CHENNAI METRO RAIL LIMITED
CHENNAI METRO RAIL PROJECT PHASE I

CONTRACT AEP-01
Traction Power Study

The Traction Power Study
has been checked by the Lead Design Checker
24.04.2012

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SPS-422-000-1105059 F

Quality Check

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Revision Log

Rev.	Author	Date	Reference	Changes/Subject of revision
A	Hergenhan Christoph	18.08.2011	All	Create all chapters
B	Hergenhan Christoph	12.09.2011	All	Chapters: 1, 2, 4.4.1, 4.4.3, 4.4.5, 4.5.6, 5.2, 6,7
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F	Hergenhan Christoph	19.04.2012	All	Chapters: 4.4.5.1, 6.3.2, 6.5, 6.7

1 Summary

Minimum overhead contact line voltage:

Under normal operation conditions with operational headway of 2,5 minutes, the voltage at the overhead contact line system remains clearly above the minimum 20 kV. The lowest calculated value while outage of Alandur RSS (fed from Chennai Central) and operational headway of 5 minutes is 23,7 kV.

Transformer power:

For all calculated versions while 2,5 and 5 minutes headway, the rated transformer power of 31,5 MVA will not be exceeded. The maximum long term r.m.s. - power, required for train operation, is about 25,7 MVA.

Overhead catenary currents:

The results show, that the current carrying capacity for the OCL system in tunnel is well within the permissible limits for all calculated versions with and without total outage of one RSS.

Taking into account the current carrying capacity of the OCL system on viaduct, the calculated values shows, that the long term and short term currents never reach the permissible limits in all calculated versions (2,5 minutes headway and 5 minutes headway) with and without total outage of one RSS.

Feeder Cable Currents:

For an operational headway of 2,5 min and 5 minutes, the feeder current is within the permissible limits for base operation and total outage of one RSS. The return currents are well within the permissible limits for base operation and total outage of one substation, since four return feeder cables are installed for up and for down track. The current capacity of the depot feeder cables is well within the permissible limit for all operational scenarios.

Note: High loaded feeder cables should be laid next to low loaded feeder cables in duct: This can reduce the thermal emission of each duct and reduce the stress of cables inside.

Currents in earth wires (AEC and BEC):

For all calculated operational headways the earth wire currents are below the current carrying capacity of the earth wires, even for the extreme ambient temperature of 46,1°C.

Recuperated Power:

In all simulated variants, no power will be recuperated to the utility infeed.

Significant Simulation Results:

Maximum long term r.m.s. – power of the traction transformer	25,7 MVA
Minimum supply voltage along the line (at pantograph)	23,6 kV
Sizing and dimensioning of cable and overhead contact line system	sufficient

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Attachments

Attachment	A:	(20 pages, 4 documents)
	A1:	Validation Sidytrac (3 Pages)
	A2:	System Design AC and DC Traction Power Supply (8 Pages)
	A3:	Siemens – Mobility division ISO 9001, 14001 & 18001 Certificates (3 Pages)
	A4 :	System Design for the High Speed Line HSL-ZUID with SITRAS SIDY-TRAC (6 Pages)
Attachment	B:	Design Checking Form (1 page)
Attachment	C:	List of detailed comments of Design Checker (1 page)
Attachment	D:	Compliance Matrix (5 pages)
Attachment	E:	Minutes of meeting between Siemens Ltd. and ABB with a test report of the traction power transformer (18 pages)

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2 Purpose and Scope

The technical feasibility of the traction power supply for the "Chennai Metro Rail" project with 25 kV/50 Hz has been investigated by means of an electrical network calculation basing on simulated train operation with the simulation program Sitras® Sidytrac.

A load flow calculation of the 25 kV traction power supply system for the "Chennai Metro Rail Project" had to be carried out in order to check the current carrying capacity of the feeder wires and overhead contact line, the transformer rating and the train supply voltage conditions.

The traction power supply of the two double track lines with a total length of approx. 44 km is simulated. The corridor 1 starts at Washermanpet and ends at to Chennai Airport. The corridor 2 starts at Chennai Central 2 and ends at St. Thomas Mount.

The document shall demonstrate that:

- The Train supply voltage does not drop below the limit of 20 kV
- The ratings of traction substation transformer are adequate under normal operation conditions and outage conditions
- The size of the feeding and return cables are adequate under normal operation conditions and outage conditions
- The rating of the overhead contact line system is adequate under normal operation conditions and outage conditions
- The impact to the utility infeed based on recuperated power of the trains during the normal operation conditions (simulated scenarios)
- Energy consumption during the different simulation scenarios

3 General

3.1 Definitions

Sign	Example	Description	Meaning
‘,’	12,3	Comma	Decimal delimiter
‘ ‘	12 345	Blank	Thousands separator

Table 3-1: Definitions

3.2 Referenced Documents

No.	Reference	Title	ISSUE date
RD 1	IRS.72.1 / Version 02	IRS Rolling Stock vs. Power Supply	19.05.2011
RD 2	GCC-490-C10-1108042-D	HORIZONTAL AND VERTICAL ALIGNMENT OF CORRIDOR – 1	06.09.2011
RD 3	GCC-490-C20-1108043-C	HORIZONTAL AND VERTICAL ALIGNMENT OF CORRIDOR – 2	23.08.2011 (transmitted)
RD 4	GCC-300-000-1001163-A	Volume 3, Addendum N°3, Attachment N°2	Sept. 2010
RD 5	Contract AEP-01 Bidding Document Volume 4	Particular Specifications	July 2010
RD 6	T/2609148/UAA01/CB/1051 T2609148UAA01-CB1051-	Tender – Chennai Metro Rail Limited Bored Tunnel – Typical Sections	June 2010
RD 7	GCC-340-C0E-0978990-C	Space Proofing Drawings – Viaduct Straight Issued for Tender Purpose	22.01.11
RD 8	MoM with Alstom	Interface Meeting: Siemens PS&OHE (AEP01), Alstom RS (ARE01) on 4 July 11, related emails.	04.07.2011
RD 9	Contract AEP-01 Bidding Document Volume 4	Appendix B – as per addendum - 061110	July 2010
RD 10	Contract AEP-01 Volume 3 Section 1	Particular Specifications	July 2010
RD 11	GC comments	2011 07 26 to 27 Flash MoM between Siemens Design team and GC	End of July 11
RD 12	SPS – 422 – 000 – 1105047 - B	110kV / 33kV Power Supply and Short Circuit Study	14.12.2011

