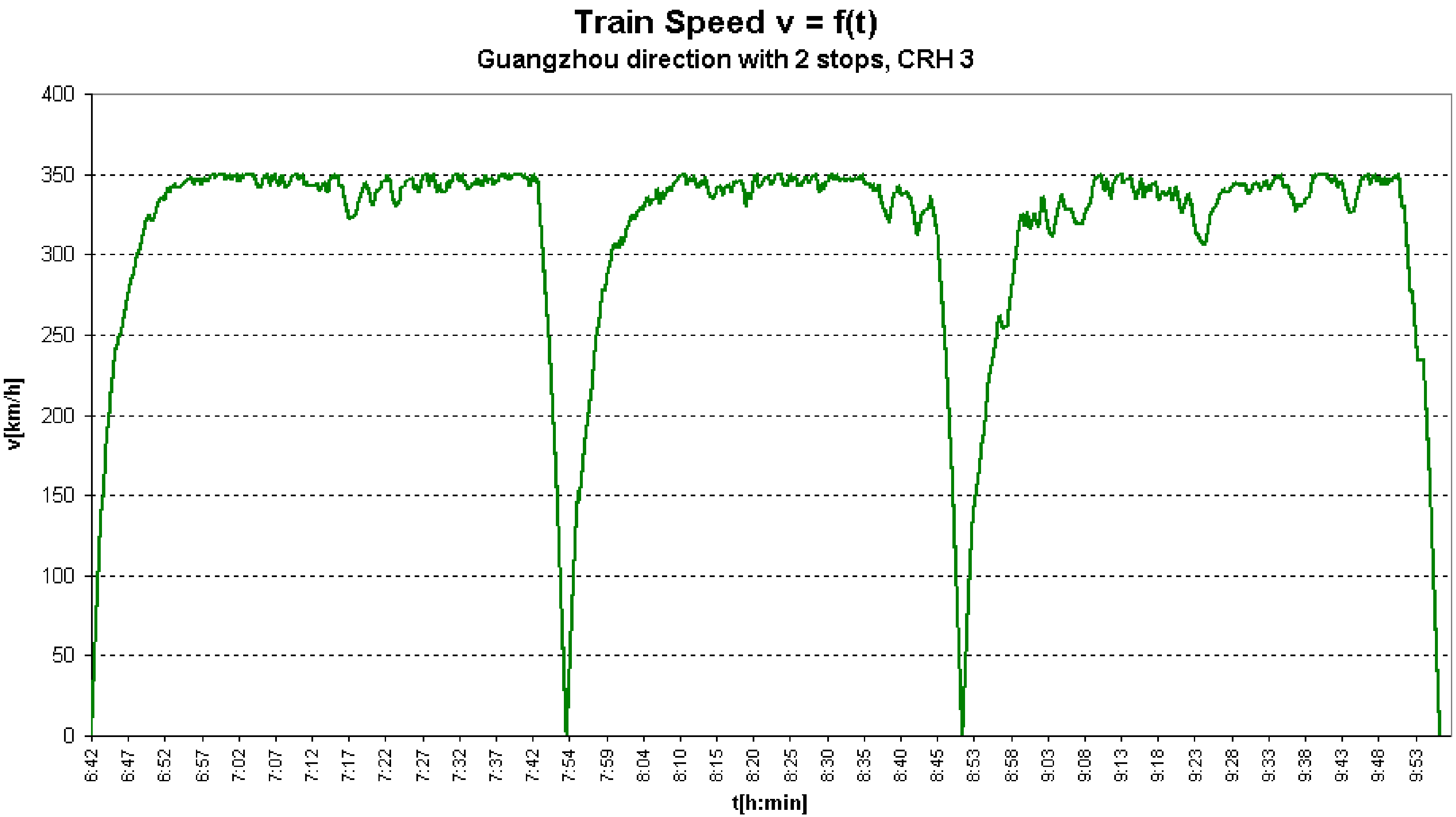
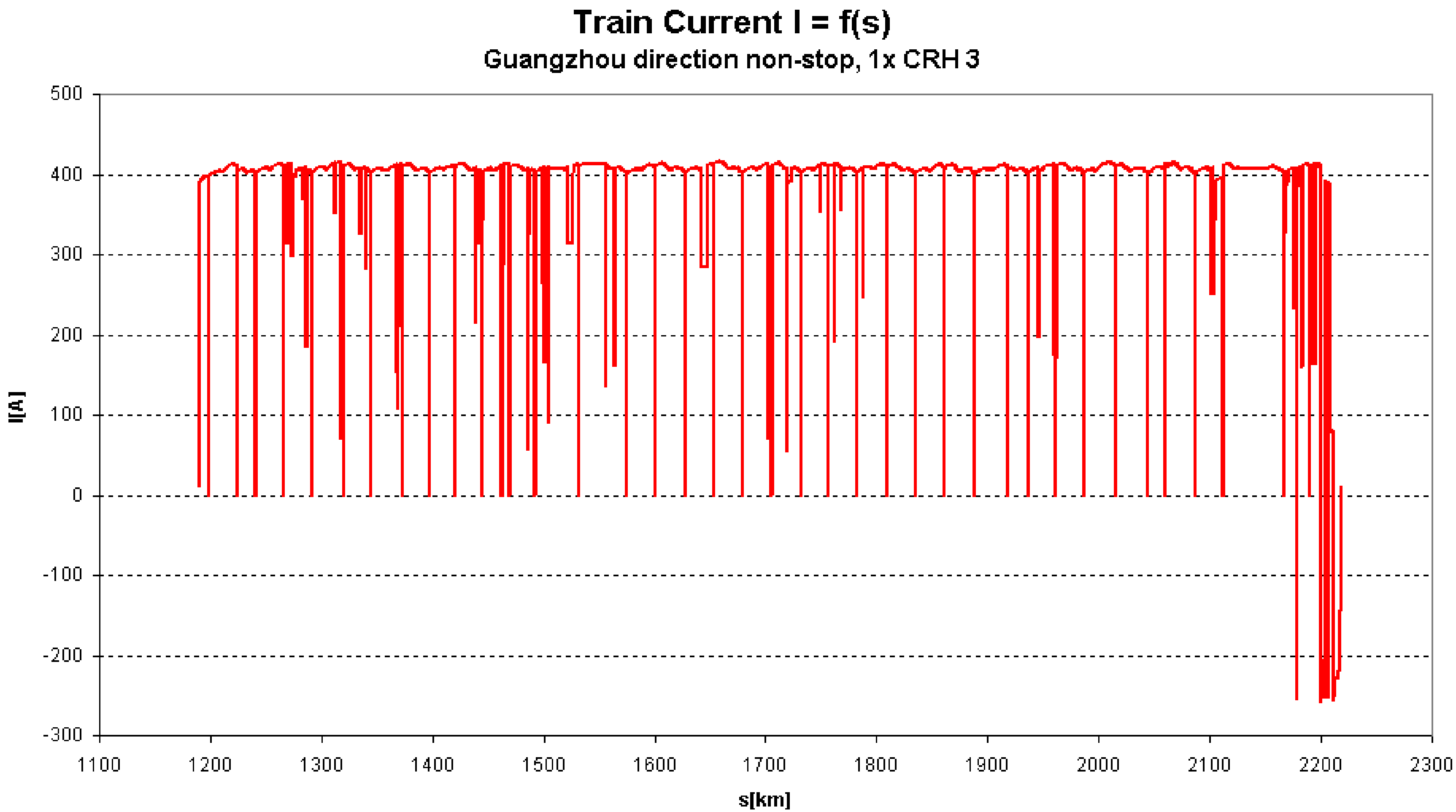
Simulation Results: High Speed Railway 2AC 25 kV



Simulation Results: High Speed Railway 2AC 25 kV



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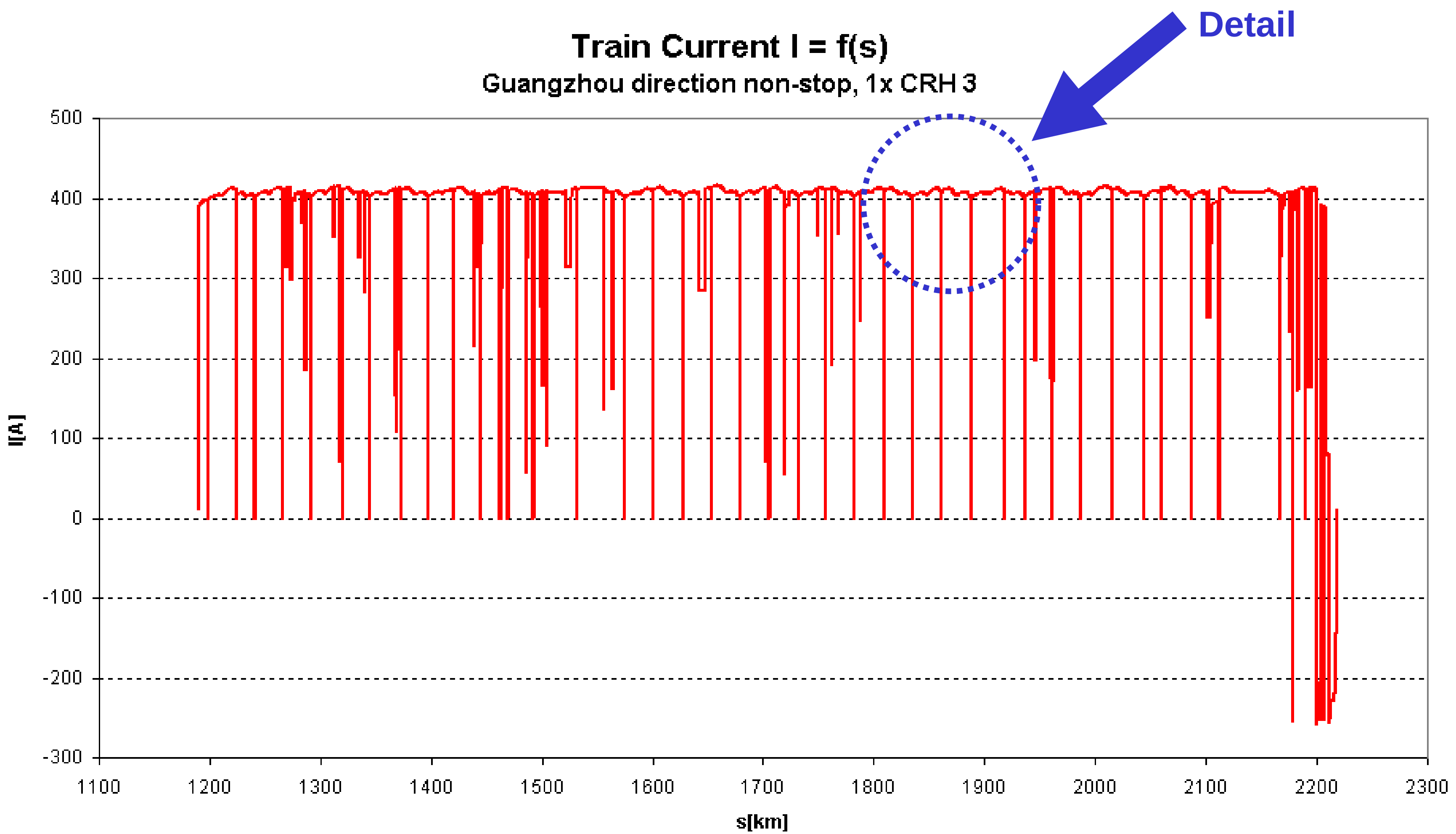

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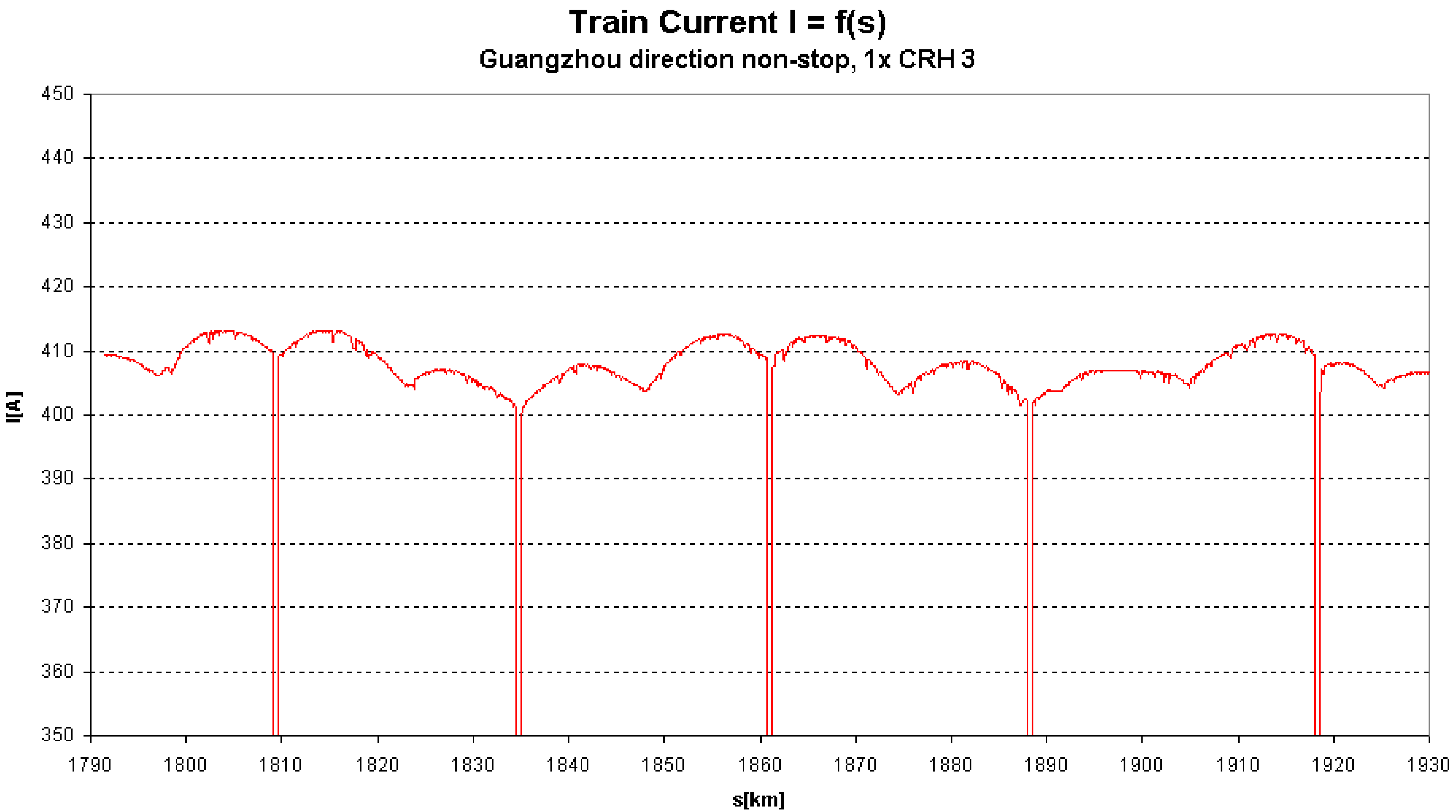

