OpenPowerNet – Simulation of Railway Power Supply Systems

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Abstract

The energy consumption of electrical railways is mainly influenced by the driving states and the propulsion efficiency characteristics of the trains as well as by the behaviour of the traction power supply system. For this reason the idea was to create a plug-in simulation module for railway power supply networks using the advantages of an existing commercial railway operation simulator. The new developed energy simulation module called OpenPowerNet works together with the Swiss OpenTrack railway operation simulator as a so called "co-simulation". OpenPowerNet is able to simulate all common AC- and DC-railway power supply systems taking into account the entire electrical network structure. It can be used as an energy prognosis and analysis tool as well as for the planning and optimisation of power supply installations. The accuracy of the simulation was verified by a lot of realtime measurements.

Keywords: Simulation Tools, Planning, Operations Quality, Energy Management, Power Supply Systems

1 Introduction

For prognosis and analysis of railway energy consumption the use of simulation tools is state of the art today. For that purpose a considerable number of software tools with different preciseness is available. But the modern software technology offers new possibilities to improve the simulation.

The electrical load flow within railway power supply networks and the train energy consumption depend both on the running trains and the power supply system characteristics. In contrast to public energy distribution systems there are moving energy consumers with a time-dependent power demand picking up and recovering energy at changing locations. The network structure and the voltage situation influence the internal load flows because:

- currents and power losses increase with decreasing voltages,
- under low voltage conditions current or power limitations of the train propulsion control can be activated with impact on the driving dynamics,
- the network voltage determines the braking energy recovering decisively.

Thus the power supply system may influence the traction characteristics of the trains and the railway energy consumption.

The simulation of these dynamic processes allows the analysis and prognosis of load flows and energy consumption as well as the design and rating verification of the electrical installations. However a realistic prognosis by simulation requires detailed information about the present power consumption, the actual position of the trains and the capability of the power supply network available simultaneously. Therefore a series of compromises either concerning the railway operation simulation or the electrical network modelling depth were made in the past. For this reason the idea was to create a plug-in simulation module for railway power supply networks using the advantages of an existing commercial railway operation simulator.

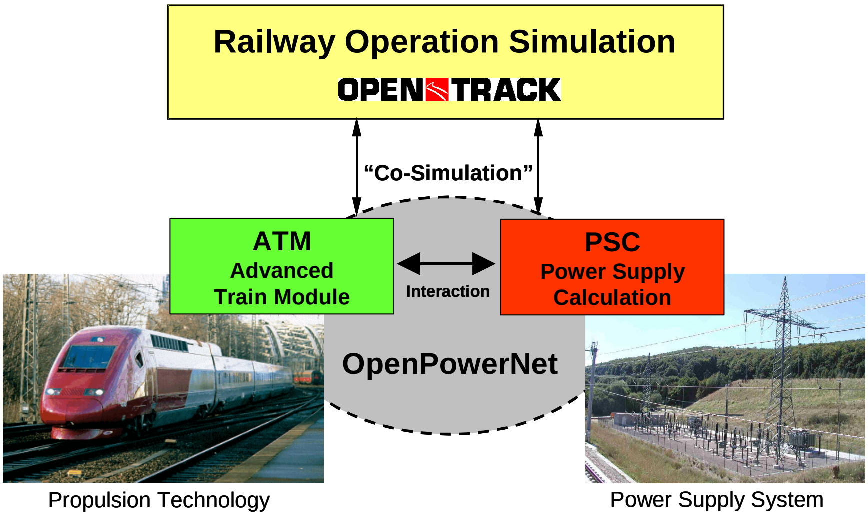


Figure 1-1 Co-simulation of railway operation and electrical network

2 General Requirements

The new electrical network simulation module called **OpenPowerNet** was designed by IFB to enable a so called "co-simulation" with the Swiss **OpenTrack** railway operation simulator (Figure 1-1). Each program should have its clearly delimited task. OpenTrack deals with the timetable-based train operation simulation using the infrastructure and train data. OpenPowerNet shall simulate in sync the entire electrical network taking into account the networks voltage situation depending on the train's power consumption and position. All retroactive effects to be considered exactly. OpenPowerNet should be able to simulate all common AC- and DC-railway power supply systems taking into account the entire electrical network structure. Furthermore different levels for the train propulsion modelling should be available. Various post-processing tools should enable multiplex data analyses.

3 Design and Functionalities

3.1 Primary Software Structure

OpenPowerNet itself consists of two modules:

- the "Advanced Train Module" (ATM) modelling the propulsion technology of the trains in detail and
- the "Power Supply Calculation" (PSC) for the electrical network calculation.

During the simulation run time both modules are coordinated with the OpenTrack railway operation simulation using a so called APServer. It is responsible for the data transfer between the single modules and the connected data bases of the network and propulsion data (Figure 3-1).