Table 3-2: Referenced Documents

3.3 Relevant International and European standards

No.	Reference	Title	ISSUE date
ST 1	IEC 60850	Railway applications – Supply voltages of traction systems	Feb. 2007

Table 3-3: Referenced Documents

3.4 Used Abbreviation

Abbreviation	Meaning
AC or a. c.	Alternating current
ACSR	Aluminium conductor steel reinforced
AEC	Aerial earth conductor
ATO	Automatic train operation
BEC	Buried earth conductor
TPS	Traction power supply
TSS	Traction sub station
RSS	Receiving Sub station
SNS	Short Neutral Section

Table 3-1: Abbreviation

3.5 Internal annotation

In order to enable a reference between study results and the corresponding simulation dataset, each simulation run generates a unique simulation ID. Table 3-4 shows the simulation ID of the conducted simulation runs which are basis for the results of this report.

Abbreviation	Meaning	Scenario
SID 1	b44acd7f – 5717 - 4d64 – 845c - 6a1114a9740e	Base and outage of one transformer in each RSS
SID 2	b611a94e - 1aea - 4fd5 - b4f3 - 7a7bda79bb37	Outage of each RSS

Table 3-4: Corresponding simulation IDs

4 Preconditions

The following paragraphs summarise the input data for the simulation of the electrical network and the train operation of the line.

Please note, that all results of this study are based on these preconditions and changes of any input data will lead to changes in the results of the simulation.

4.1 Route

4.1.1 General

The track alignment has been taken from RD 2 and RD 3:

- Total length of the line: 44 358 m
- Number of tracks: 2
- Number of corridors: 2
- Number of traction substations: 3
- Number of stations: 34 (with 2 platforms for each station)
- Tunnel factor: 1 (at viaduct); 1,5 (in tunnel)

The following figure shows an overview of the line and gives information about the height profile, locations of stations and the tunnel factor in corridor 1 (Washermanpet to Chennai Airport).

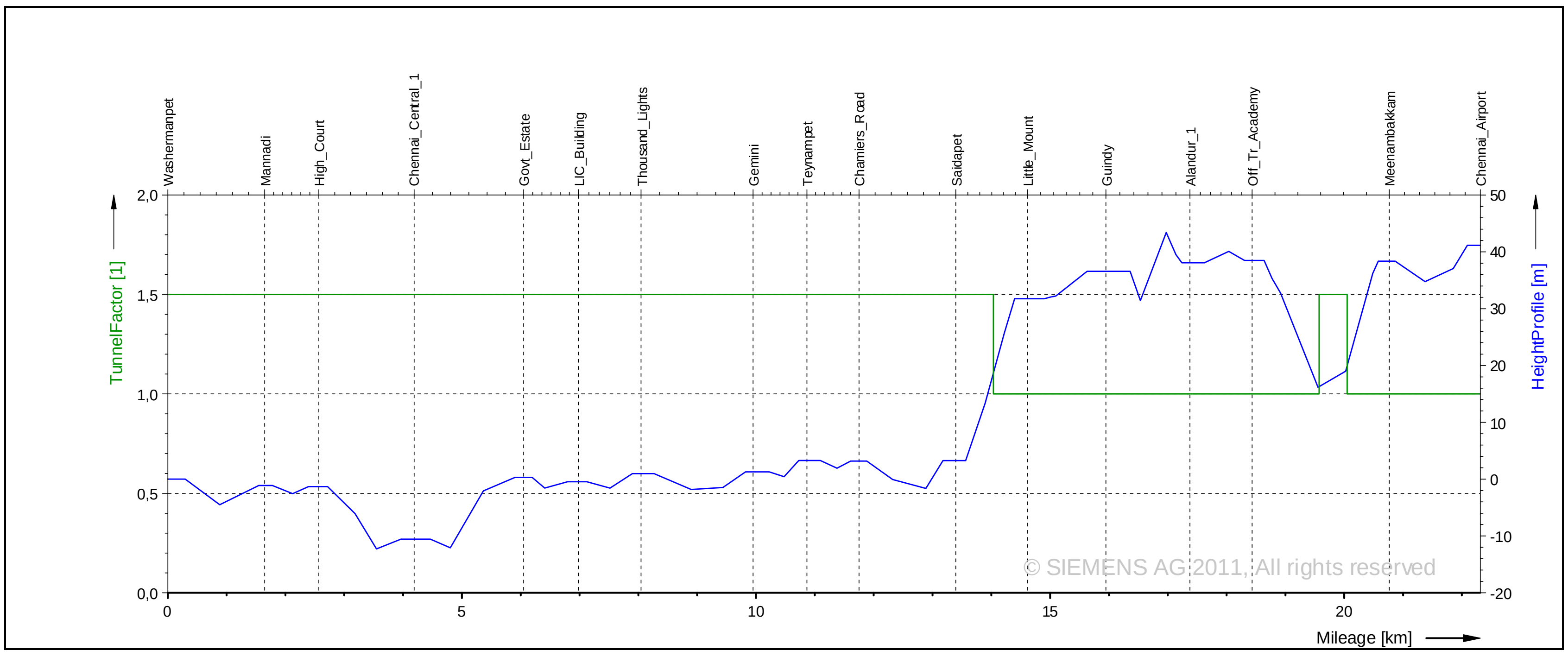

Figure 4-1: Track information corridor 1

The following figure shows an overview of the line and gives information about the height profile, locations of stations and the tunnel factor in corridor 2 (Chennai Central 2 to St. Thomas Mount).