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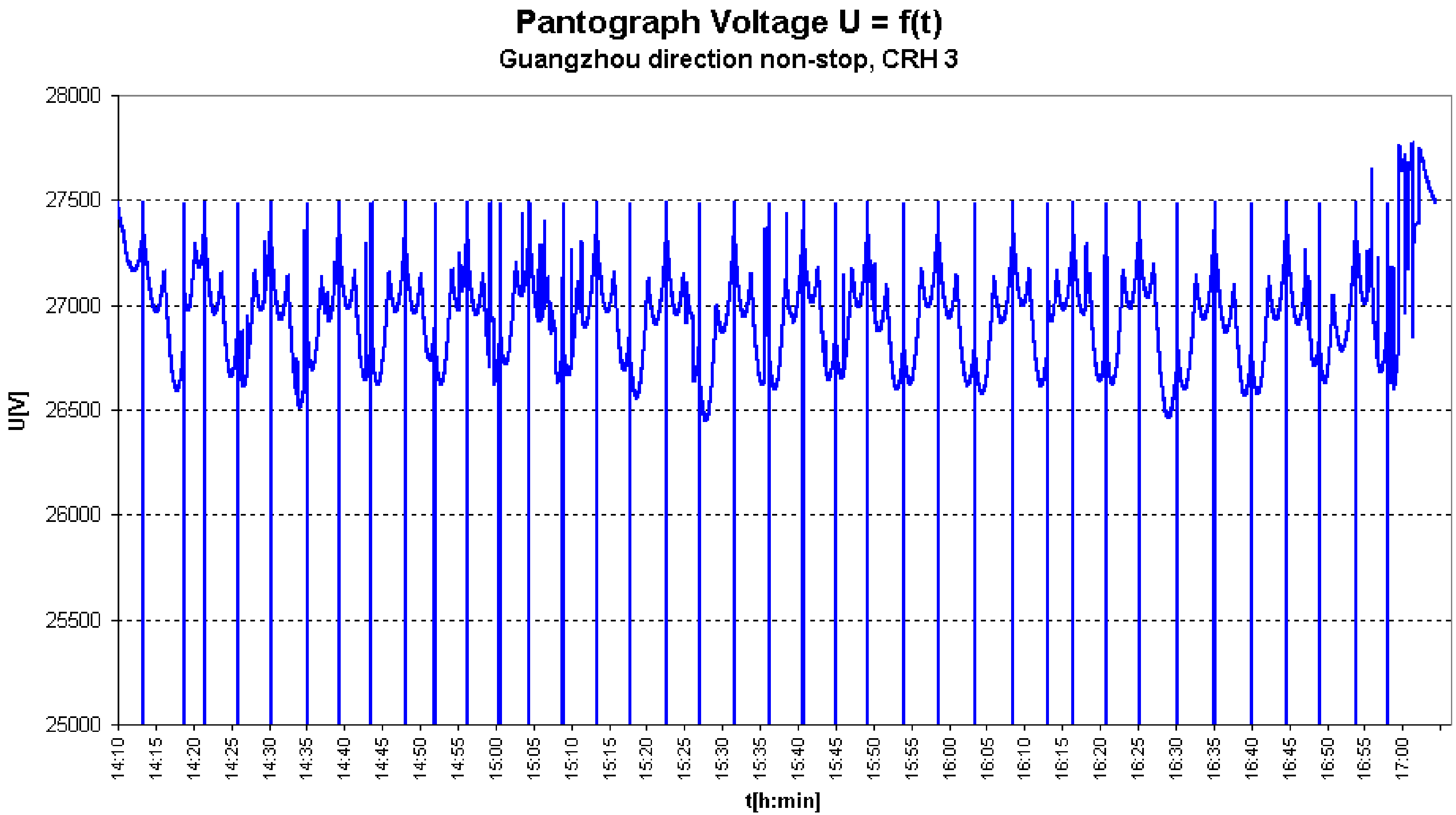

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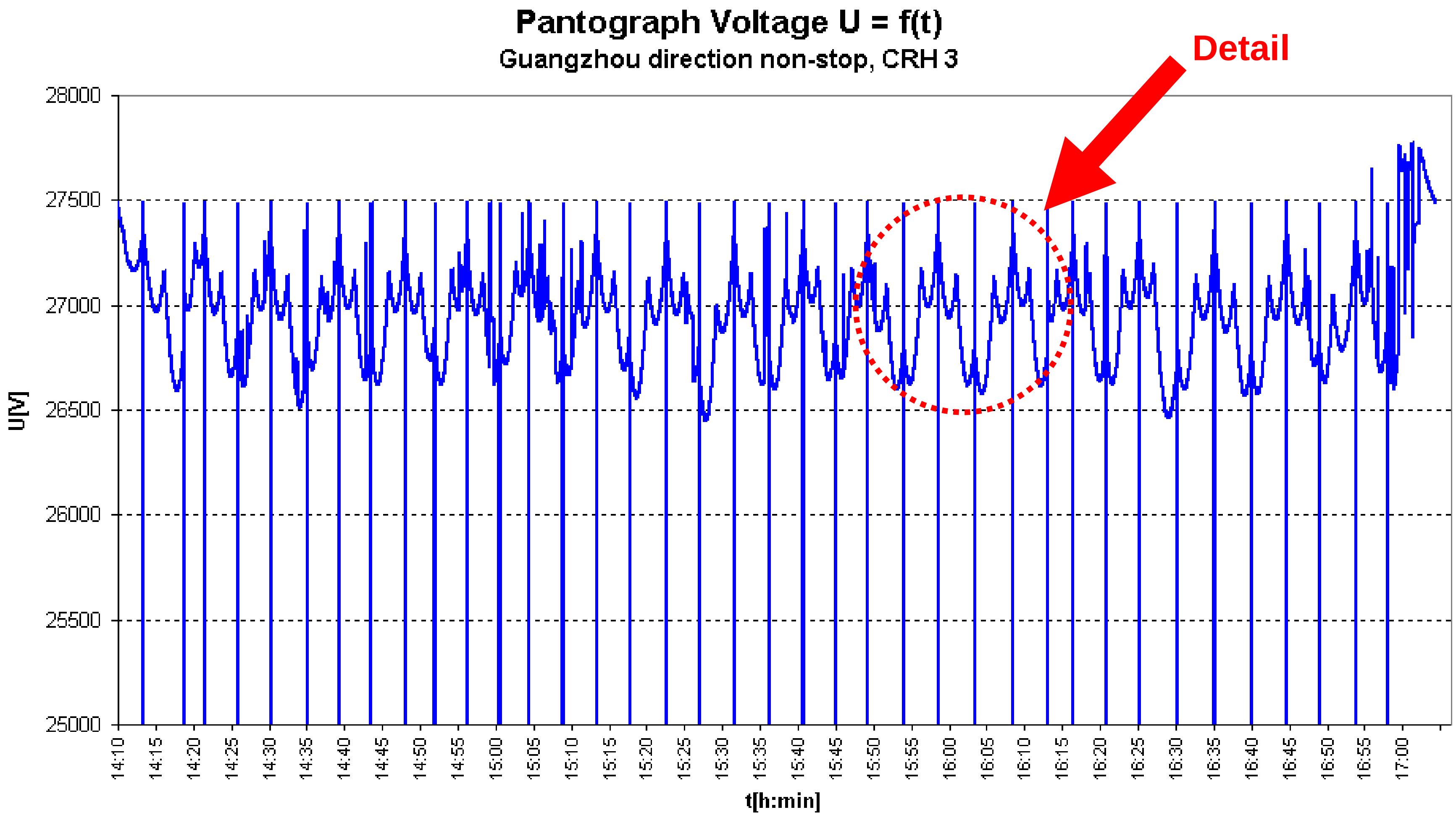

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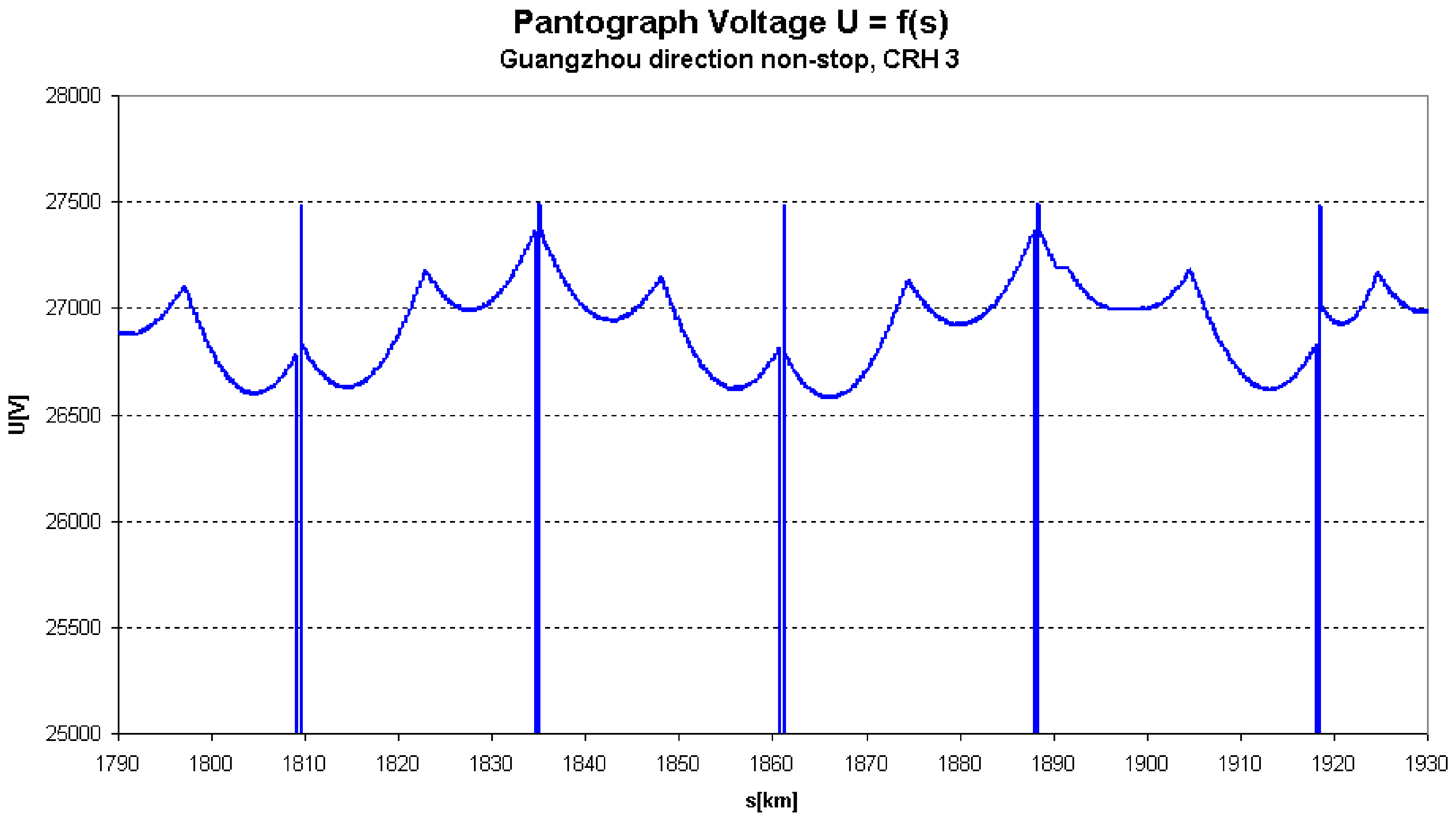
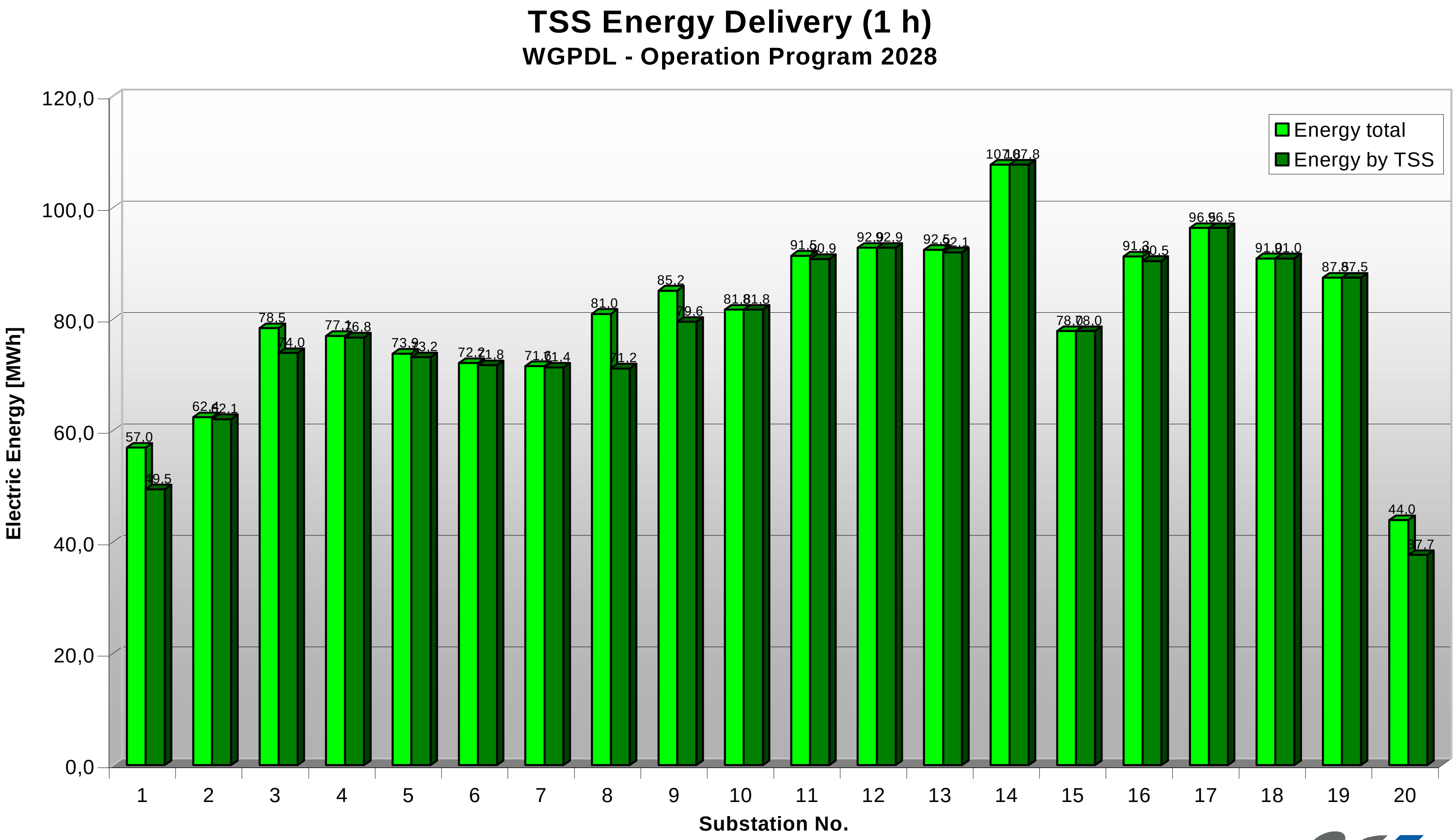
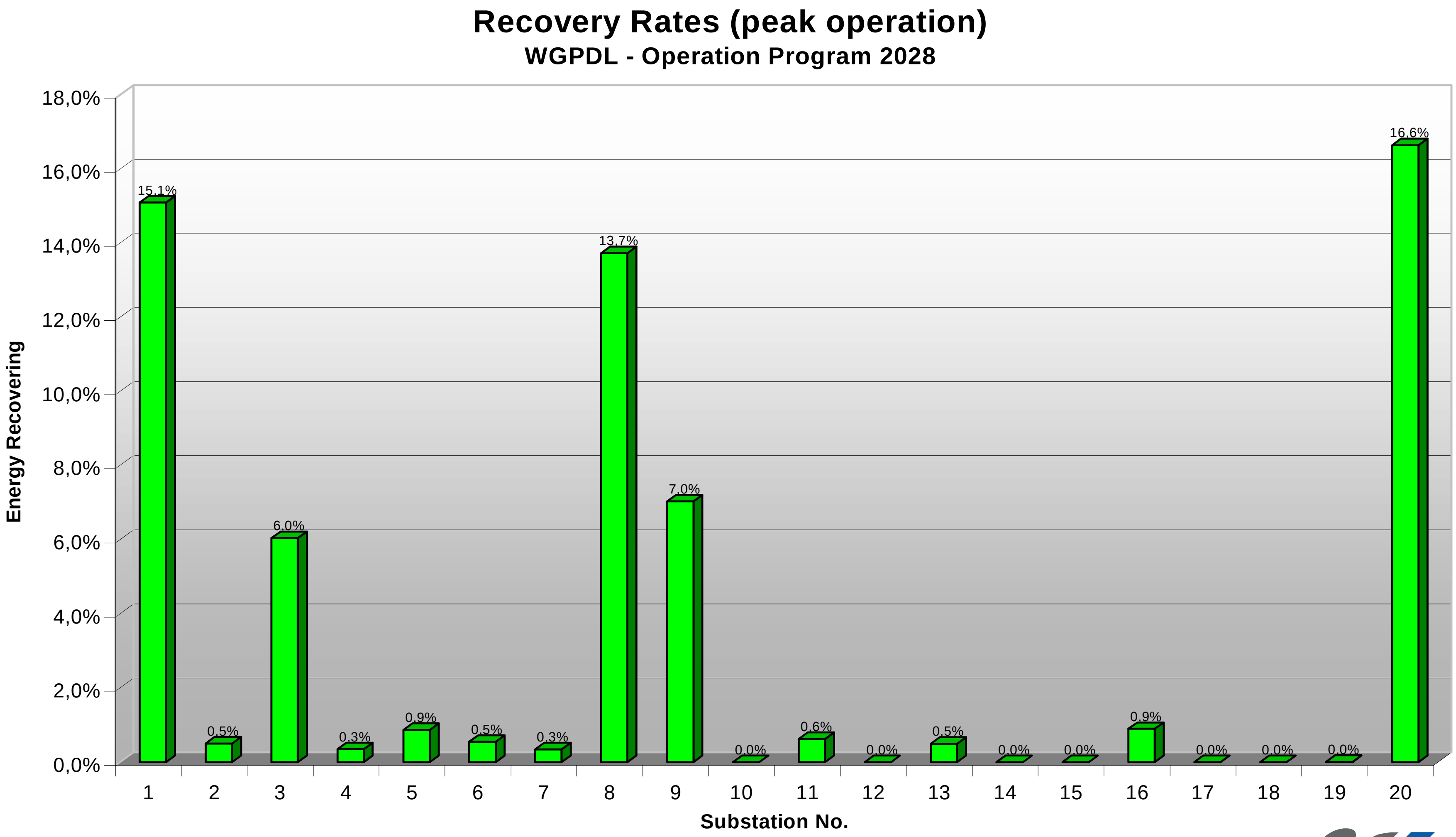