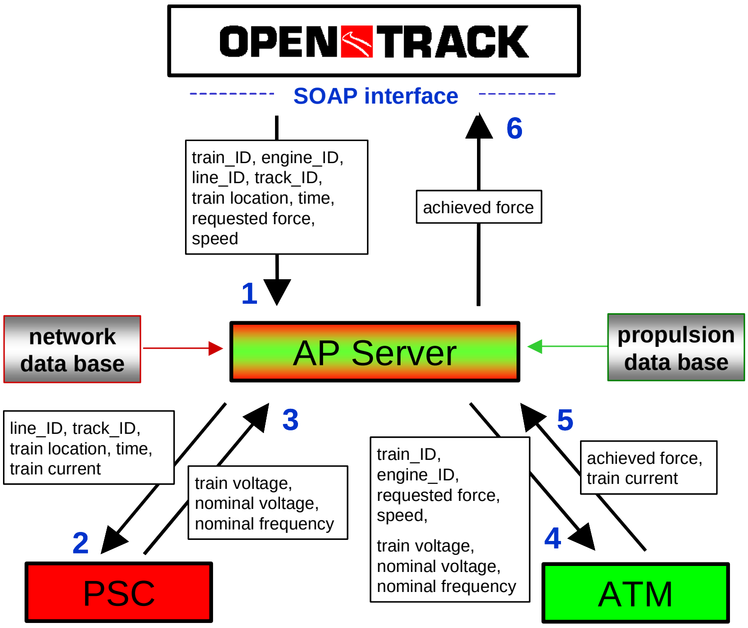


Figure 3-1 Simulation steps and data transfer

OpenPowerNet is working on a time step basis synchronised to OpenTrack. In the following the simulation procedure within one time step is explained: To calculate the train driving dynamics OpenTrack normally uses the tractive effort characteristics of its own database. Connected with the OpenPowerNet simulator OpenTrack stops at this point and sends a calculation request to the connected electrical network and propulsion simulation. Therefore all needed information as train_ID, engine_ID, line_ID, track_ID, present train location, speed and simulation time are transferred to OpenPowerNet. The AP Server ensures that the corresponding electrical loads of the trains are interpolated at the right positions of the electrical network (mileage, track). During the network calculation it controls the iteration processes between the ATM and PSC modules and delivers the results to the data base as well as back to OpenTrack.

Respecting the train positions obtained from OpenTrack the electric power data of the trains are transferred to the PSC. Considering all electrical train loads of the previous time step the PSC at first delivers an initial network voltage distribution. Following the predefined pantograph voltages of the trains are transferred to the ATM. Therewith the propulsion calculation reflecting all properties and limiting values is performed resulting in torques, revs, tractive forces and train currents. Afterwards these current values are transferred back to the PSC network calculation and the calculation cycle is repeated until an iteration limit is fallen short of. Lastly the achieved tractive force reflecting the propulsion capacity under the real voltage conditions is transferred back to the railway operation simulation. OpenTrack now continues its operation simulation using the results of OpenPowerNet. Thus the influence of the electrical processes on the railway operation is modelled exactly. Additionally all power supply network and energy consumption data are available for further evaluation.

The communication between OpenTrack and OpenPowerNet is realised via a SOAP (Simple Object Access Protocol) interface using XML-based data descriptions and TCP/IP protocols. Normally both software systems should run on the same hardware simultaneously due to performance criteria, but it is also possible to run the simulations in parallel on different computers connected via Internet. The data transfer between the modules is organised utilising the RailML standard.

3.2 ATM - Advanced Train Module

The Advanced Train Module (ATM) was integrated into OpenPowerNet in order to simulate the propulsion system behaviour of the trains depending on the networks voltage situation. It offers a more detailed modelling as it is implemented in the railway operation simulation. Thus the propulsion characteristics resulting from the ATM calculation have top priority. Besides the propulsion characteristic simulation the ATM also controls the energy recovering management during braking processes considering the energy absorption capability of the power supply network.

Within the ATM there are 4 modelling levels available for the propulsion simulation:

1) constant efficiency factors for the entire propulsion equipment,
2) driving state related efficiency factors,
3) load depending efficiency factors of single components,
4) detailed mathematical engine models of components.

Additionally the auxiliary and the eddy current break power consumption can be considered as fixed values or time functions respectively. Furthermore any limiting values of the propulsion control (e.g. voltage related current or power limitations) are implemented. The component structure of the ATM is shown in Figure 3-2 for an AC powered train.