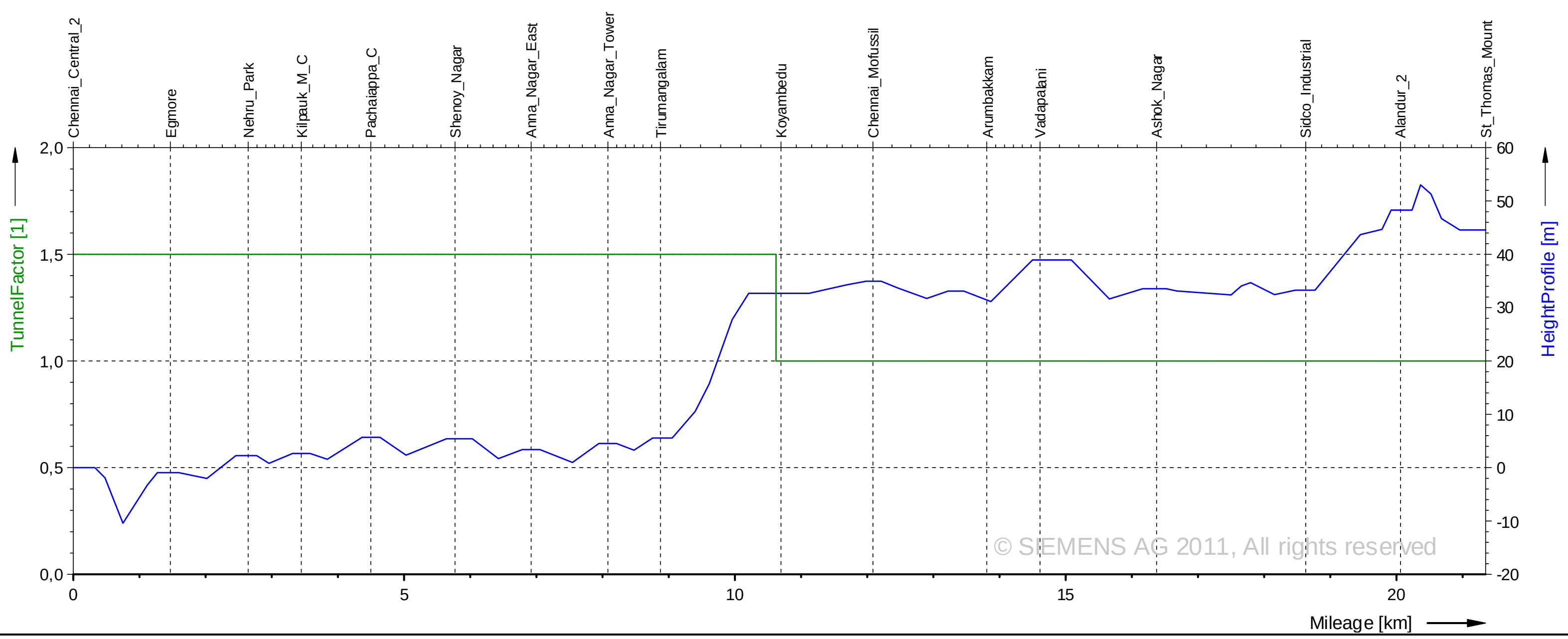

Figure 4-2: Track information corridor 2

4.1.2 Speed profile

There is no available information about the speed profile of the route. Following speed limitations based on the curve radius are expected. Assumptions are based on experiences in similar projects.

Curve Radius [m]	Maximum speed [km/h]
< 280	80
280 – 220	70
220 – 160	60
160 – 110	50
110 – 60	40
60 – 30	30
30 – 10	20

Table 4-1: Speed limitation due to the curve radius

4.1.3 Passenger stations and dwell time

The following table shows the passenger station names, locations and dwell times in corridor 1 [RD 2, RD 3 and RD 5]. The dwell time is the stop time of the trains in the stations in order to allow passengers to enter and leave the train.

Station name	Location [m]	Dwell time [s]
Washermanpet	0	120
Mannadi	1 670	30
High court	2 590	30
Chennai Central 1	4 210	30
Govt. Estate	6 072	30
LIC Building	7 004	30
Thousand Lights	8 068	30
Gemini	9 972	30
Teyampet	10 888	30
Chamiers Road	11 773	30
Saidapet	13 419	30
Little Mount	14 640	30
Guindy	15 970	30
Alandur 1	17 399	30
Officers Training Academy	18 456	30
Menambakkam	20 788	30
Chennai Airport	22 335	120

Table 4-2: Passenger station names, location and dwell times in corridor 1

The following table shows the passenger station names, locations and dwell times in corridor 2 [RD 2, RD 3 and RD 5]. The dwell time is the stop time of the trains in the stations in order to allow passengers to enter and leave the train.

Station name	Location [m]	Dwell time [s]
Chennai Central 2	- 80	120
Egmore	1 388	30
Nehru Park	2 564	30
Kilpauk Medical College	3 366	30
Pachaiappas College	4 417	30
Shenoy Nagar	5 690	30
Anna Nagar East	6 841	30
Anna Nagar Towers	8 001	30

Thirumangalam	8 795	30
Koyambedu	10 617	30
Chennai Mofussil Bus Terminal (CMBT)	12 007	30
Arumbakkam	13 278	30
Vadapalani	14 532	30
Ashok Nagar – KK Nagar	16 294	30
SIDCO Industrial Estate	18 548	30
Allandur 2	19 982	30
St. Thomas Mount	21 267	120

Table 4-3: Passenger station names, location and dwell times in corridor 2

4.1.4 Overview of the RSS in corridor 1 and 2

The following figure gives an overview of the three RSS in both corridors and the station.