Simulation Results: High Speed Railway 2AC 25 kV



Simulation Results: High Speed Railway 2AC 25 kV



Simulation Results: High Speed Railway 2AC 25 kV

Vehicle Energy Consumption And Recovery Overview, Wuhan - Guangzhou

Ygm 1862-1918

Vehicle Type	EngineID	Transport Work [tkm]	Total Energy [kWh]	Specific Energy [Wh/tkm]	Consumed Energy [kWh]	Recovered Energy [kWh]	Degree Of Regeneration [%]	Available Braking Energy [kWh]	Used Braking Energy [kWh]
CRH3	G469-0	26001,806	1754,227	67,466	1755,741	1,513	0,1	1,942	1,596
CRH3	G469-1	26001,806	1754,227	67,466	1755,741	1,513	0,1	1,942	1,596
CRH3	G371-0	25973,739	1759,052	67,724	1759,052	0,000	0,0	0,000	0,000
CRH3	G371-1	25973,739	1759,052	67,724	1759,052	0,000	0,0	0,000	0,000
CRH3	G299-0	26002,845	1754,247	67,464	1755,755	1,508	0,1	1,936	1,591
CRH3	G299-1	26002,845	1754,247	67,464	1755,755	1,508	0,1	1,936	1,591
CRH3	G355-0	25996,262	1756,881	67,582	1758,806	1,926	0,1	3,791	2,009
CRH3	G355-1	25996,262	1756,881	67,582	1758,806	1,926	0,1	3,791	2,009
CRH3	G509-0	8741,502	588,711	67,347	588,711	0,000	0,0	0,000	0,000
CRH3	G509-1	8741,502	588,711	67,347	588,711	0,000	0,0	0,000	0,000
CRH3	G600-0	7635,276	533,004	69,808	533,004	0,000	0,0	0,000	0,000
CRH3	G600-1	7635,276	533,004	69,808	533,004	0,000	0,0	0,000	0,000
CRH3	G520-0	15460,187	1068,943	69,142	1068,943	0,000	0,0	0,000	0,000
CRH3	G520-1	15460,187	1068,943	69,142	1068,943	0,000	0,0	0,000	0,000

Simulation Results: High Speed Railway 2AC 25 kV

Energy Consumption And Losses Overview, Wuhan - Guangzhou

Cha 1532-1600

Energy output to catenary at substation [kWh]	72300,187
Energy input from catenary at substation [kWh]	1154,082
Total energy at substation [kWh]	**71146,105**

Vehicles energy consumption [kWh]	78540,848
Vehicles braking energy used for auxiliaries [kWh]	639,139
Vehicles braking energy recovered by catenary [kWh]	9230,867
Total used vehicles braking energy [kWh]	9870,007
Total vehicles energy [kWh]	**69309,980**

Total energy consumption [kWh]	**81016,112**
Energy consumption from national power grid [kWh]	71233,480

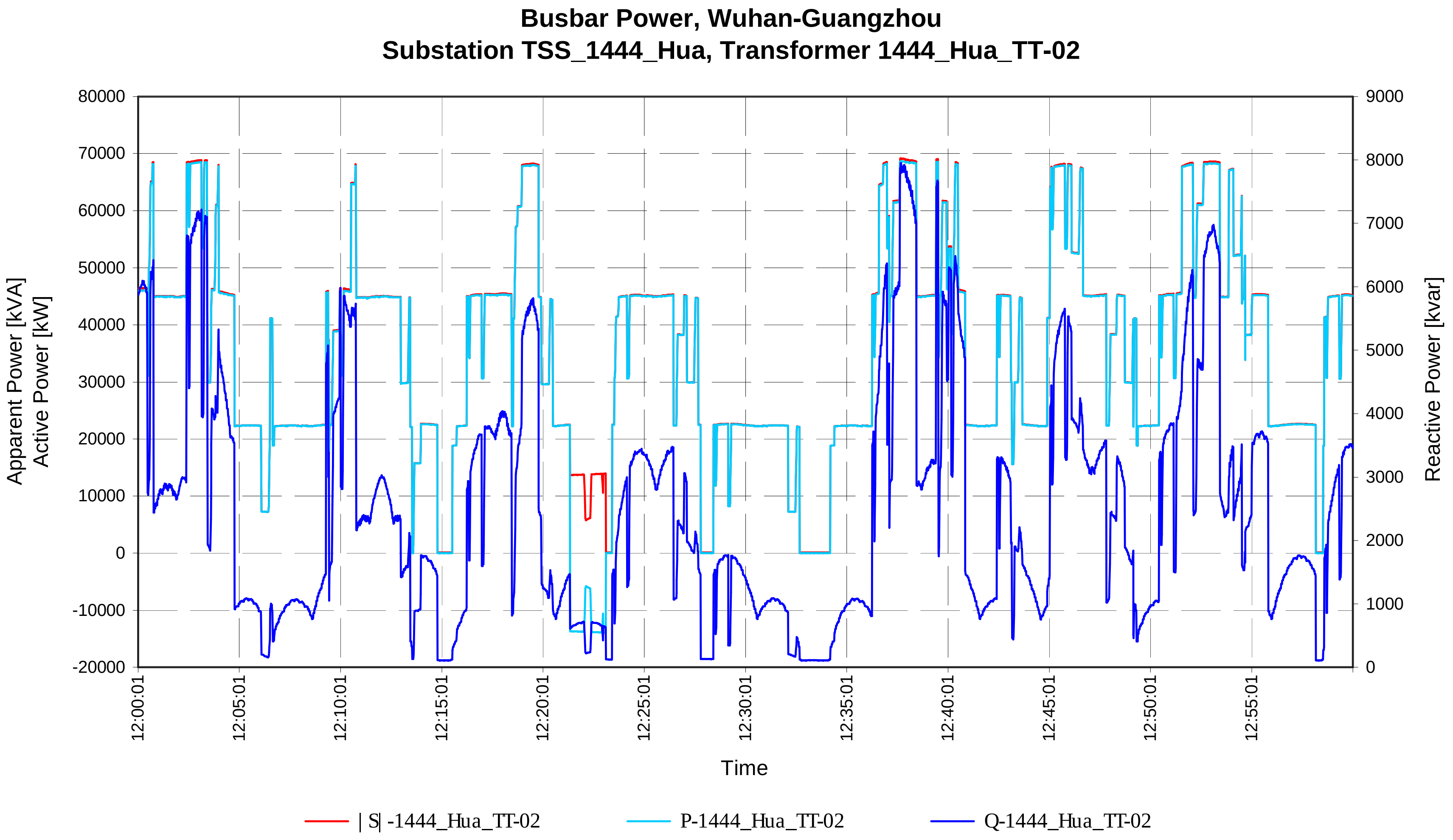
Average efficiency of traction power supply	**97,6%**

Losses in contact wire [kWh]	525,588
Losses in messenger wire [kWh]	565,248
Losses in negative feeder [kWh]	481,426
Losses in return conductor [kWh]	138,879
Losses in left rail [kWh]	13,174
Losses in right rail [kWh]	13,196
Losses in LEBC [kWh]	31,117
Total losses in conductors [kWh]	1768,629
Losses in connectors [kWh]	1,495
Losses in autotransformers [kWh]	21,896
Total losses in catenary system [kWh]	**1792,020**

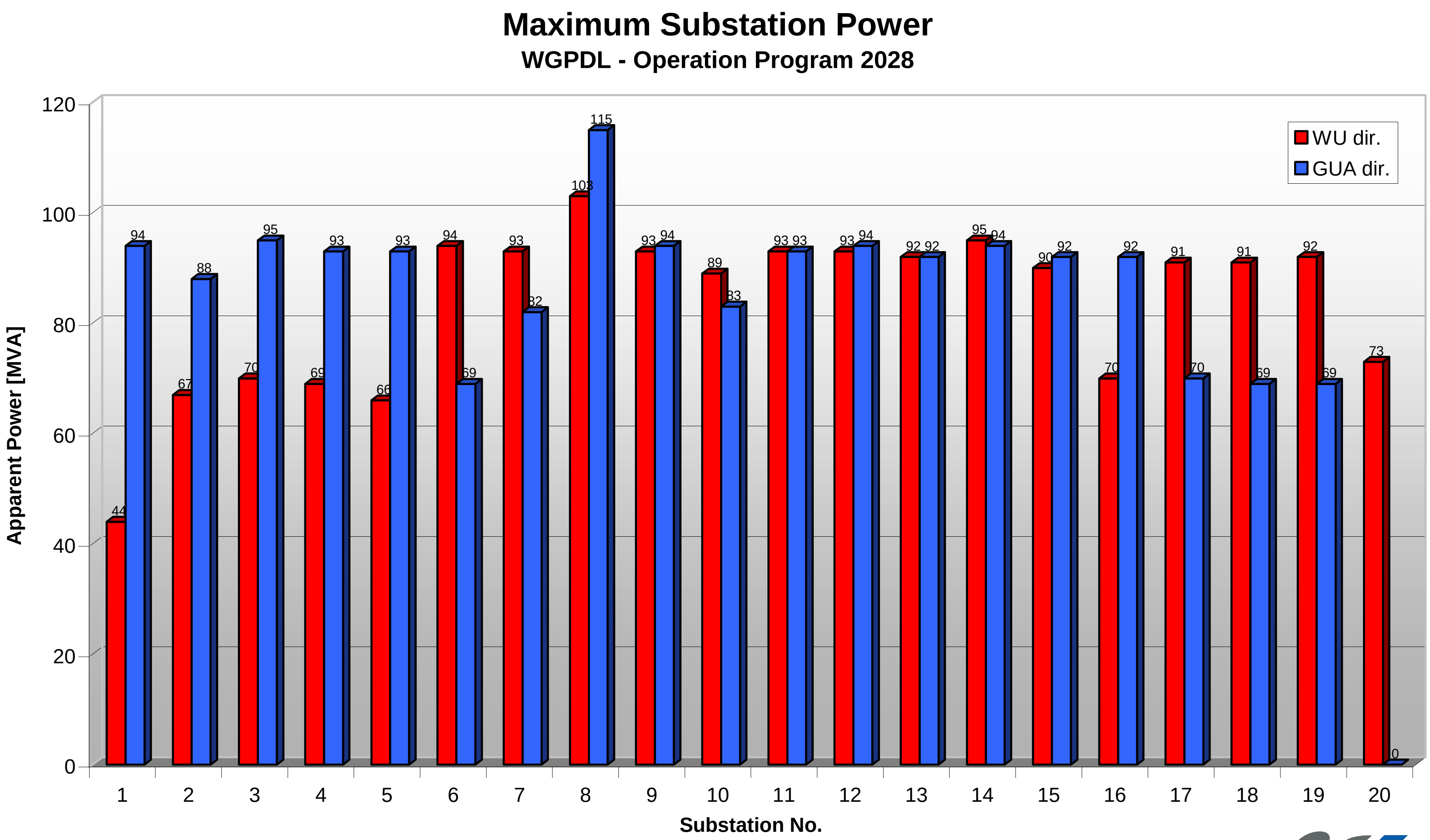
Losses in feeders [kWh]	44,072

Losses in traction transformers [kWh]	87,375

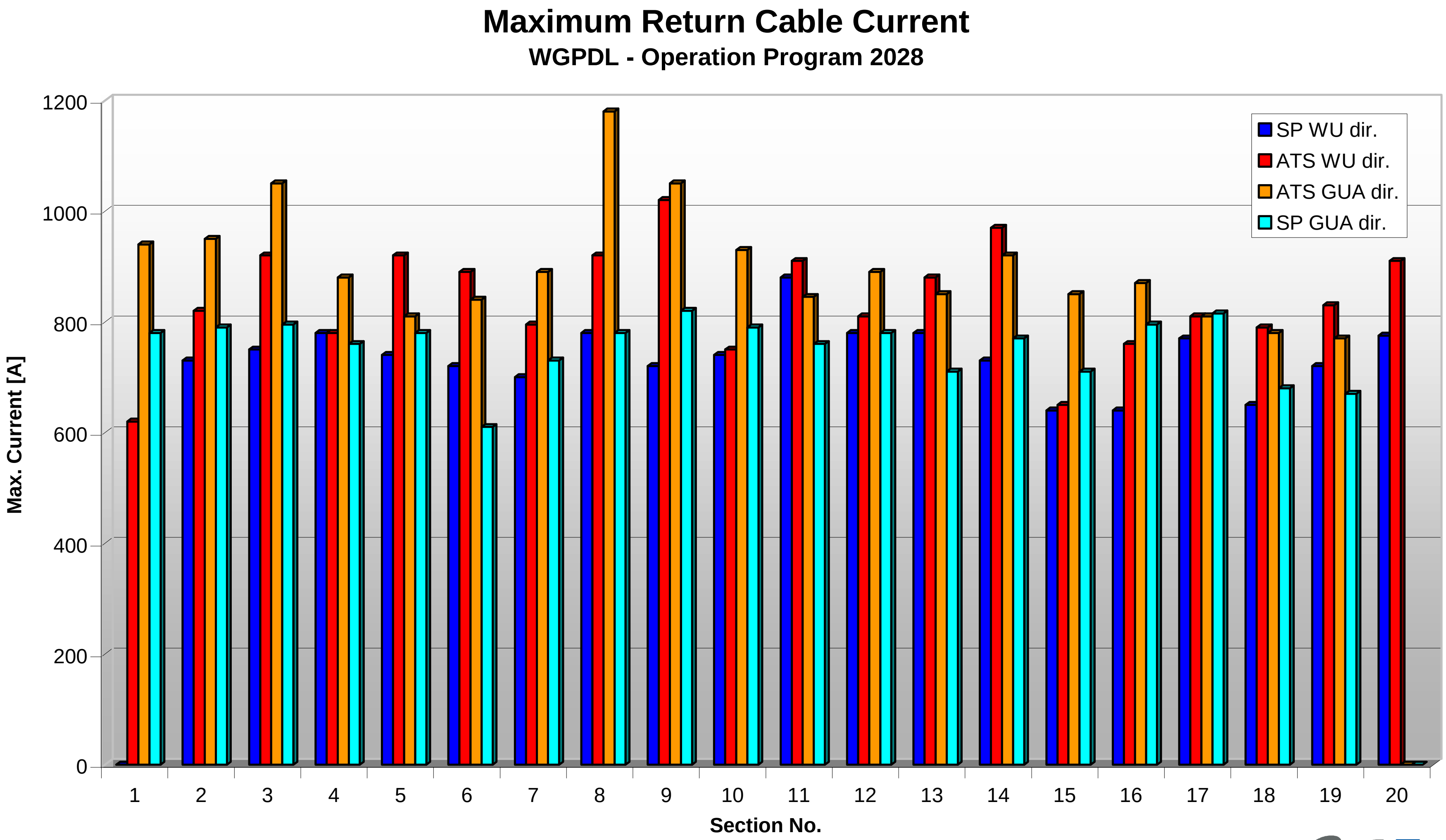
Simulation Results: High Speed Railway 2AC 25 kV