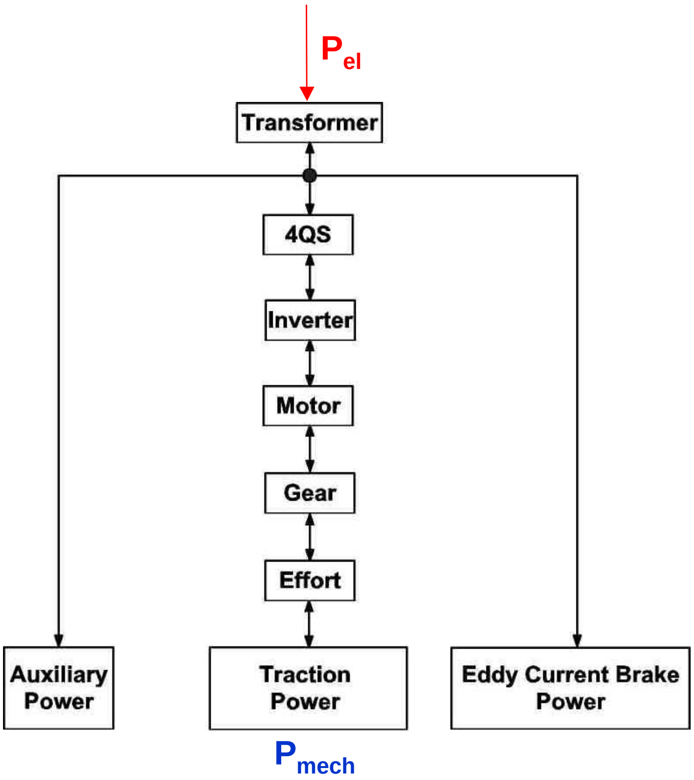


Figure 3-2 Arrangement of the propulsion system components for the ATM

The propulsion simulation was verified by a lot of comparison measurements. As an example Figure 3-3 shows the pantograph voltage and the current characteristics of a high speed train accelerating up to 300 kph, persisting at the maximum speed and braking to zero again. It is clearly visible how the network voltage is influenced by the train's power depending on its position. On the other hand the decreasing network voltage increases the current level. During the braking phase the voltage is raised due to the energy recovering. (Further simulation and measurement examples will be shown in the conference presentation.)

Using the existing data interfaces the ATM could be replaced in the future by an origin train propulsion control unit enabling a so-called “hardware in the loop” simulation. This would offer the possibility to use a common railway operation simulator for equipment test laboratories dealing with realistic railway line simulations.

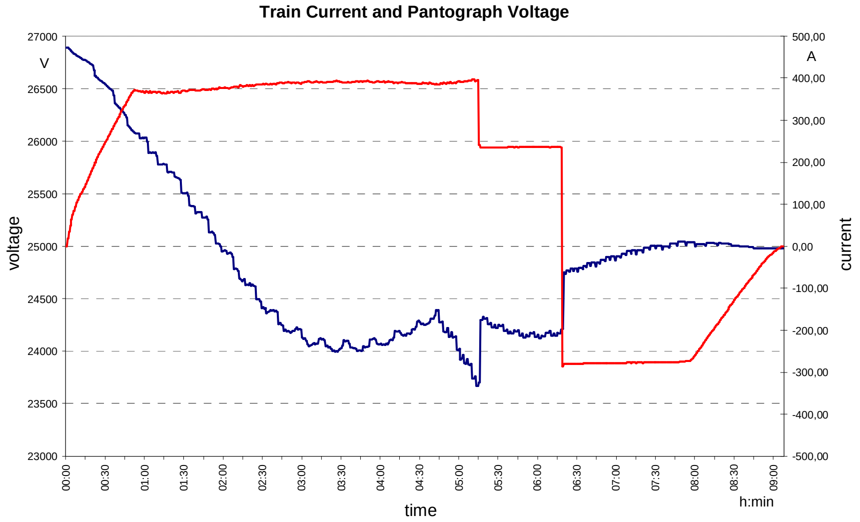


Figure 3-3 Propulsion model verification

3.3 PSC – Power Supply Calculation

Regarding conventional task formulations for power supply network simulations the following development requirements to the PSC module were set up:

- simulation of all common AC and DC railway power supply systems,
- representation of the entire electrical network structure,
- unrestricted configuration of longitudinal conductors along the line,
- precise consideration of the electromagnetic coupling effects between the longitudinal conductors within single phase AC systems,
- switch status changes of the railway power supply system during the simulation run,
- retroaction to the railway operation simulation (OpenTrack),
- iterative communication with the propulsion simulation (ATM),
- configurable data output,
- interfaces to professional post-processing tools like MATLAB or EXCEL.

Figure 3-4 shows the universal power supply network structure for a DC 0.6 kV system, Figure 3-5 gives an example for an AC 2 x 25 kV 50/60 Hz railway power supply. The modelling of the electrical network structure (i.e. feeding sections, feeding points, connecting points, switch status) must be in congruence to the track topology of the railway operation simulation. Therefore a uniform mileage as well as a coordinated line_ID and track_ID declaration is to apply. Respecting this basic approach the following data have to be implemented:

- electrical properties of the feeding power grid,
- electrical characteristics of the substations (transformers, converters, switchgears),

- electrical characteristics of the installed conductors (cables, catenary wires, tracks, rails),
- electrical characteristics rail-to-earth,
- modelling of additional power consumers (e.g. switch heatings, depot loads),
- loading capacities (cables, wires, converters, transformers),
- protection settings.