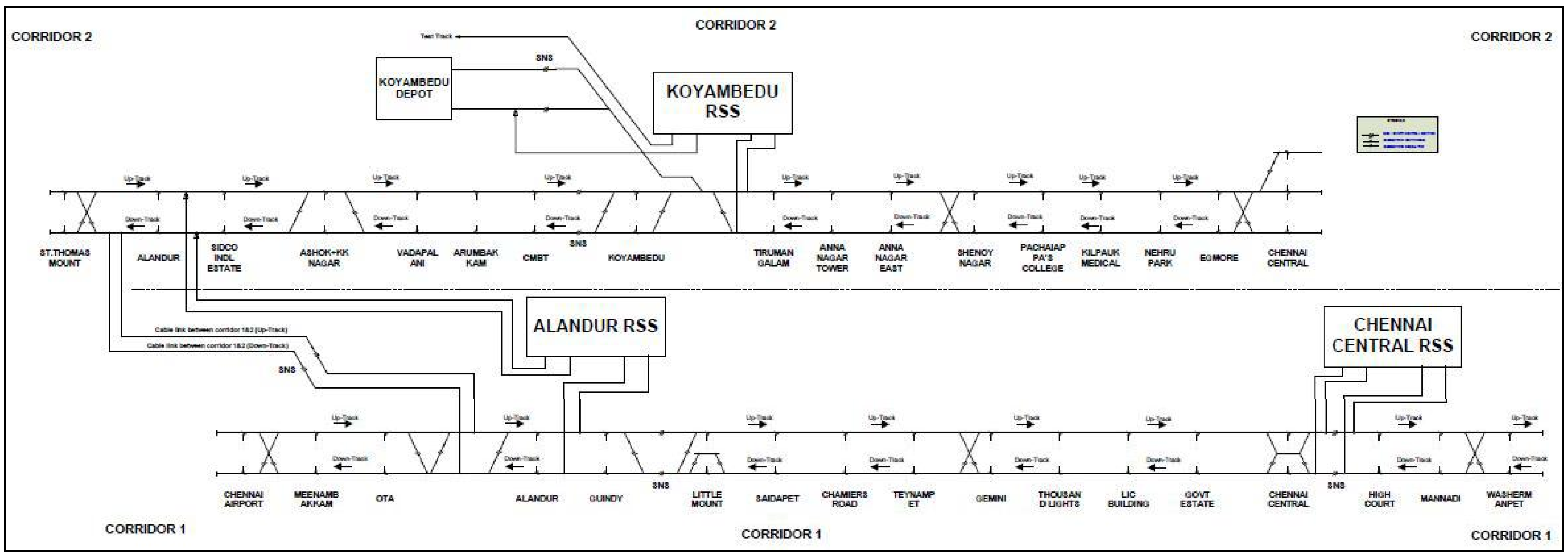

Figure 4-3: Overview of the RSS in both corridors with the stations

4.1.5 Electrical feeding sections

Based on the overview of the both corridors in Figure 4-3 the following table shows the electrical sectioning arrangement in the corridors:

Feeding section in Corridor 1 and 2	Track alignment
Corridor 1 - Chennai Central North Section	Beginning of corridor 1 to 3 600 m
Corridor 1 - Chennai Central South Section	3 600 m to 15 545 m
Corridor 1 - Alandur Section	15 545 m to end of corridor 1
Corridor 2 - Alandur Section	11 698 m to end of corridor 2
Corridor 2 - Koyambedu Section	Beginning of corridor 2 to 11 698 m
Koyambedu Depot Section	Only Depot Ring

Table 4-4: Electrical sectioning arrangement

4.2 Operational conditions and stages

The following table shows the calculated versions.

Version	Train configuration / headway	Description
Base	6 car / 2:50 min. headway	Normal operation – one Transformer in each RSS in operation
Out. Chennai C.	6 car / 5:00 min. headway	Outage of RSS Chennai Central
Out. Koyambedu	6 car / 5:00 min. headway	Outage of RSS Koyambedu
Out. Alandur fed Chennai C.	6 car / 5:00 min headway	Outage of RSS Alandur fed from Chennai Central
Out. Alandur fed Koyambedu	6 car / 5:00 min headway	Outage of RSS Alandur fed from Koyambedu

Table 4-5: Calculated versions

Based on the described feeding sections in Table 4-4 and the calculated versions in Table 4-5 the following detailed feeding conditions are taken into account for outage feeding conditions:

- In case of an outage of RSS Chennai Central the parallel switch of the SNS in Corridor 1 (near 15 545 m) are closed. That means in detail:
  - that the “Corridor 1- Chennai Central North Section” and the “Corridor 1- Chennai Central South Section” is fed from the traction transformer in RSS Alandur
- In case of an outage of RSS Koyambedu the parallel switch of the SNS in Corridor 2 (near 11 698 m) are closed. That means in detail:
  - that the “Corridor 2 - Koyambedu Section” and the “Koyambedu Depot Section” is fed from the traction transformer in RSS Alandur

- In case of an outage of RSS Alandur fed from Chennai Central the parallel switches of the SNS in Corridor 1 (near 15 545 m) are closed. That means in detail:
    - that the “Corridor 1 - Alandur Section” and the “Corridor 2 - Alandur Section” is fed form the traction transformer in RSS Chennai Central

- In case of an outage of RSS Alandur fed from Koyambedu the parallel switches of the SNS in Corridor 2 (near 11 698 m) will be closed. That means in detail:
    - that the “Corridor 1 - Alandur Section” and the “Corridor 2 – Alandur Section” is fed form the traction transformer in RSS Koyambedu

4.3 Description of the driving mode

The Chennai Metro will operate with trains driven by train operators and using Automatic Train Operation (ATO).

For the design simulations a realistic driving pattern has been assumed with a time reserve of up to 4 %. The time reserve is realised by coasting of the trains before the final breaking phase in the stations. The value has been assumed based on experience, and means a conservative value since higher time reserve values are commonly applied in mass transit systems.

The time reserve in % is referenced to “all out mode” driving, which is the theoretical minimum of the time for a drive cycle between two stations.

“Time reserve with coasting” means a more realistic driving pattern, especially as a time reserve is vital for ATO driving, consists of four phases:

- acceleration with maximum value
- steady state
- coasting
- braking with maximum value

The following figure shows the time reserve driving mode.