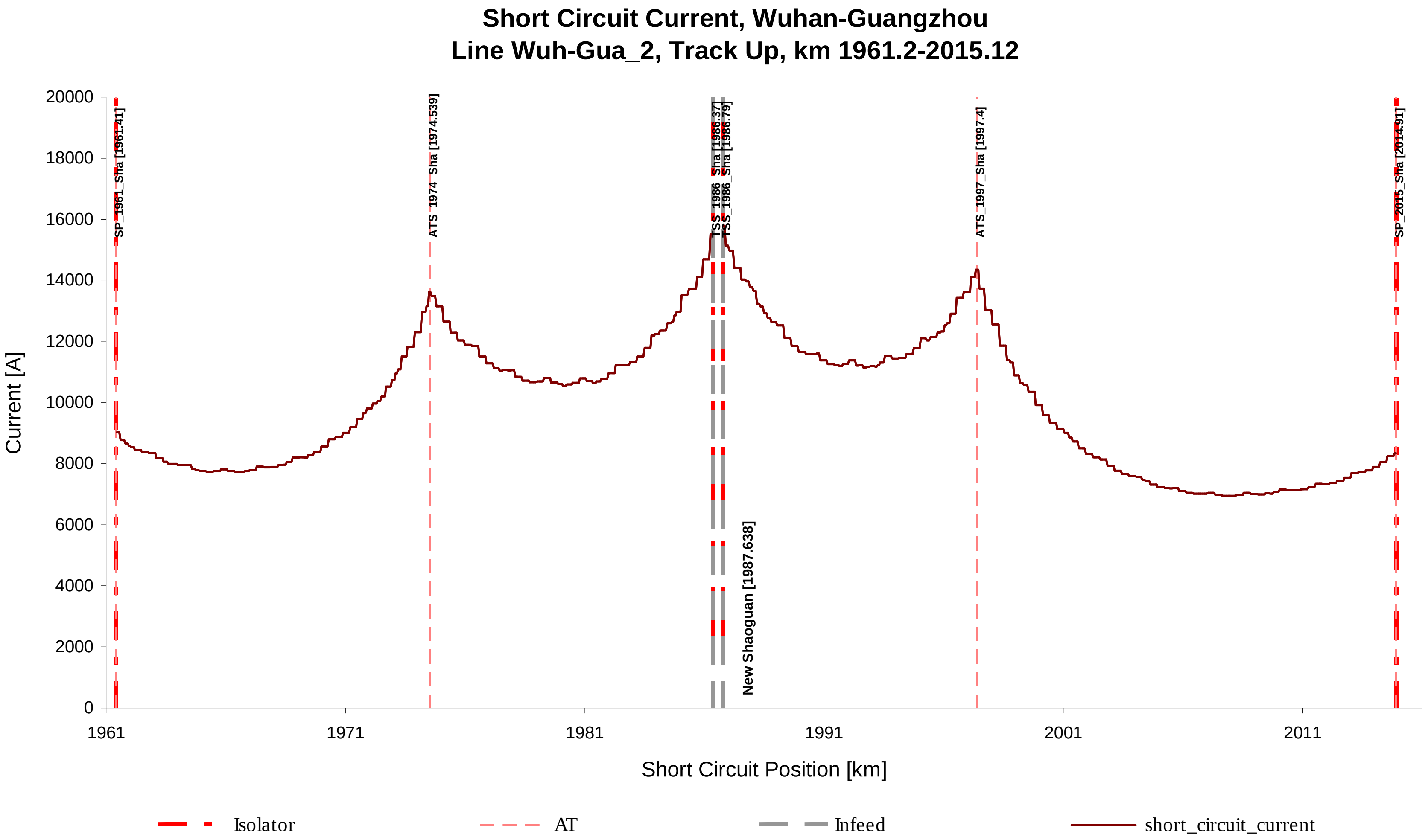
Simulation Results: High Speed Railway 2AC 25 kV



Simulation Results: High Speed Railway 2AC 25 kV



Simulation Results: High Speed Railway 2AC 25 kV



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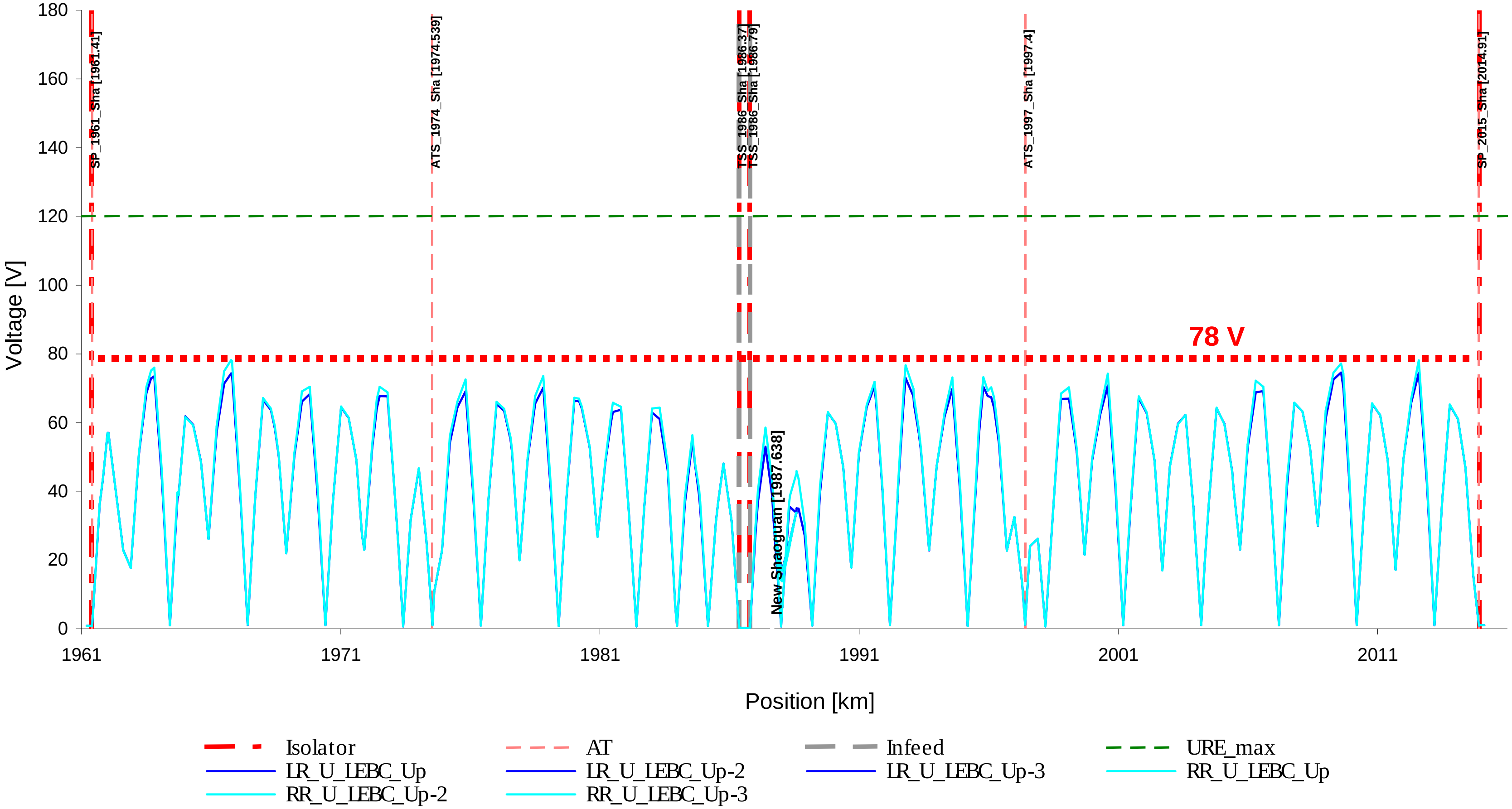
Simulation Results: High Speed Railway 2AC 25 kV

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



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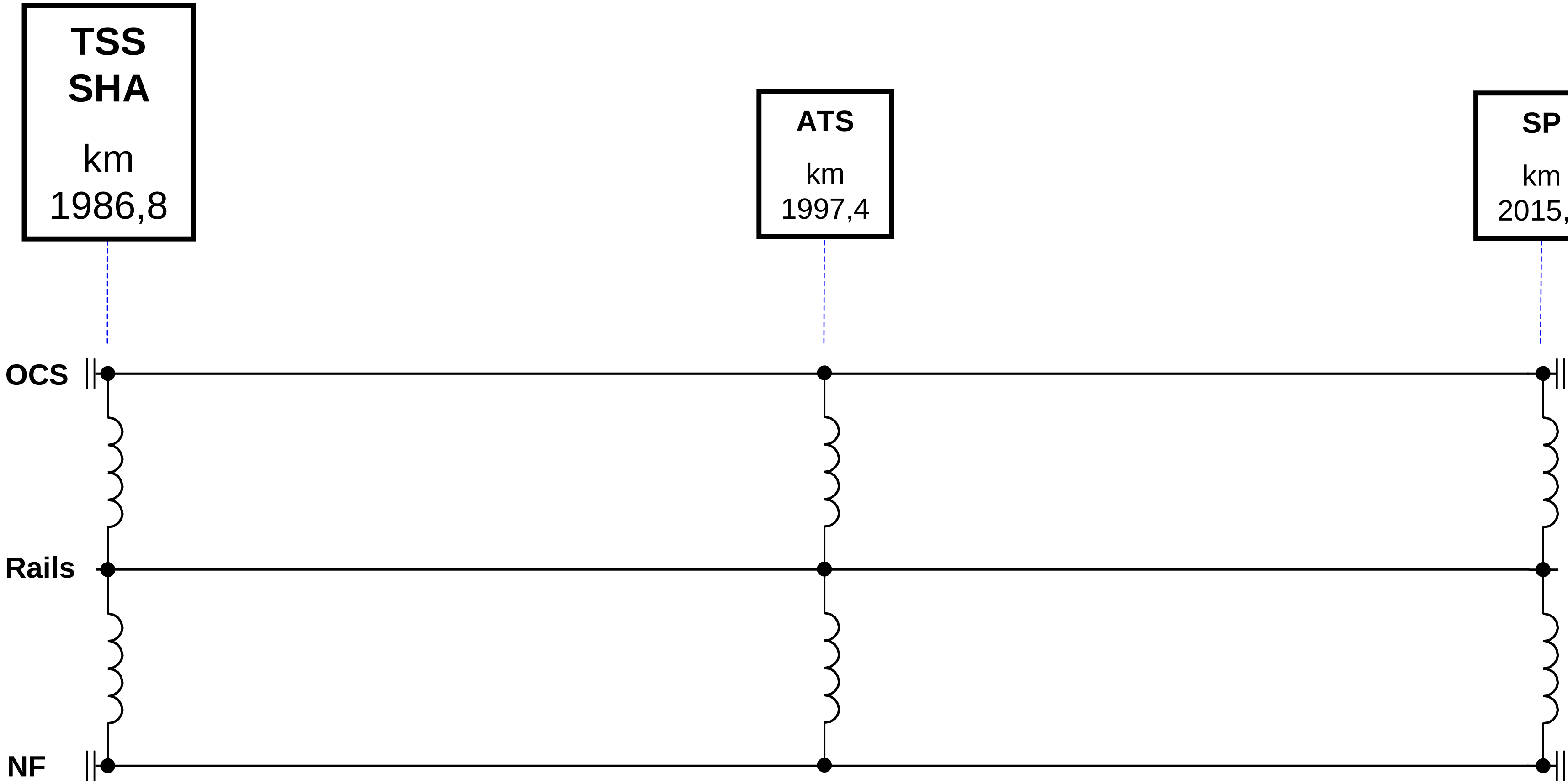

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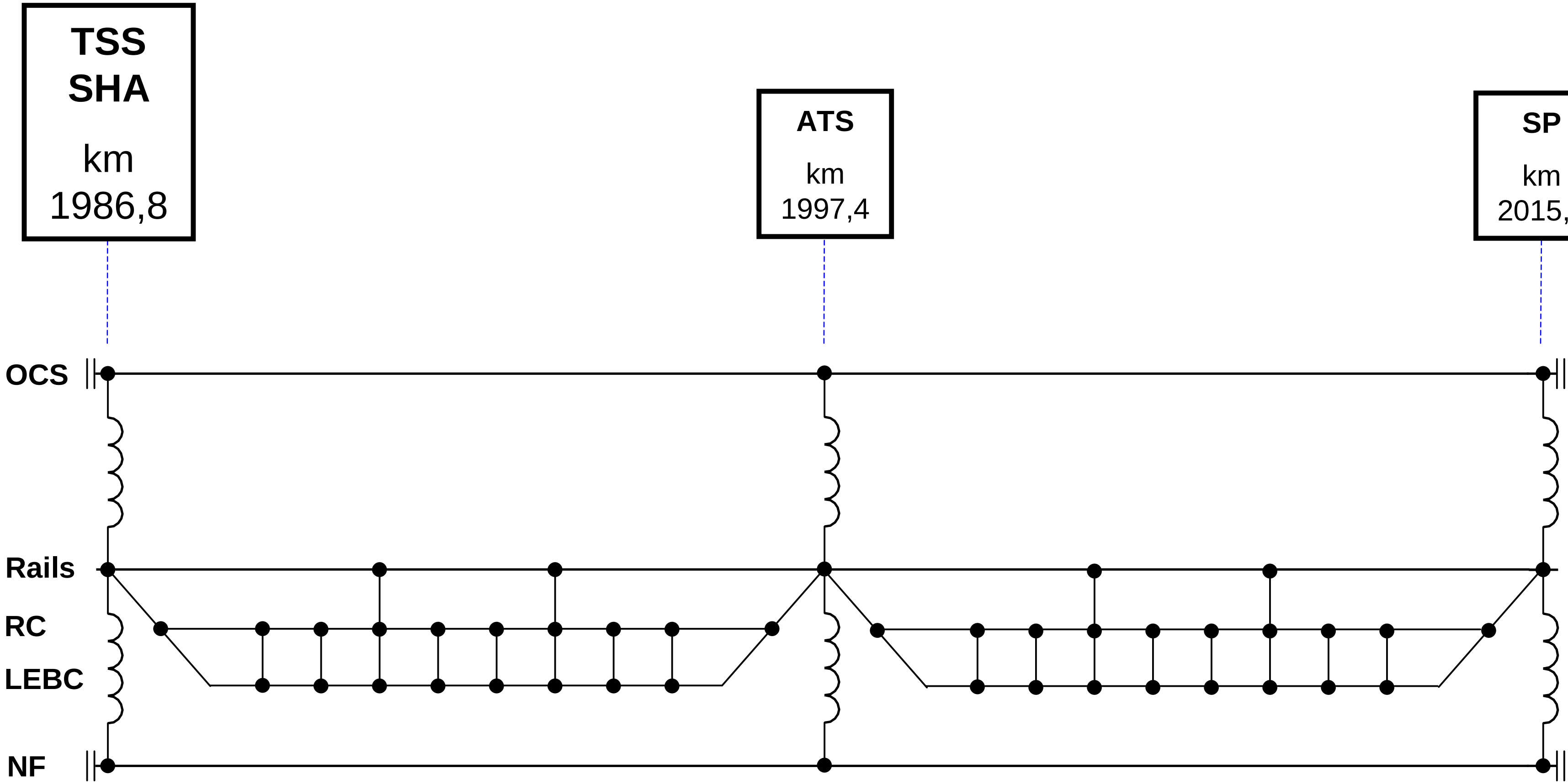