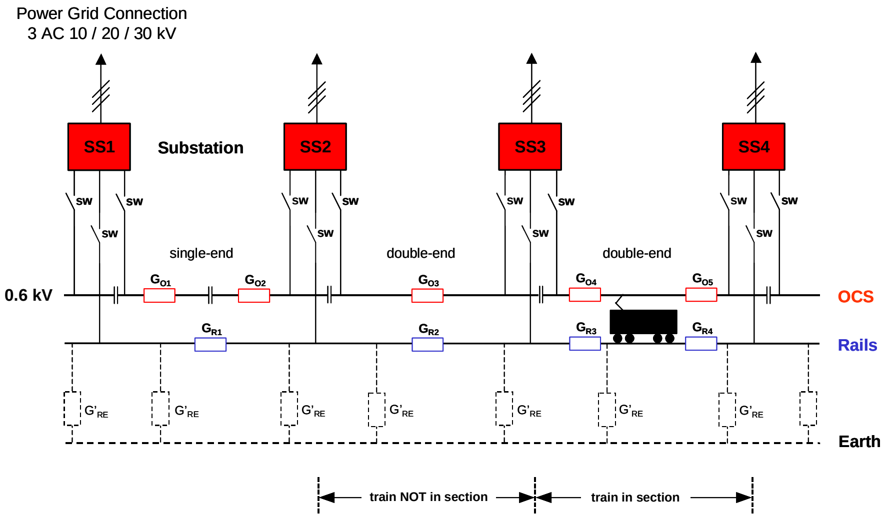


Figure 3-4 Power supply network structure (DC 0,6 kV)

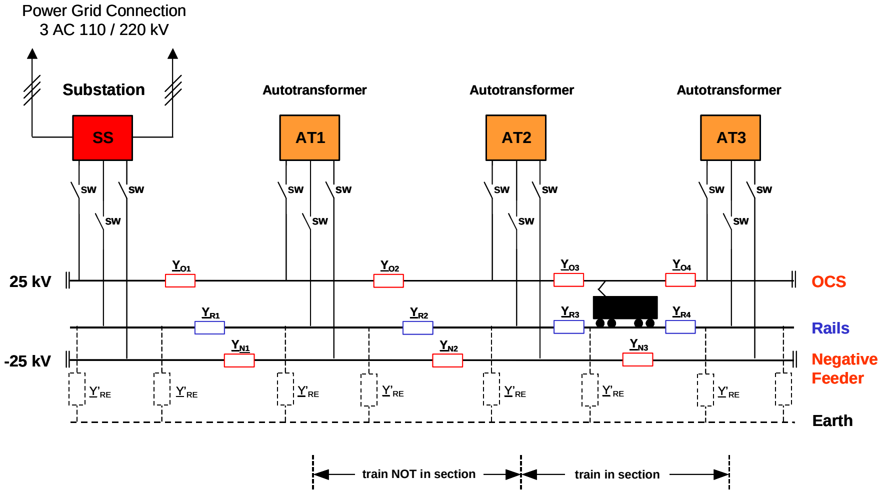


Figure 3-5 Power supply network structure (AC 2 x 25 kV 50/60 Hz)

The modelling of the overhead catenary and return current system (Figure 3-6) is realised by a sequence of slices representing only the geometric conductor arrangement and the material properties (Figure 3-7). Thus an arbitrary number of longitudinal conductors can be modelled. Based on the conductor's positions and the current direction the electromagnetic coupling effects and their impact on the current distribution of the single conductors within AC systems is considered.