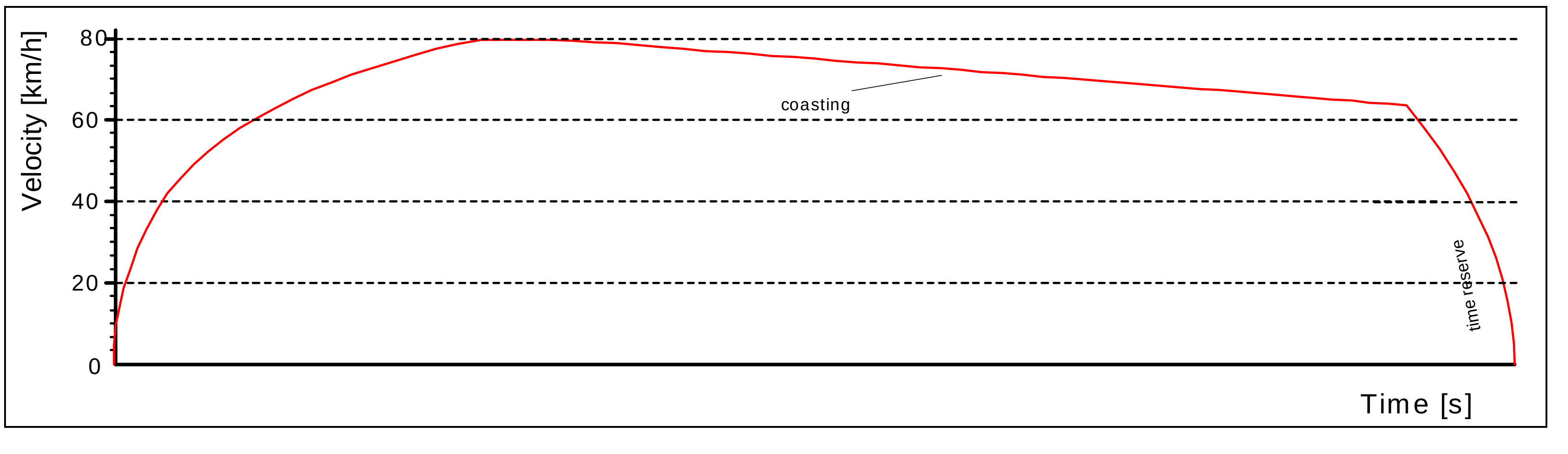

Figure 4-4: Time reserve driving mode

4.4 Electrical network data

4.4.1 Running Rails

- Type of running rail: UIC 60
- Electrical cross section: 5883 mm² (15 % abrasion)
- Resistance per unit length **per** rail at 60°C: 25,7 µΩ/m (used for simulation)

One rail of each track is earthed on special points (e.g. Stations and/or infeed points). The other rail is connected with the earthed rail also at special points (e.g. S-Bonds, Rail-Bonds, Stations and/or infeed points).

4.4.2 Environmental conditions

The maximum ambient temperature of the environment is 41,9 °C [RD 10]. With a safety margin of 10 % (based on chapter 1.12 in [RD 10]) the design temperature is 46,1 °C.

4.4.3 Overhead contact line system (on viaduct)

- Contact wire: Cu 150 mm² (20% abrasion)
- Messenger wire: CdCu 65 mm²
- Rails: UIC 60, (15% abrasion)
- Buried earth conductor: Cu 35 mm²

Figure 4-4 shows a cross section of the considered overhead contact line system including all relevant horizontal and vertical measures of conductors and running rails based on [RD 7].

Note: **No** AEC is considered for this study on viaduct section. Only for the tunnel section an AEC is considered (see chapter 4.4.4). This is a worst case scenario.

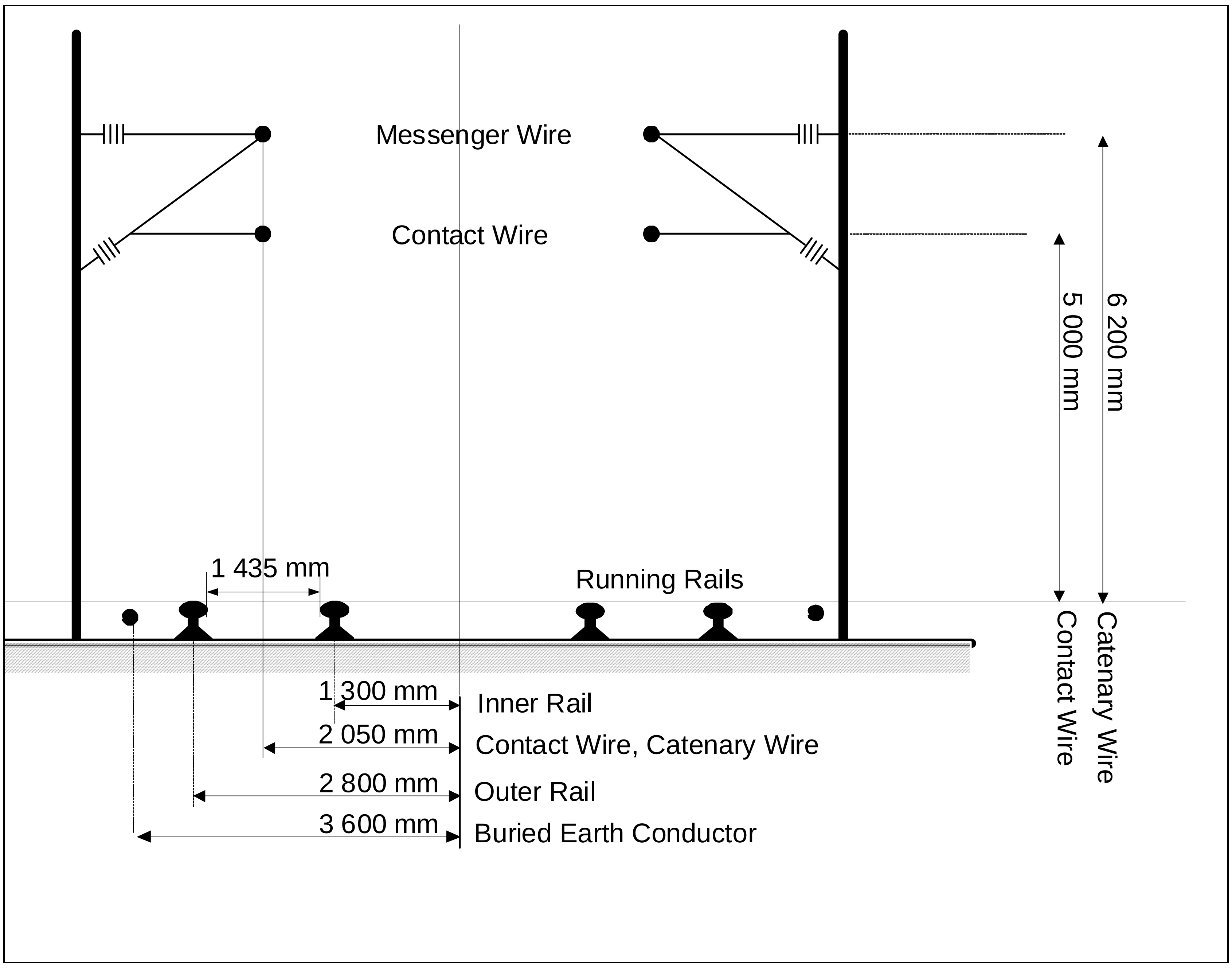

Figure 4-5: Configuration of Overhead contact line system (on viaduct)