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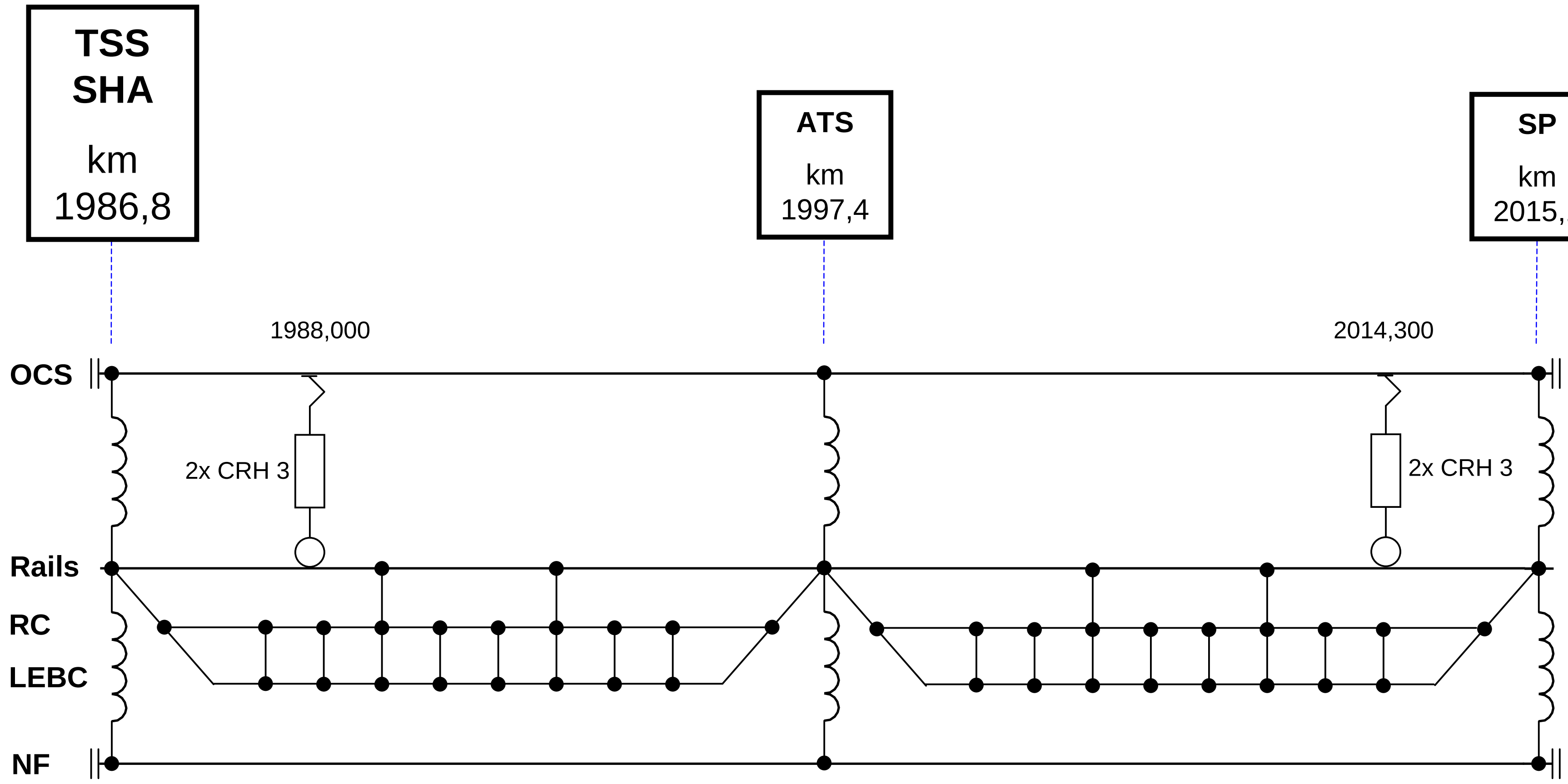

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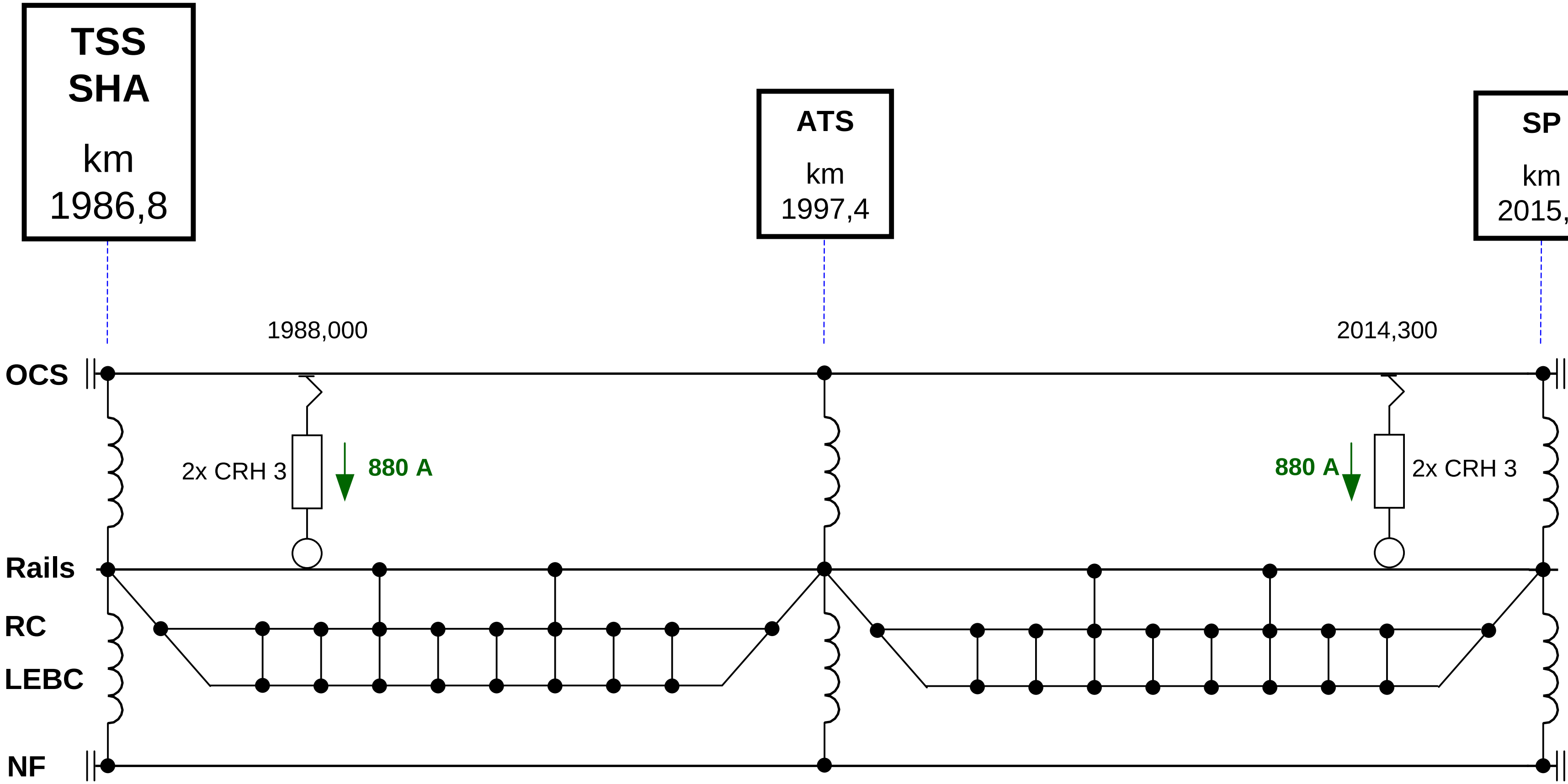

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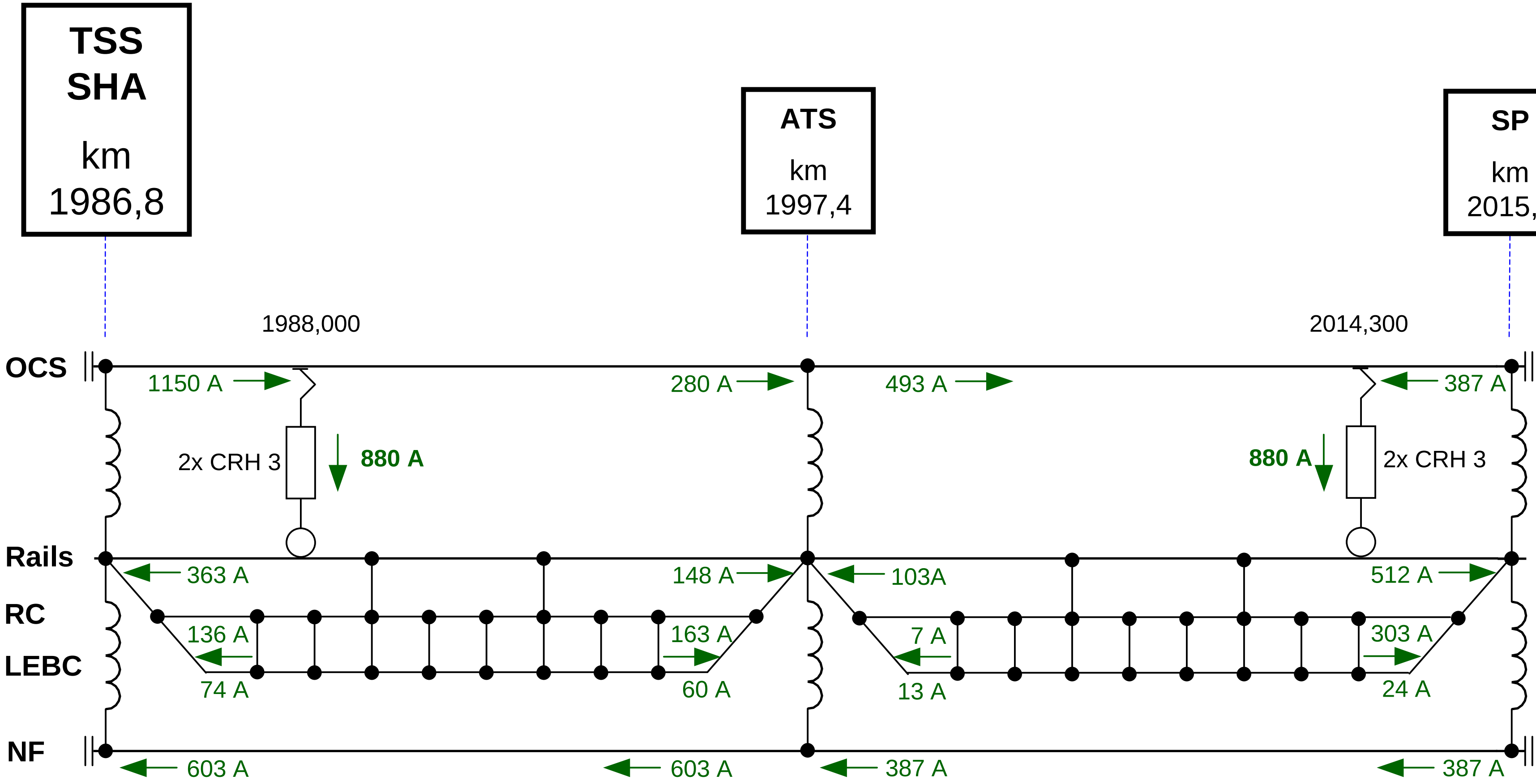

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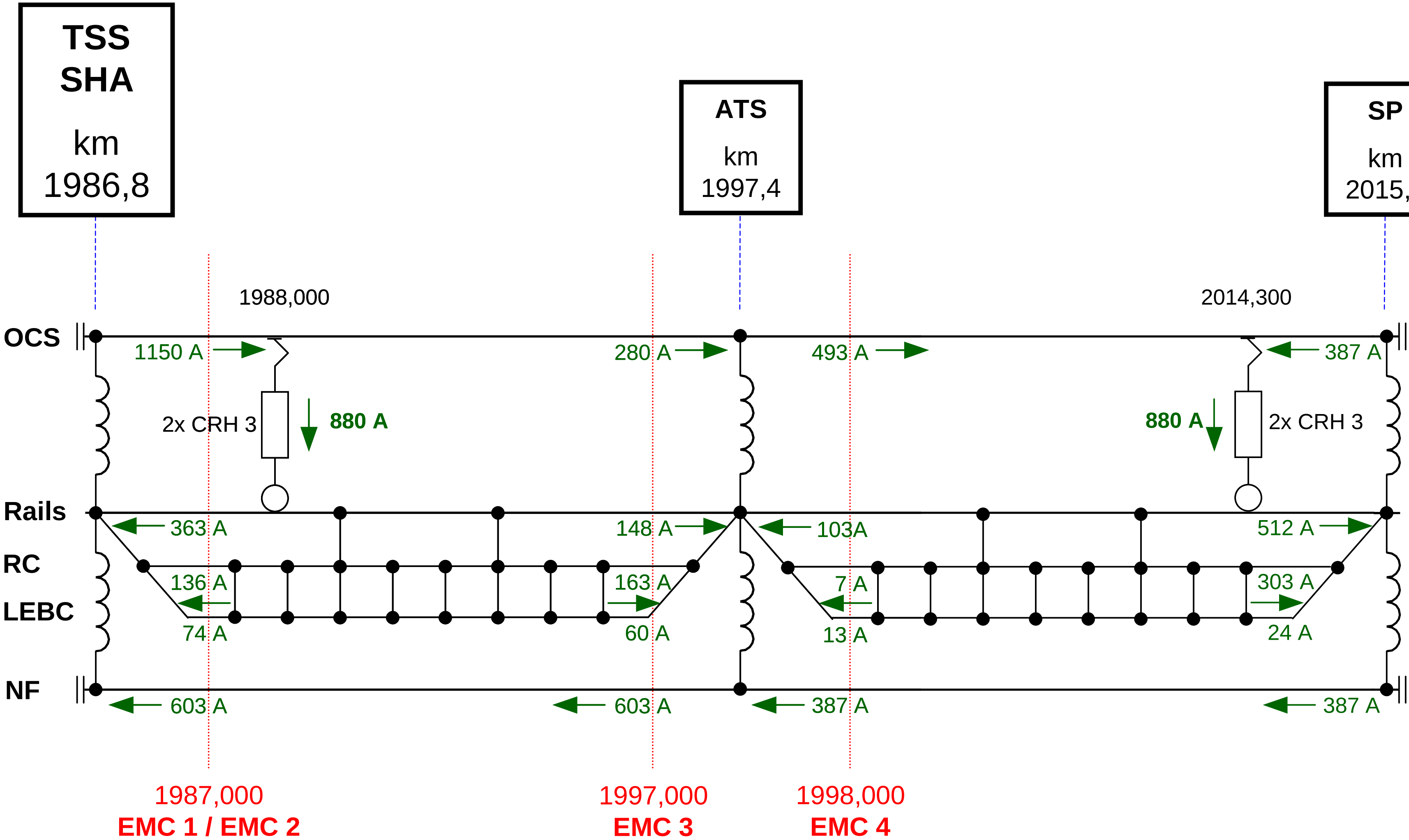
Simulation Results: High Speed Railway 2AC 25 kV