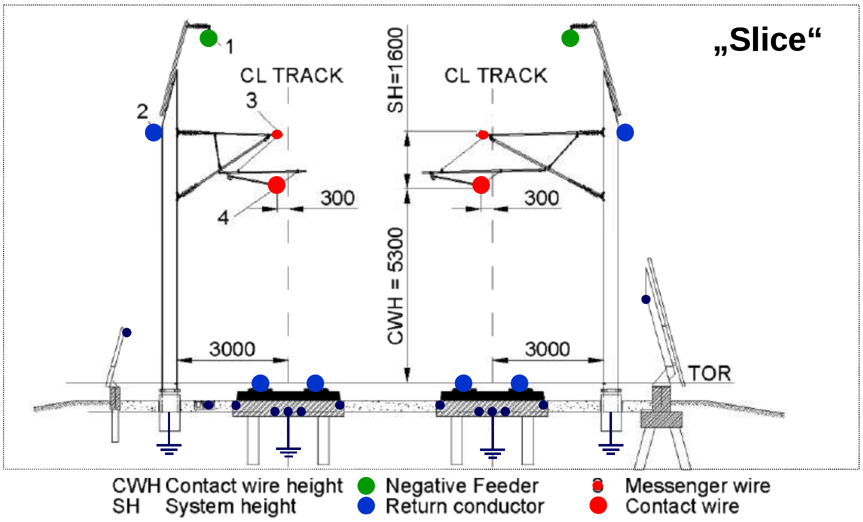


Figure 3-6 Arrangement of conductors of the overhead catenary system

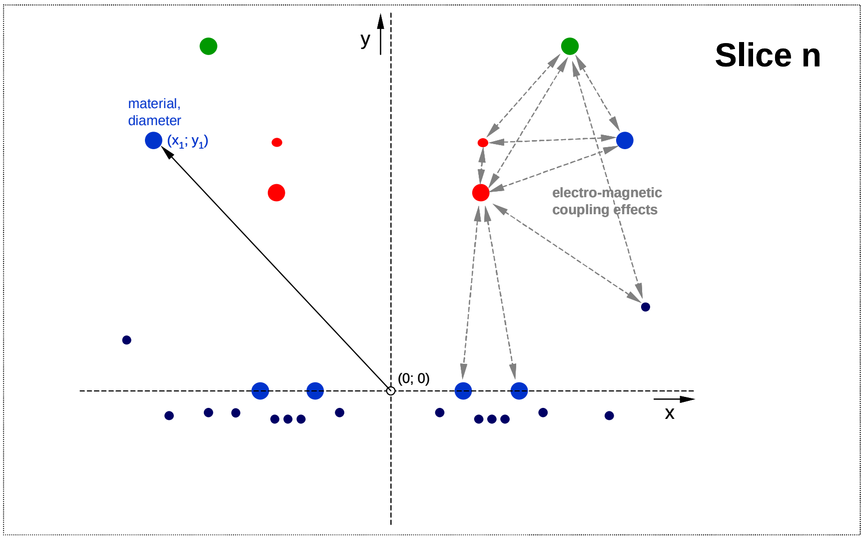
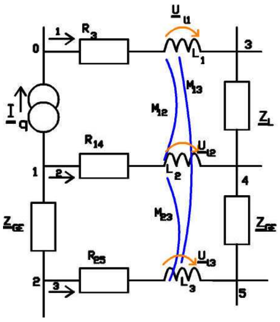


Figure 3-7 Geometric conductor model for the overhead catenary system

Due to the excessive geometrical arrangement description there is no need for any impedance determination in advance. For the electrical network calculation the well known method of nodes is applied using an automated matrix and vector description. However there is a special extension of this method considering the voltage drops caused by self- and mutual induction by a new mathematic procedure (for AC systems only). Using transformation matrices for the inductive voltages the electromagnetic coupling is implemented without the need of an iteration. Thus both the computing time and the result inaccuracy could be decreased.



Electrical network calculation using the advanced method of nodes

$$[\underline{Y}]_{(v,v)}(\underline{U}_{v0})_{(v,1)} - [\underline{Y}_2]_{(v,LL)}(\underline{U}_L)_{(LL,1)} = (\underline{I}_q)_{(v,1)}$$

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

Figure 3-8 Electrical network calculation principles applied in OpenPowerNet

The verification of the PSC was done at first by a large number of punctual theoretical tests as

- current sum zero for single network slices,
- energy picking up and recovering balances,
- correspondence of voltage minima / maxima and jumps respectively with the network structure during constant load test.

Additionally the simulation results were compared with network measurement data of predefined load cases from tramway and trolleybus networks as well as from high speed railway lines. As evaluation criteria the driving dynamics of the trains, the current-, voltage- and power characteristics were utilised. The differences ascertained by comparison of simulation results and measurement data were less than 3 %. (Some examples will be shown in the conference presentation.)

4 Commercial Application

4.1 Intentions and Advantages

The railway power supply simulator OpenPowerNet superimposing on the railway operation simulation tool OpenTrack can be used as an energy prognosis and analysis tool as well as for design and optimisation tasks of power supply installations. The outstanding advantage of the co-simulation is the separation of the different simulations tasks. From the software provider's view this allows an independent development and maintenance strategy for both software tools respecting only the interface specification. Each side can focus on the improvement of its own very specialised tasks. But also from the user's view the presented solution offers respectable advantages: The railway power supply simulation requires a network modelling with a very high complexity. Therefore the set up of an executable operation simulation at first without the complex electrical network is a solid basis. After that the electrical simulation can be added step by step. Thus the fault probabilities are minimised.

Meanwhile a lot of railway and tram operators use operation simulation tools like OpenTack for planning and analysis tasks in their daily business. However the electrical network simulation is restricted to very special problem cases because of the extensive modelling effort. Besides mostly a department different from the operation planning team is responsible for the electrical issues. Applying conventional power supply network simulators in each case the railway operation simulation must be set up once again. Using OpenPowerNet the already existing railway operation models of OpenTrack as track alignment, signalling structure, train and engine library or time table can be easily adopted. The modelling process can be concentrated on the electrical issues exclusively. This saves time and costs.

4.2 Simulation Examples

4.2.1 High Speed Railways with AC Power Supply

On the new High Speed Line Zuid in the Netherlands the OpenPowerNet simulator is intended to apply for the commercial train energy billing of different train operators. Based on the present timetables and the used train types (Figure 4-1) the energy consumption of all trains including the electrical network losses is simulated and partitioned to the train operating companies on substation level (Figure 4-2). The simulation results for the failure-free operation are the basis for the monthly energy cost accounting. Thus extensive measurements onboard the trains of different train operators and a voluminous data transfers is not necessary.