Continuous current carrying capacity at maximum catenary temperature of 80°C, 20 % wear of contact wire, 1 m/s wind speed and solar radiation (1 200 W/m^2) and 46°C ambient temperature:

- 1 Minute r.m.s. (short term): 1 243 A
- Continuous: 689 A

Sharing ratio of catenary while 20% wear of the contact wire:

- Contact wire: 57,73 %
- Messenger wire: 42,27 %

4.4.4 Overhead contact line system (in tunnel)

- Contact Wire / Rigid Rail: Cu 1 313 mm² (equivalent)
- Rails: UIC 60, (15% abrasion)
- Aerial earth conductor: Steel reinforced aluminum stands (ACSR) 93,3 mm²

- Buried earth conductor: Cu 35 mm²

Figure **4-6** shows a cross section of the considered overhead contact line system including all relevant horizontal and vertical measures of conductors and running rails.

The distance between the both tunnels is assumed with 14 m.

Continuous current carrying capacity of overhead contact line system in all tunnel (Chennai Airport section excluded) sections at maximum conductor temperature of 80°C, 20% wear, 1 m/s wind speed and without solar radiation and 46°C ambient temperature:

- 1 min r.m.s. (short term): > 6 500 A
- Continuous: > 2 000 A

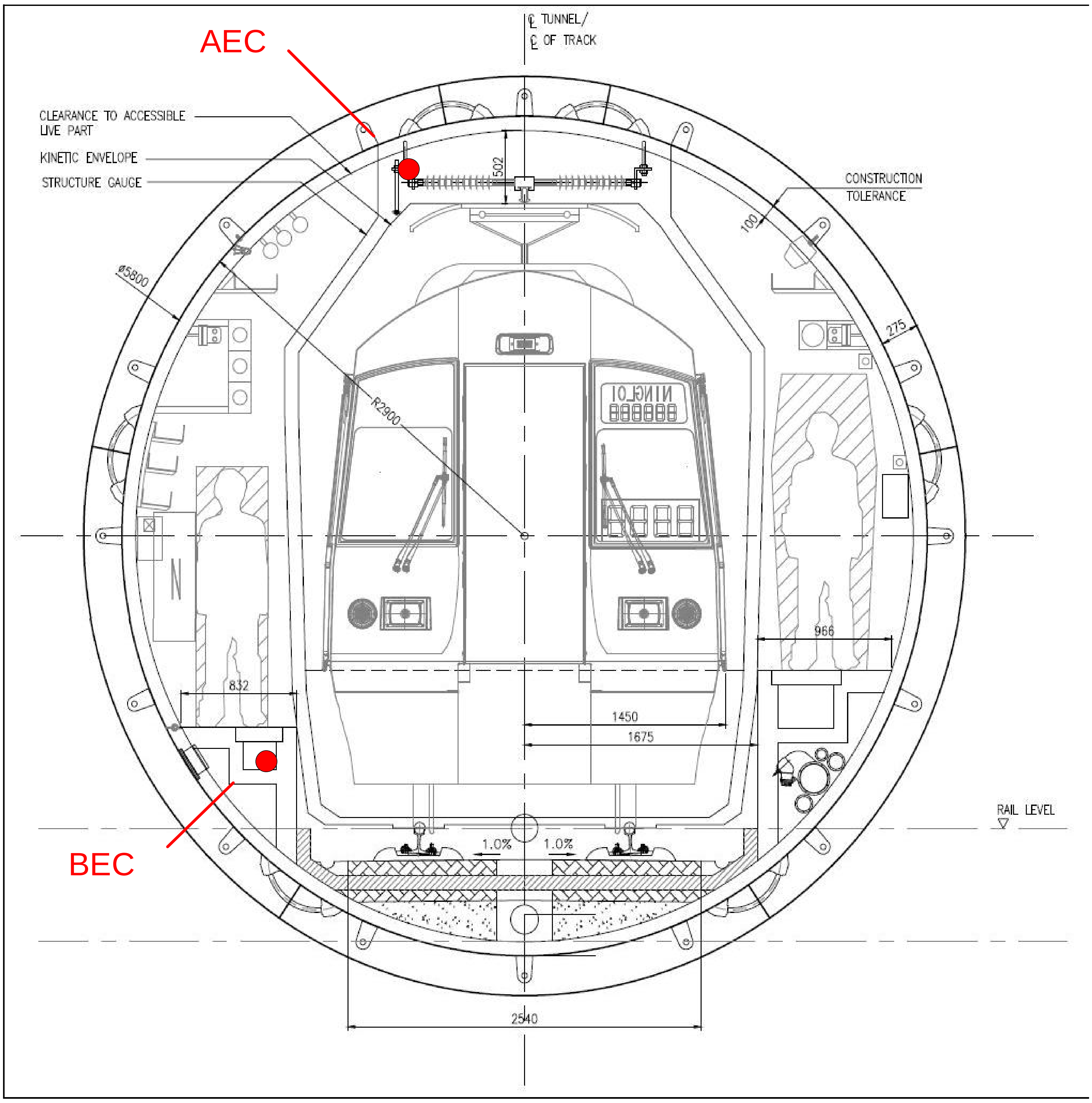

Figure 4-6: Configuration of Overhead contact line system (in tunnel) [RD 6]

Version	Horizontal position related to centre of track [m]	Vertical position Description related to top of rail [m]
Contact wire / Rigid Rail:	0	4,35
Aerial earth conductor:	1,7	4,425
Buried earth conductor:	2,2	0,6

Table 4-6: Position of conductors in tunnel section

4.4.5 Traction power substations (TPS) and fault conditions

Three traction power substations realize the traction power supply of the 1x25 kV-System with six feeding sections. Each substation is equipped with two transformers. One transformer per substation supplies both feeding section of each RSS. The second transformer is a spare unit in a "hot standby" mode. Two 31,5 MVA transformer are located in each TPS. The characteristic transformer data are [RD 9]:

- U_r = 110/27,5 kV
- S_r = 31,5 MVA ONAN used for simulation (40 MVA ONAF)
- u_{Kr} = 12,5 %
- Maximum no load losses = 14,7 kW (14 kW +5%) used for simulation [RD 9]
- Maximum load Losses = 147 kW (140 kW +5%) used for simulation [RD 9]

The main electrical characteristic of the traction transformer (which is important for the traction power simulation) does not change if it is an ONAN or ONAF transformer.