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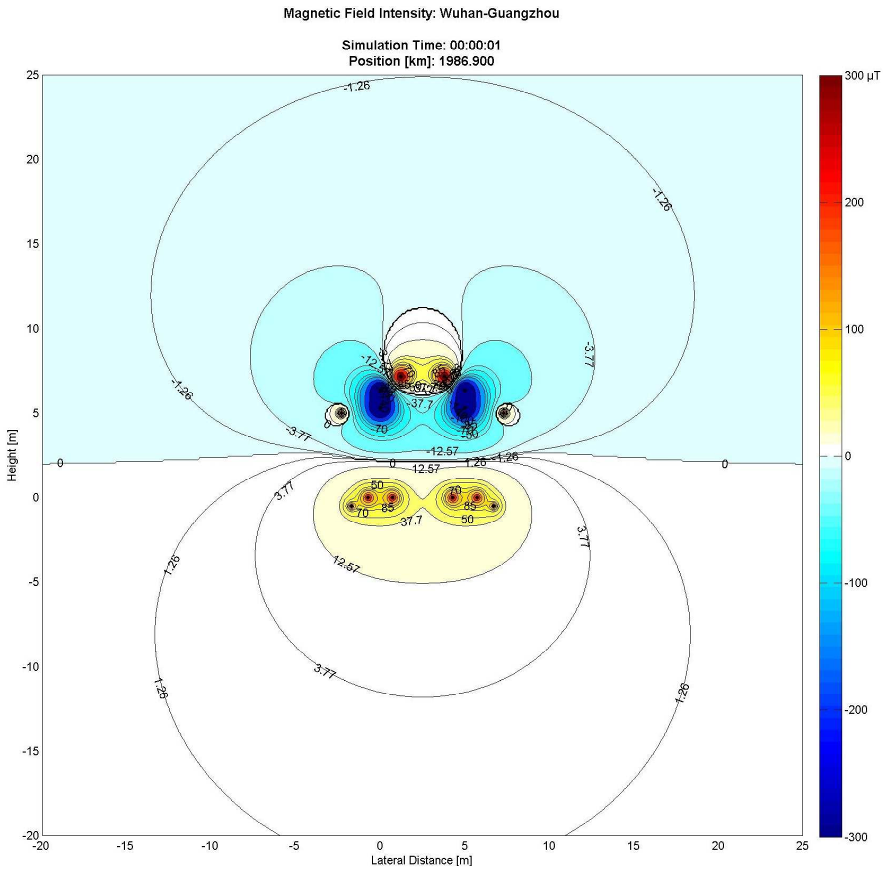
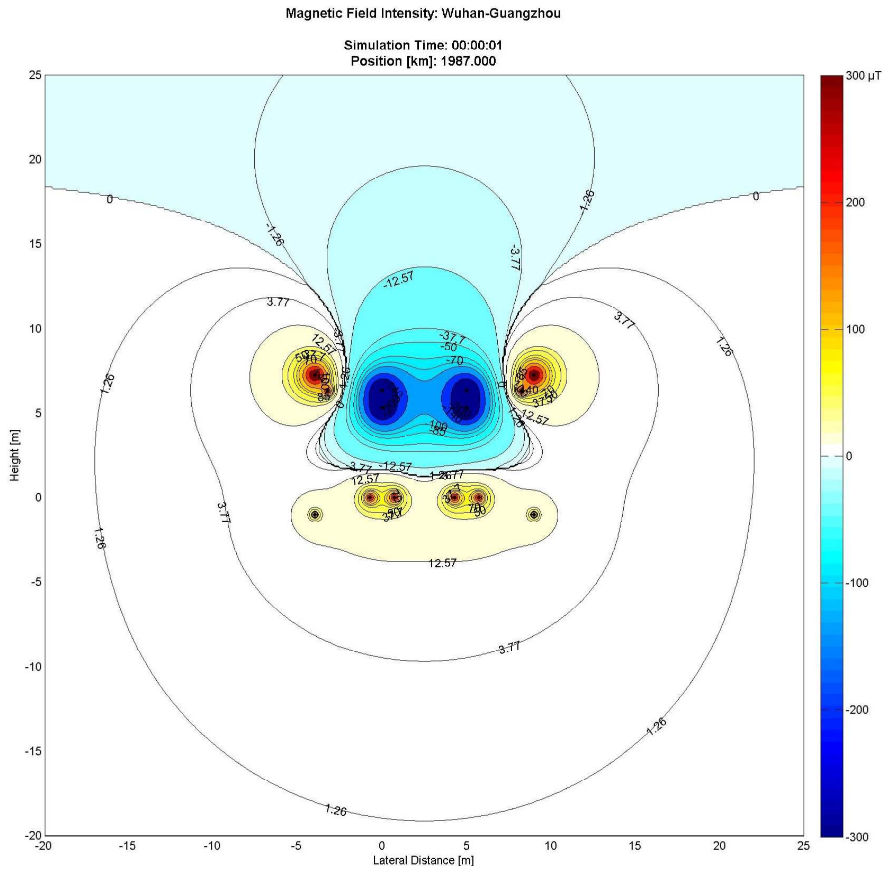


tunnel



subgrade

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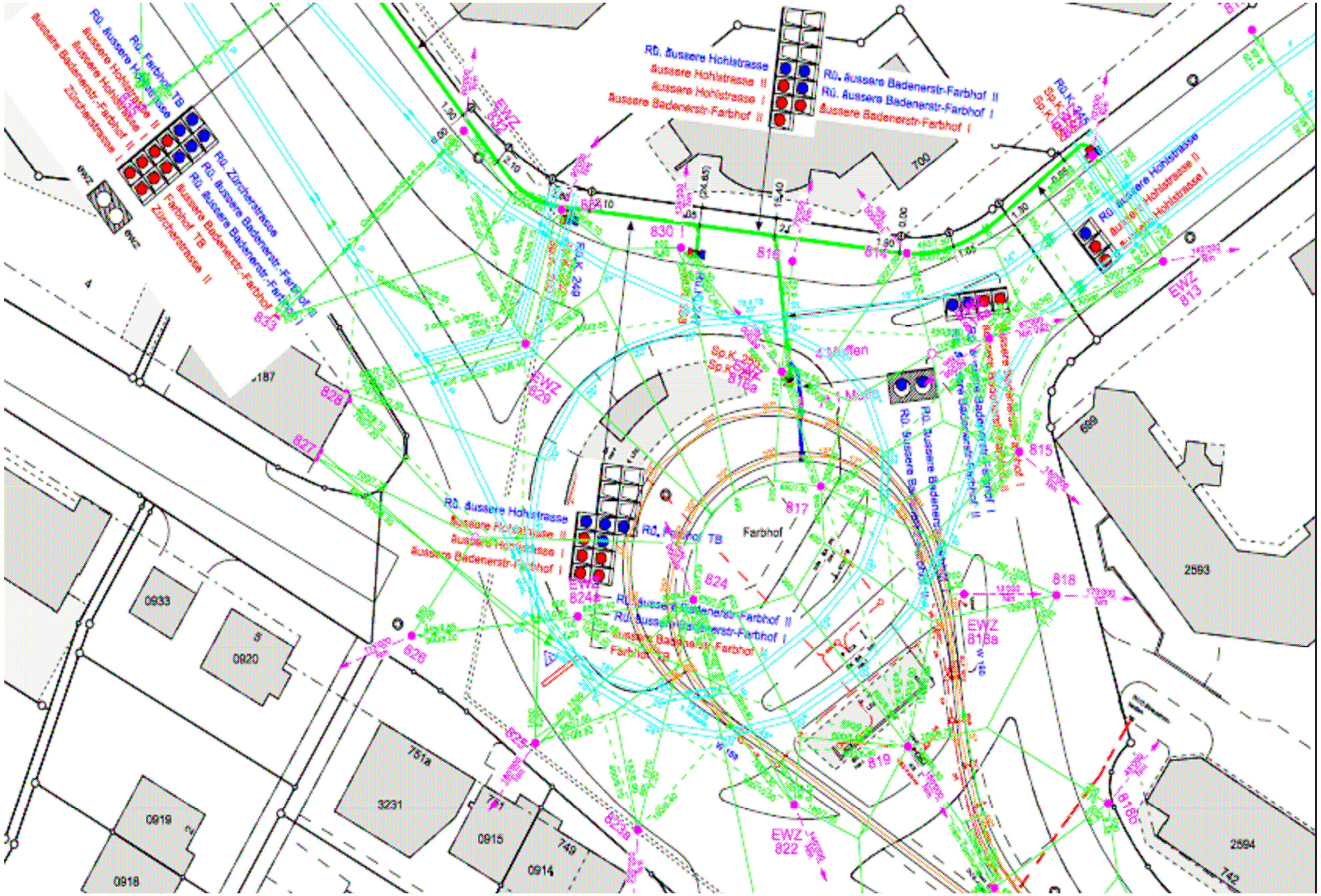
City Light Rail Network
300 km TRAM
220 km Trolleybus
DC 600 V

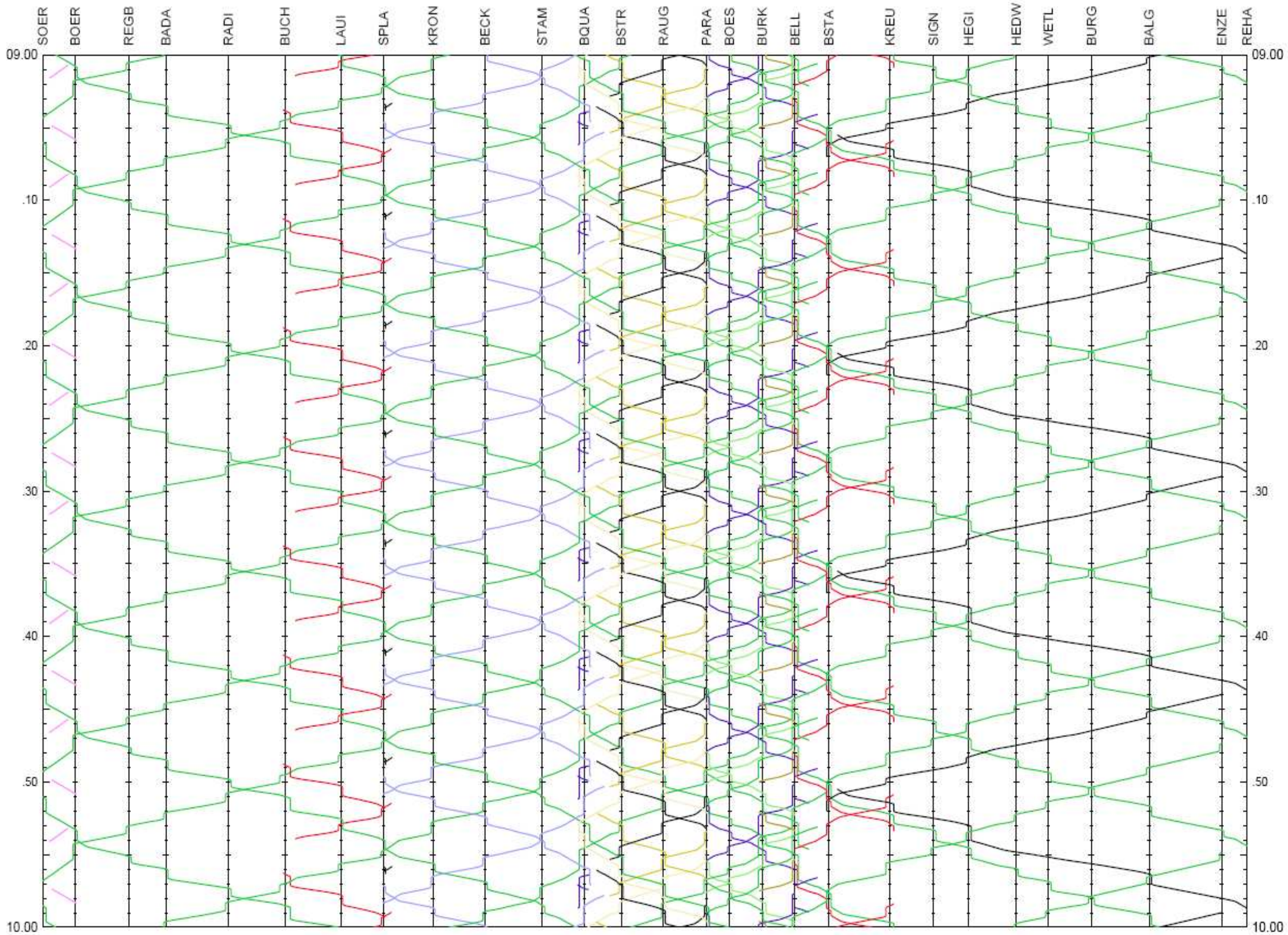
Network modelling: Catenary and cable plan detail

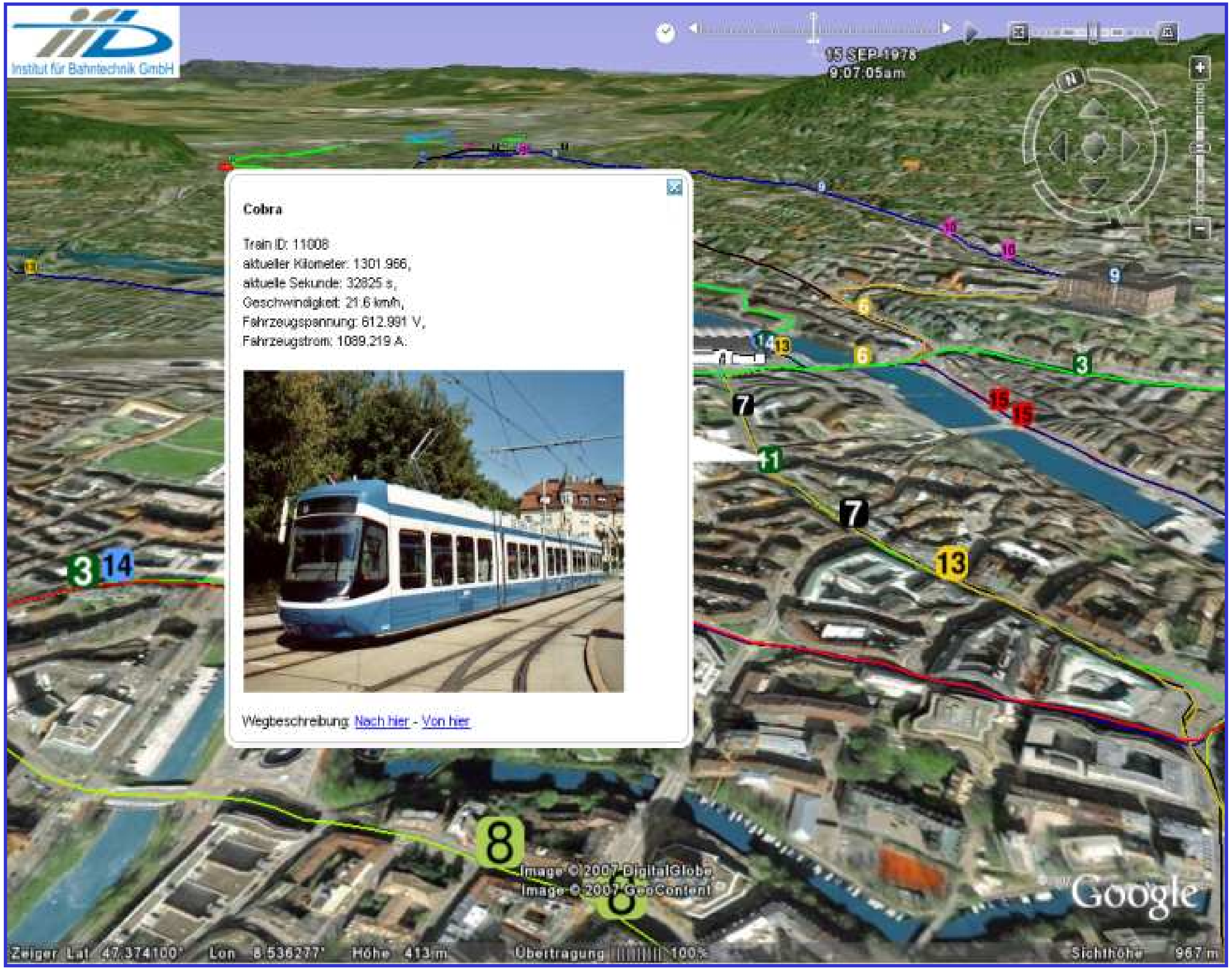


Vehicle modelling
TRAM und Trolleybus

Graphical time table

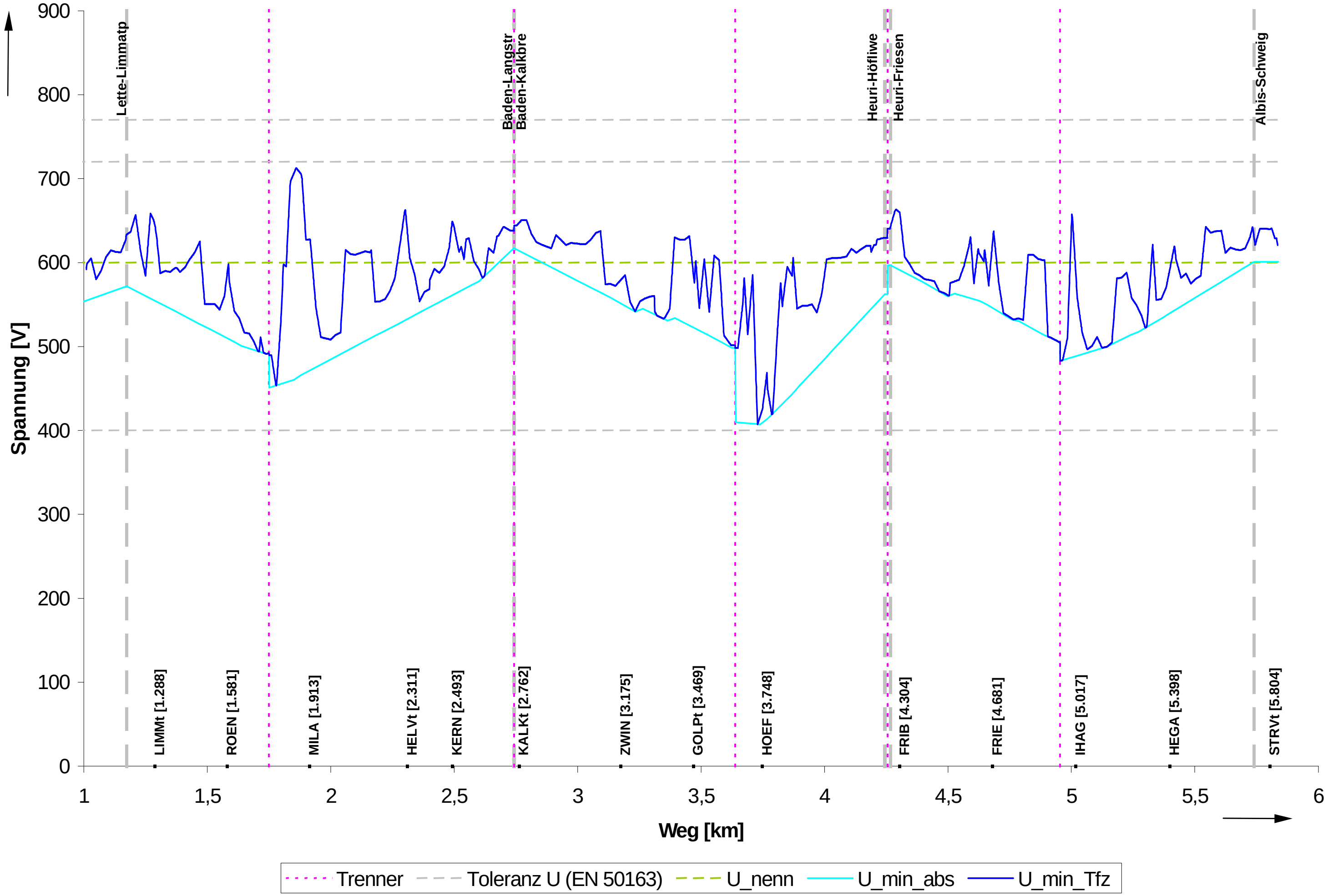
Line A




Institut für Bahntechnik GmbH
15 SEP 1978
9:07:05am
Cobra
Train ID: 11008
aktueller Kilometer: 1301.966,
aktuelle Sekunde: 32825 s,
Geschwindigkeit: 21.6 km/h,
Fahrzeugspannung: 612.991 V,
Fahrzeugstrom: 1089.219 A.
Wegbeschreibung: Nach hier - Von hier
Image © 2007 DigitalGlobe
Image © 2007 GeoContent
Google
Zeiger Lat 47.374100° Lon 8.536277° Höhe 413 m
Übertragung 100%
Sichthöhe 967 m