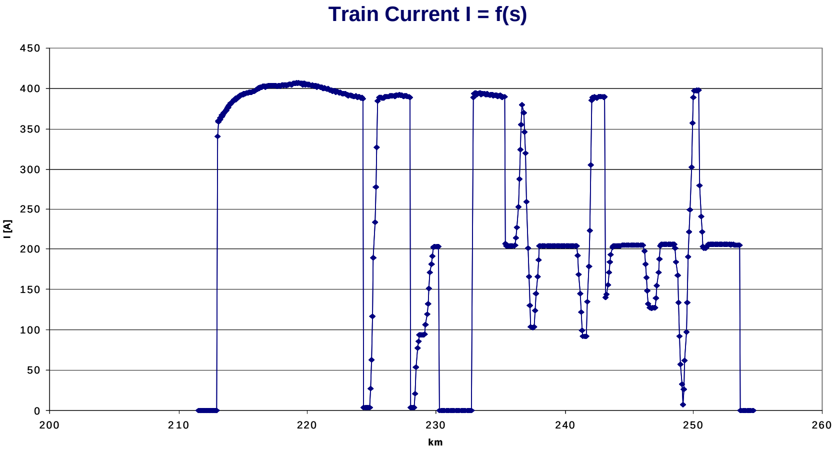


Figure 4-1 Simulated current diagram of a high speed train on HSL Zuid (NL)

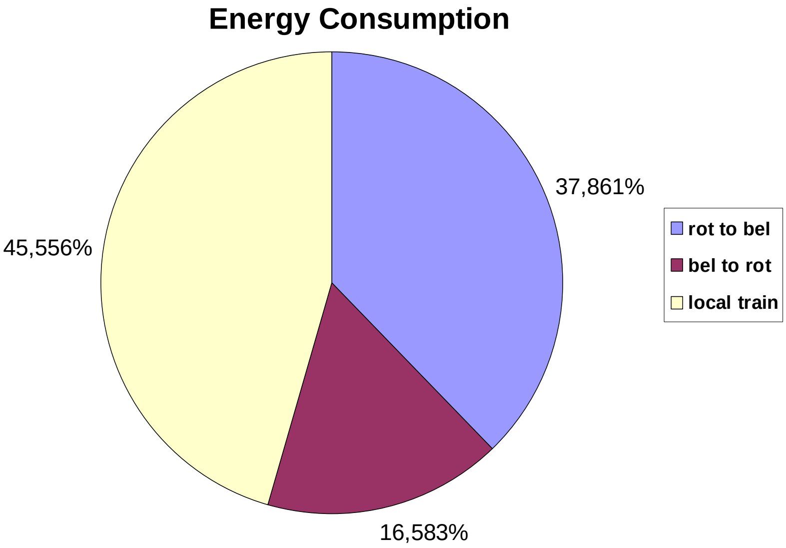


Figure 4-2 Partition of the total energy consumption to different train groups

Currently for the new Chinese high speed line from Wuhan to Guangzhou with a length of approximately 1,000 km the rating of the entire power supply and return current system is examined with OpenPowerNet. For the regular daily operation with high speed and regional trains a minimum operating headway of 3 min is required. The enormous extent of the line and the densely operation program can be considered as a worst case for the capability of the simulation tools.

Nevertheless OpenPowerNet was able to simulate the entire power supply network structure including the overhead catenary system of the line for a representative 2 hours peak operation phase. As results the following values and characteristics were obtained:

- train diagrams (speed profiles, graphical timetables),
- train current characteristics,
- minimum and maximum pantograph and overhead line voltages,
- contact wire and cable currents,
- transformer loads,
- power and energy consumption on substation and power grid level,
- total energy balance,
- efficiency characteristics including component-related power losses balance,
- rail-to-earth potentials.

(Some typical examples will be shown in the conference presentation.)

4.2.2 Tramway and Trolley Bus Networks with DC Power Supply

Recently the analysis and optimisation of the entire Zurich Tram and Trolley bus power supply network was successfully performed with OpenPowerNet. The purpose of this investigation was on the one hand a weak point analysis for the power supply system and than again a network optimisation study for future operation and rolling stock scenarios. Considering a Tram network length of approximately 300 km and an electrical connected Trolleybus network of 220 km length with more than 40 DC 0.6 kV substations in total also this application can be indicated as a worst case from the simulation point of view. However OpenTrack as well as OpenPowerNet were able to simulate the afternoon peak operation with 7.5 min headway on each line all at once without separating any parts of the operation or the electrical network. Due to the large network size the electrical simulation needs multiple real time. That’s why the simulation duration should be restricted to the peak operation interval with the maximum load .

Considering the enormous amount of result data coming out of the simulation the post-processing (i.e. the creation of diagrams and statistics) had to be automated using the commercial MATLAB software. Respecting the investigation tasks with simulations of 4 future operation scenarios (2007, 2010, 2015, 2020) approximately 2,500 result diagrams were produced automatically only for the weak point analysis. The diagrams and tables from Figure 4-3 to Figure 4-8 show some selected result examples. (Further diagrams and a simulation movie will be shown in the conference presentation.)