4.4.5.1 25 kV Traction network fault conditions

The maximum short circuit current for the 25 kV TPS Network is limited by the traction power impedance (u_{Kr} = 12,5 %). Based on the listed traction transformer data (for both power values) in Attachment F (see page 8 and 9 of Attachment F) the resulted maximum short circuit current can be calculated as follows:

- For 30 MVA: **I_K" = 8,73 kA** (Sr /(u_{Kr} * Ur) = 30 MVA /(0,125 * 27,5 kV))
- For 42 MVA: **I_K" = 8,48 kA** (Sr /(u_{Kr} * Ur) = 42 MVA /(0,18 * 27,5 kV))

This maximum short circuit value (**I_K" = 8,73 kA**) will be used to check the traction network fault conditions.

The short-circuit capability can be verified on basis of short-circuit current by using following formula:

$$t_{\max} \leq \left(\frac{I_{th}}{I''_{K3}} \right)^2 \cdot t_{Kr}$$

The short-circuit capability of the cables depends on the fault clearing time of the network protection (detail design).

The minimum symmetrically three phase short circuit power (S_{K3}'' min.) for the RSS was taken from document GCC-282-000-1112159 "TNEB answers to the SIEMENS technical questionnaire for AEP-01 Contract", please refer to [RD 12]. The respective values are listed below:

	S_{K3}'' min.
RSS Chennai Central:	5,36 GVA
RSS Alandur:	3,33 GVA
RSS Koyambedu:	4,58 GVA

The substation infeed with two transformers is shown in Figure 4-7.

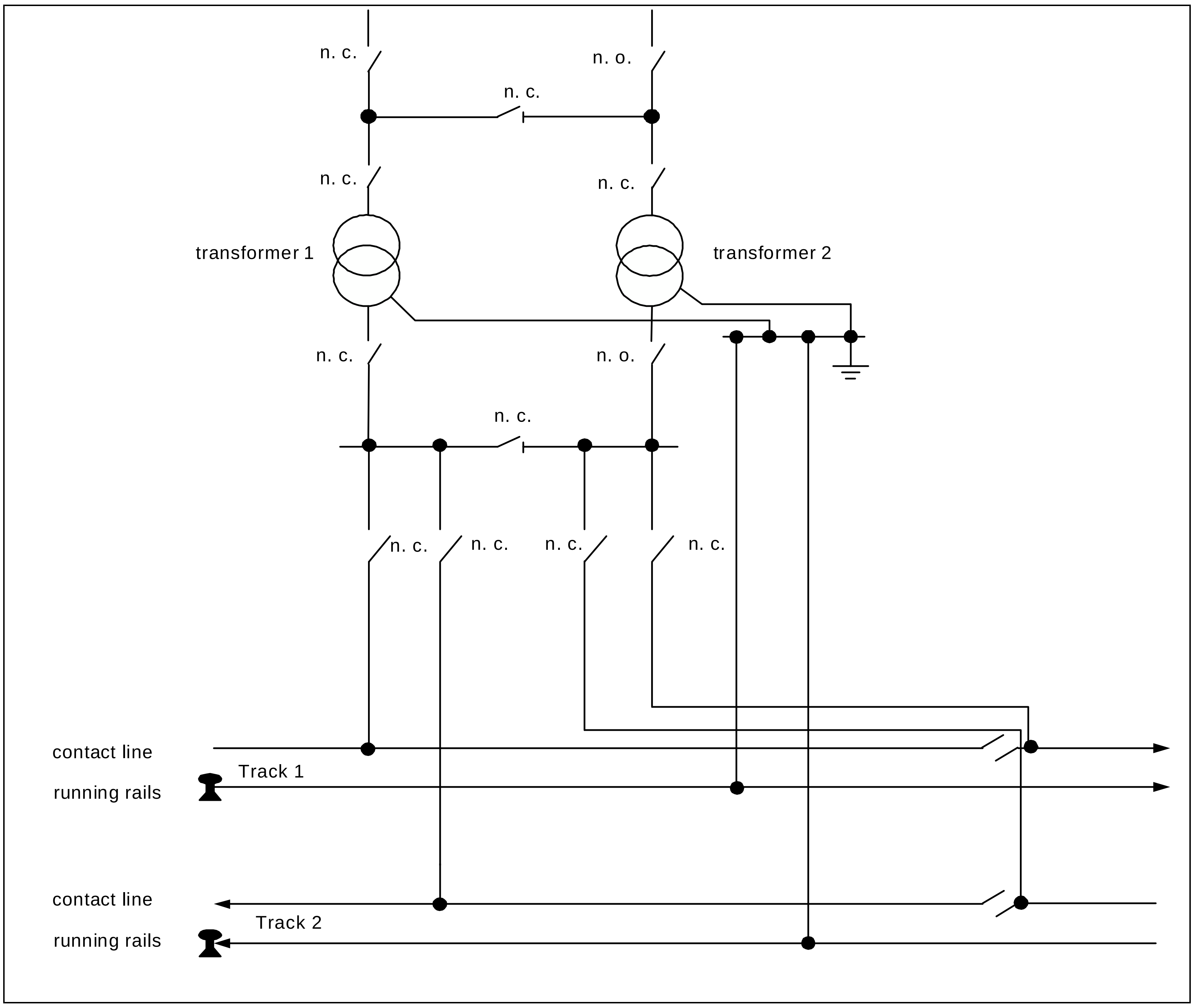

Figure 4-7: Substation infeed

4.4.6 Depot / Test Track

A static load of approx. 2,1 MVA has been taken into account representing the depot loading [RD 11]. A depot load of 2,1 MVA is assumed as realistic, while eight trains is assumed in depot with no additional train on test track. It is assumed that the trains need full auxiliary power in this time period. If there is a train on the test track, the trains in the depot will not consume the complete 2,1 MVA power. The time periods of acceleration are very short on the test track and so the r.m.s. - value of traction power can be seen as low. In addition with the auxiliaries of all eight trains, the assumed depot load is 2,1 MVA [RD 11].