Minimum voltage: catenary and pantograph

Normal operation



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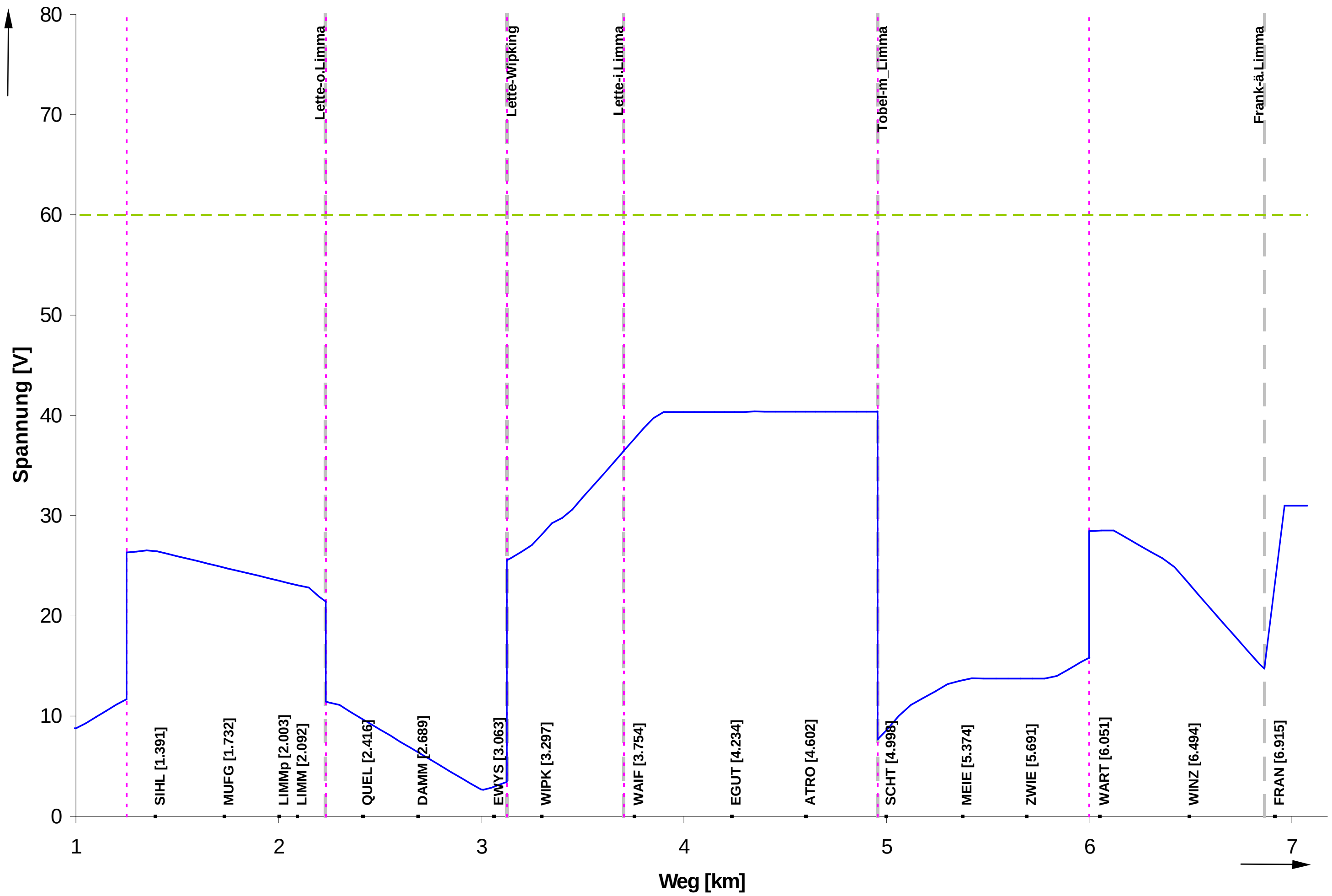
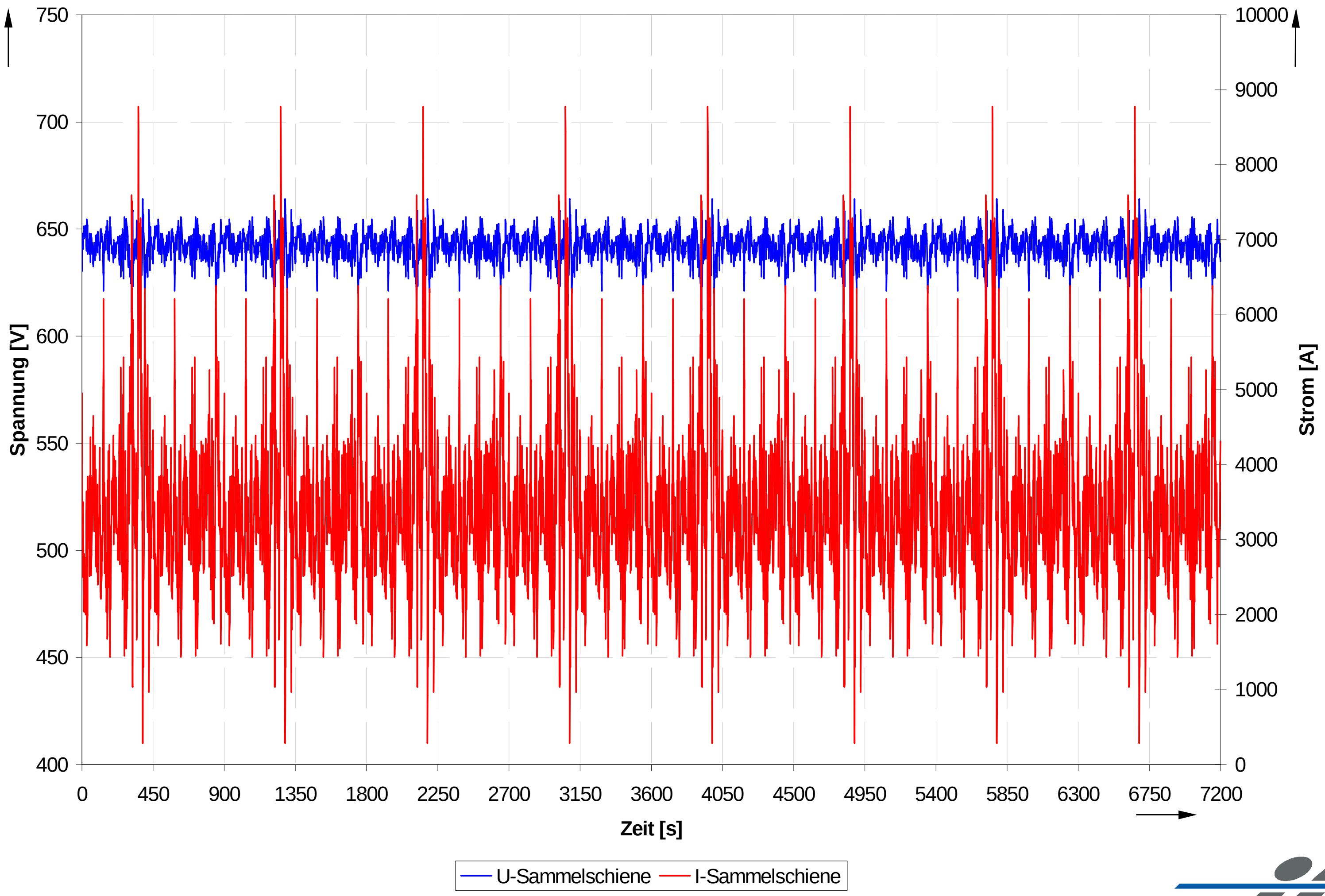
Rail-to-earth potential Normal operation



Converter current and bus-bar voltage   Normal operation



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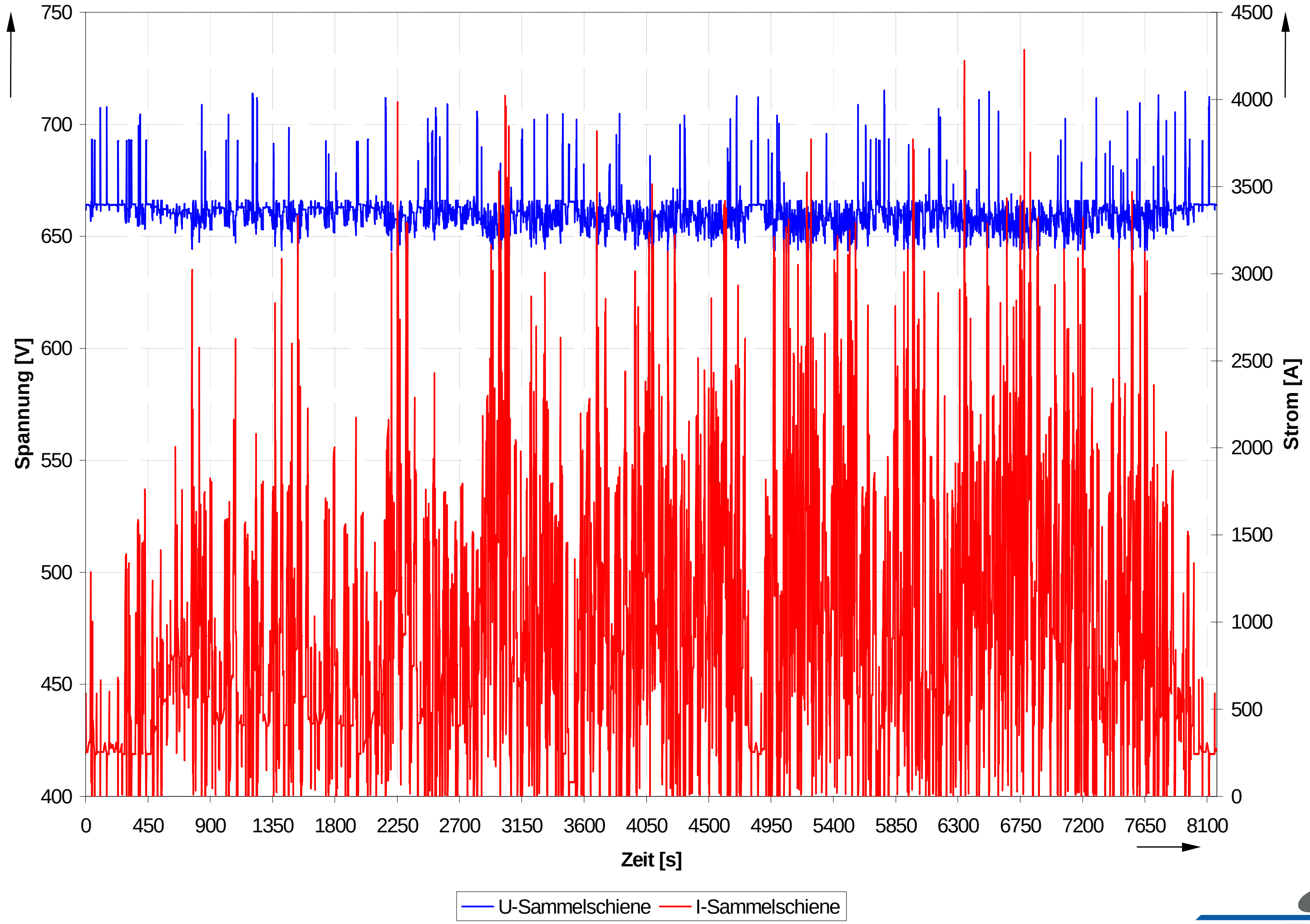
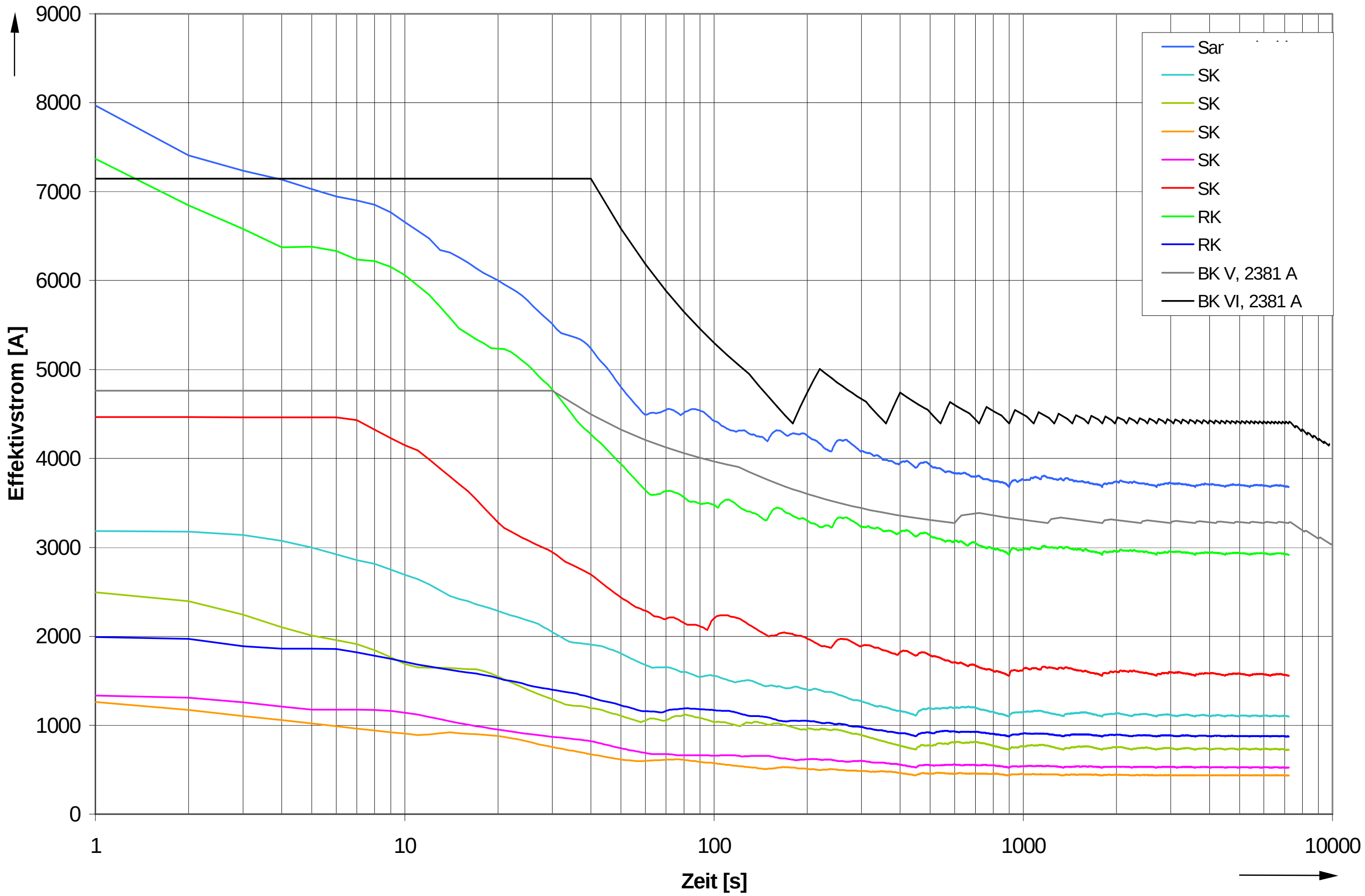
Converter current and bus-bar-voltage Depot gateway 4:50 - 7:05 h