Line A

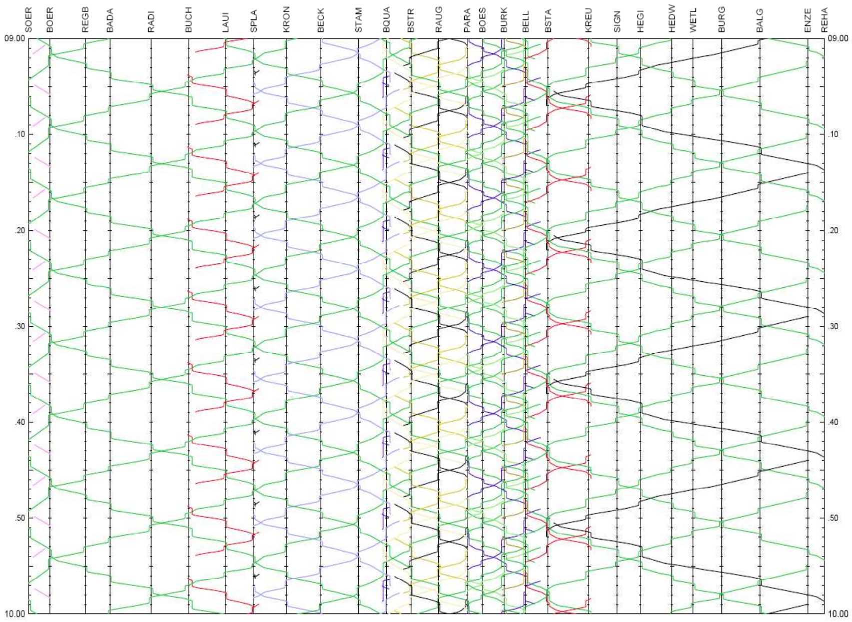


Figure 4-3 Train graph (graphical timetable) of a Zurich tramway line

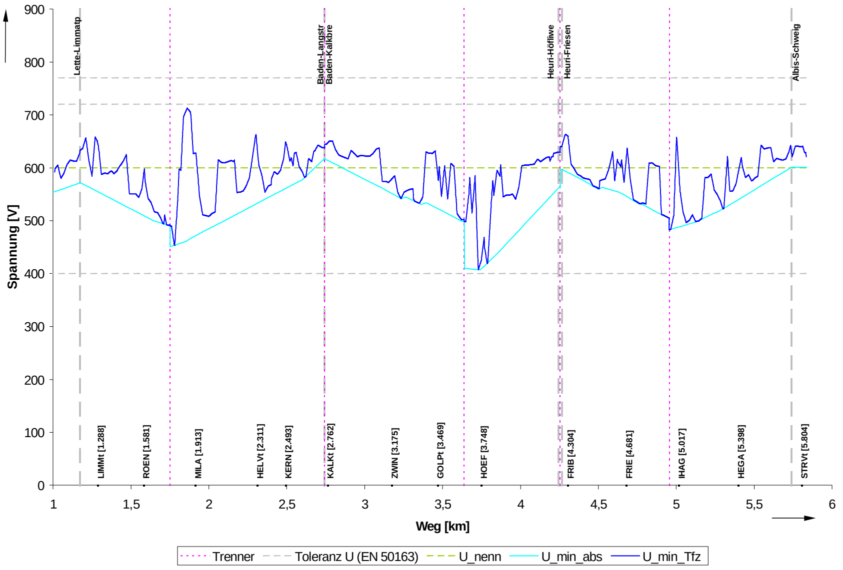


Figure 4-4 Minimum pantograph and overhead line voltage level of all courses

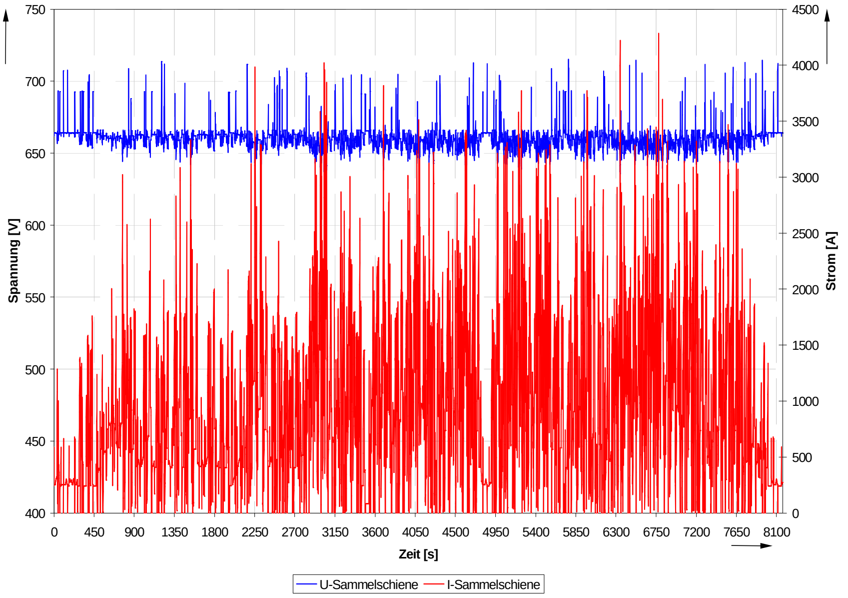


Figure 4-5 Converter current and substation busbar voltage during operation

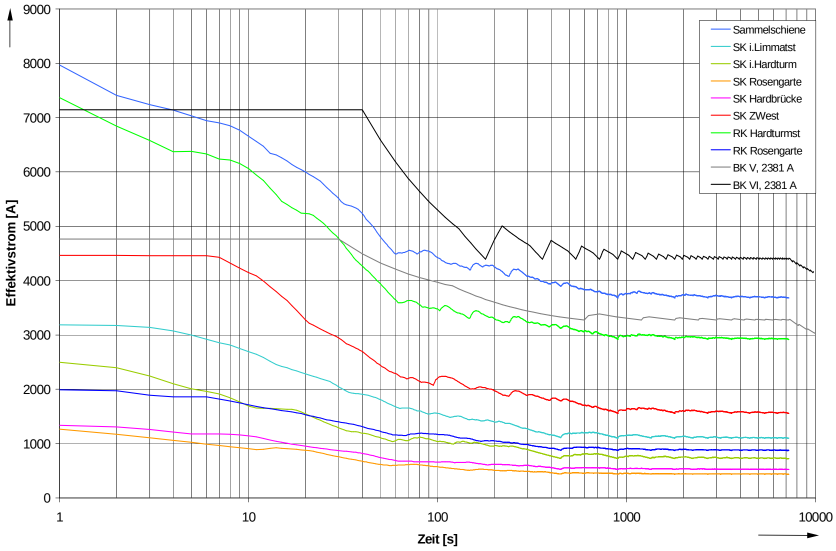


Figure 4-6 Substation load diagram and converter load capacity curves

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

Figure 4-7 Cable load statistics and protection limits of a substation switchgear

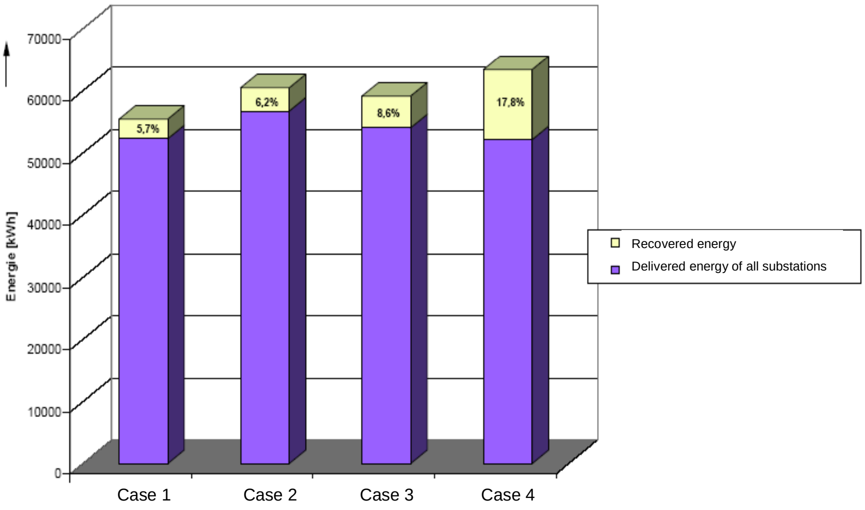


Figure 4-8 Total network energy balance for 2 hours peak operation

5 Summary

In order to simulate railway power supply networks based on the operation program considering all infrastructural and rolling stock related impacts a new simulation tool called OpenPowerNet was developed by IFB. OpenPowerNet works together with the common Swiss railway operation simulator OpenTrack as a co-simulation. The tasks and properties of the simulation tools can be summarised as follows:

Operation Simulation (OpenTrack)

- precise railway operation simulation as a commercial simulator,
- co-simulation with the electrical network calculation of OpenPowerNet,
- online-communication between operation and electrical network simulation via SOAP-Interface using the RailML data interchange format,
- retroaction of the electrical network conditions to the train driving dynamics within the railway operation simulation,
- automatic disturbance generating caused by the power supply.

Load Flow and Energy Calculation (OpenPowerNet)

- complete electrical network calculation reflecting the network structure, the conductor properties and the electromagnetic coupling effects,
- input of the electrical network parameters by use of the geometrical conductor arrangement and the material properties with unrestricted configuration,
- switch status changes of the electrical network during the simulation,
- configurable modelling depth for the train propulsion system,
- comprehensive analysing and interpreting tools (energy, load flows, currents, voltages, temporal / local) as well as data export for post-processing.

The main advantage of this solution is the clear separation of the different simulations tasks. On the one hand this allows an independent development and maintenance strategy for both software tools respecting only the interface specification and on the other hand it decreases the modelling effort and the failure possibilities.

OpenPowerNet can be used for the entire spectrum of railway power supply systems from DC tramway networks up to AC powered high speed railways. By means of selected simulation results the capability of OpenPowerNet as a new OpenTrack family member could be demonstrated.