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%
	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: Feeder cable
RK: Return current cable

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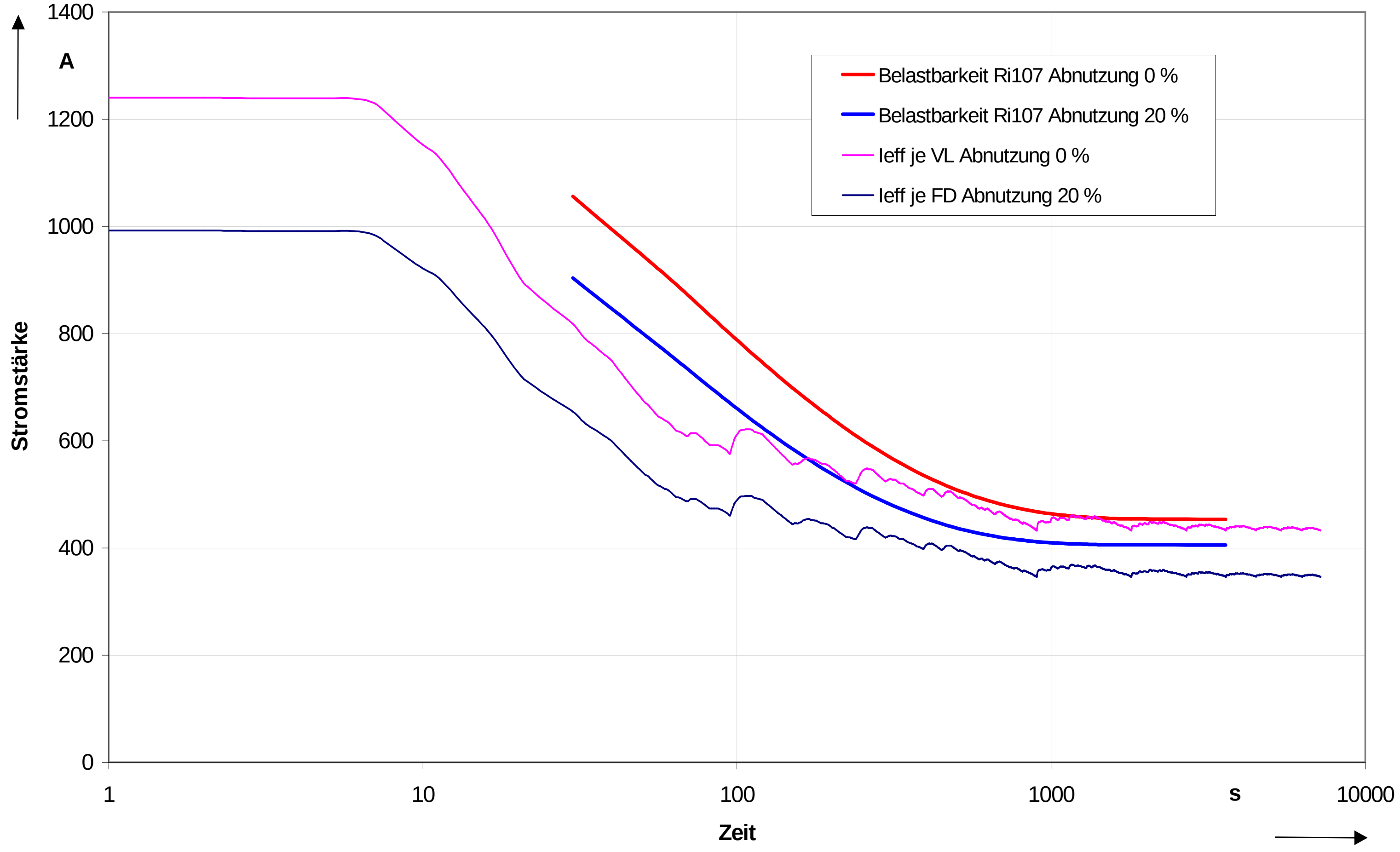
Load and loading capacity

Catenary wire at feeding point

Normal operation, blackout in neighbouring subst.



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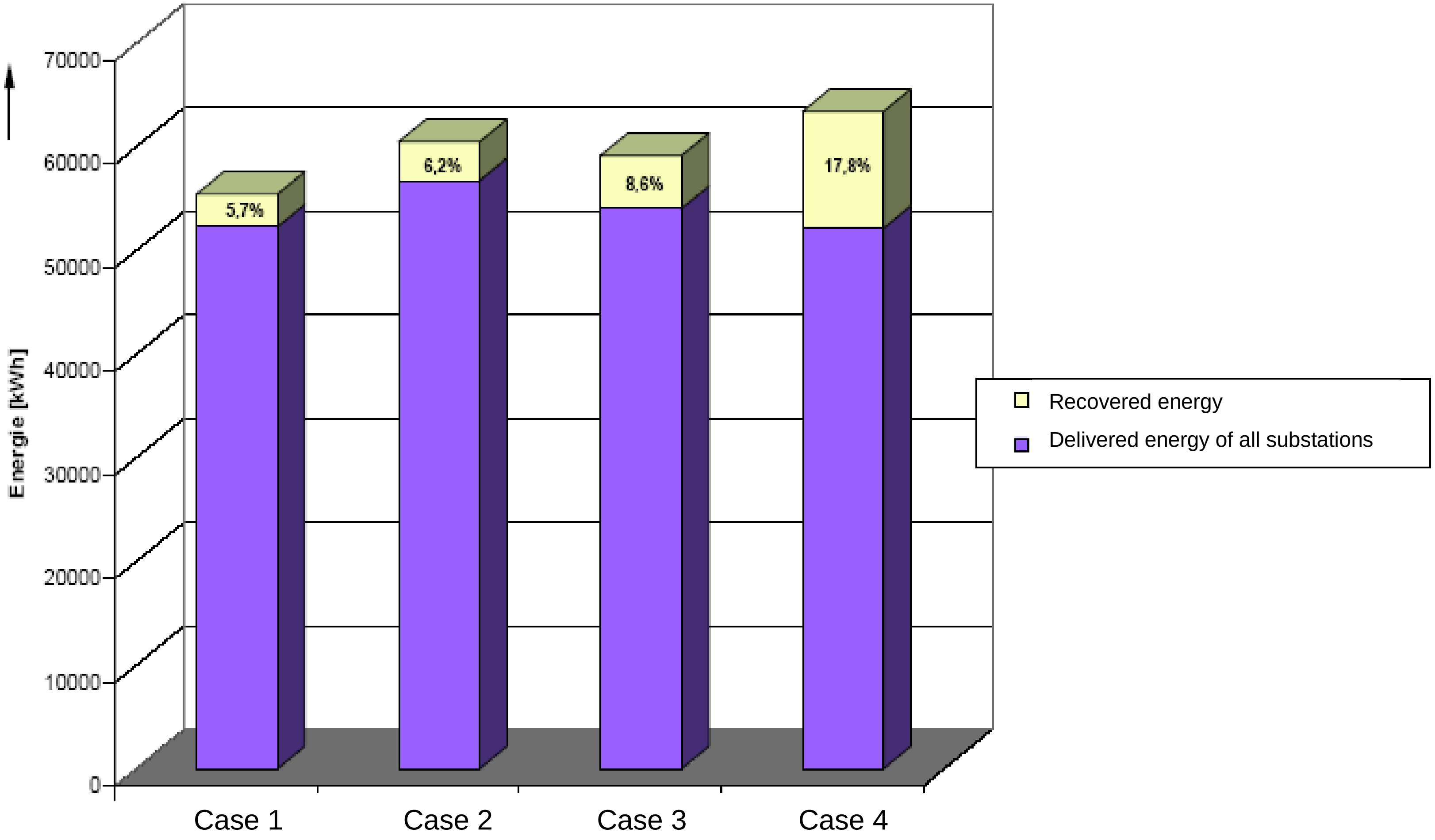
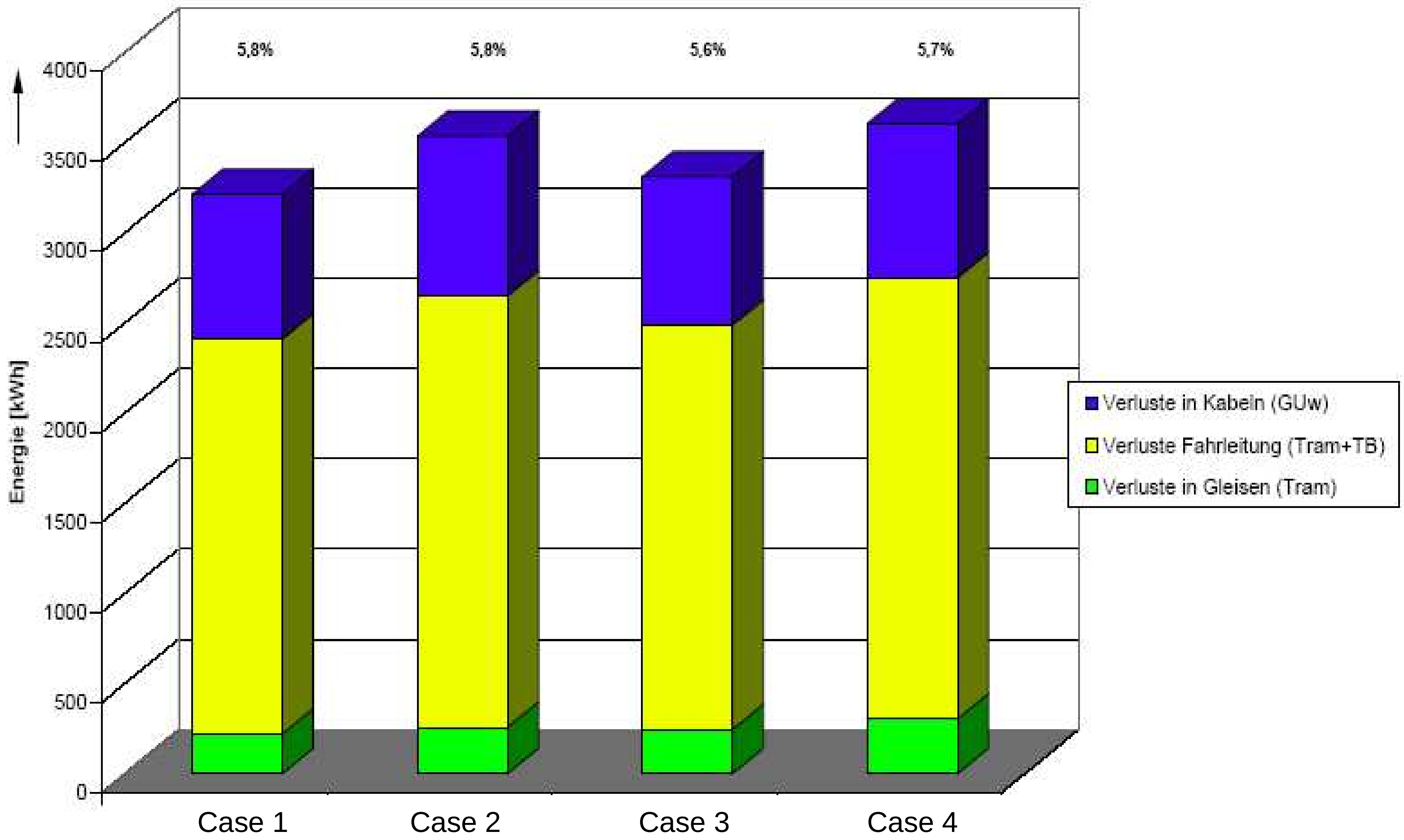
Energy balance



Power losses balance



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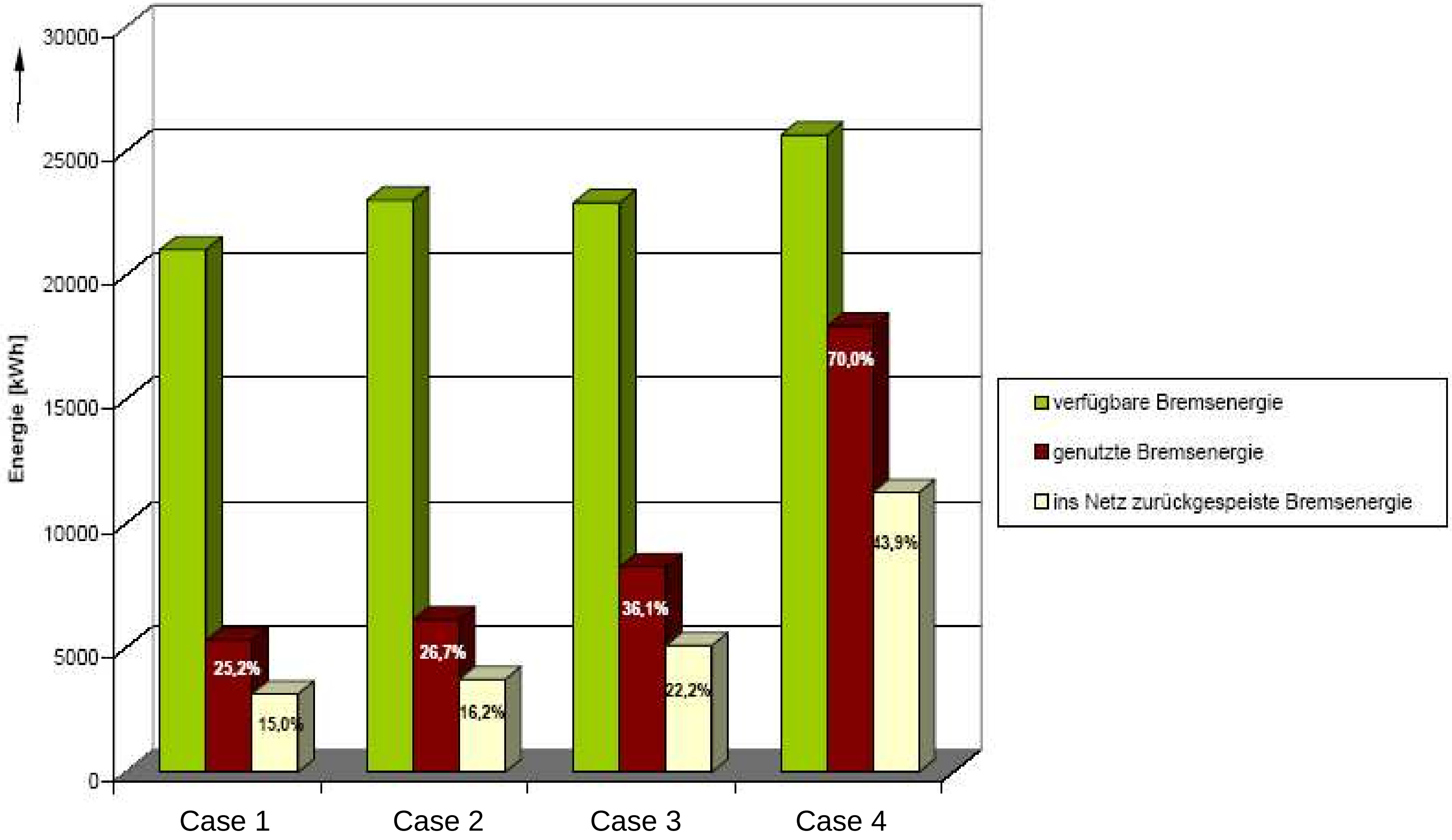
Recovering balance



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- **Simulation service can be provided including or excluding the operation modelling (… already existing models can be used easily).**
- **OpenPowerNet is intended to bring into the market after a further internal test and documentation phase.**

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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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