4.5 Train data – 6 car train

Based on the 4car-Traindata [RD 1] and on the mentioned train of the 6car-Traindata [RD 8] we expected following input date for the 6car-Train. Some values are the 4car-Traindata with a multiplicity factor of 1,5. The important expected data are described with notes and must be clarified or confirmed.

4.5.1 Voltage Conditions

- Nominal voltage: 25 kV
- Minimum voltage: 22,5 kV
- Highest permanent voltage $U_{max,1}$: 27,5 kV
- Highest non permanent voltage $U_{max,2}$: 29 kV

4.5.2 Mechanical Conditions

- Tare weight: 260 t
- Rotary portion of tare weight: 10 %
- AW4 (8 pas/m²) payload: 124 t
- Maximum weight AW4: 384 t
- Train length: 128 m

4.5.3 Movement features

- Maximum design speed: 80 km/h
- Maximum acceleration: 0,82 m/s²
- Maximum deceleration: 1,0 m/s² (electro dynamical break)

4.5.4 Efficiency

- Gear efficiency: 97 %
- Traction efficiency (PMCF + Inverter + Traction motor) [RD 1]: 92,8 %
- Traction efficiency (PMCF + Inverter +

Traction motor + gear) [RD 1]: 90 %

- Transformer: 92 %
- Resulting total efficiency: 82,8 %

4.5.5 Auxiliaries

- Voltage independent loads 435 kW

4.5.6 Further Data

- Power factor: 0,98 (Phi 11,48 °)

The power factor of the train is very important for the simulation results. A power factor of 0,8 leads to 20% higher apparent power instead of a power factor of 0,98.

4.5.7 Tractive and breaking effort diagram, train resistance

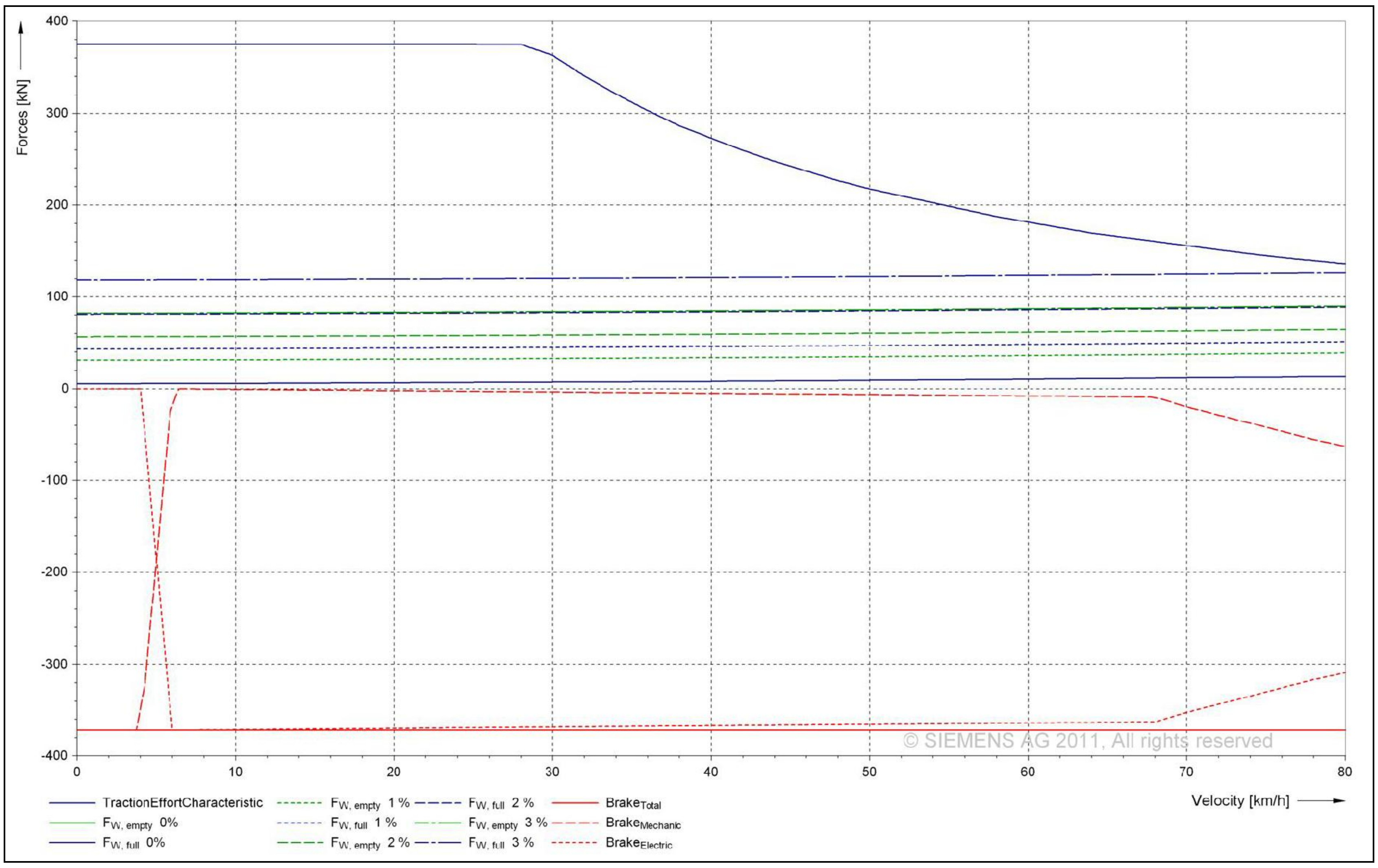

Figure 4-8 Tractive and breaking effort and train resistance (Fw) – 6 car train

Note: The values for the tractive and breaking effort of the 6car train are based on the values of the 4car train. The values for the 6car train are the values for the 4car train multiplied with 1,5.

4.5.8 Traction current limit

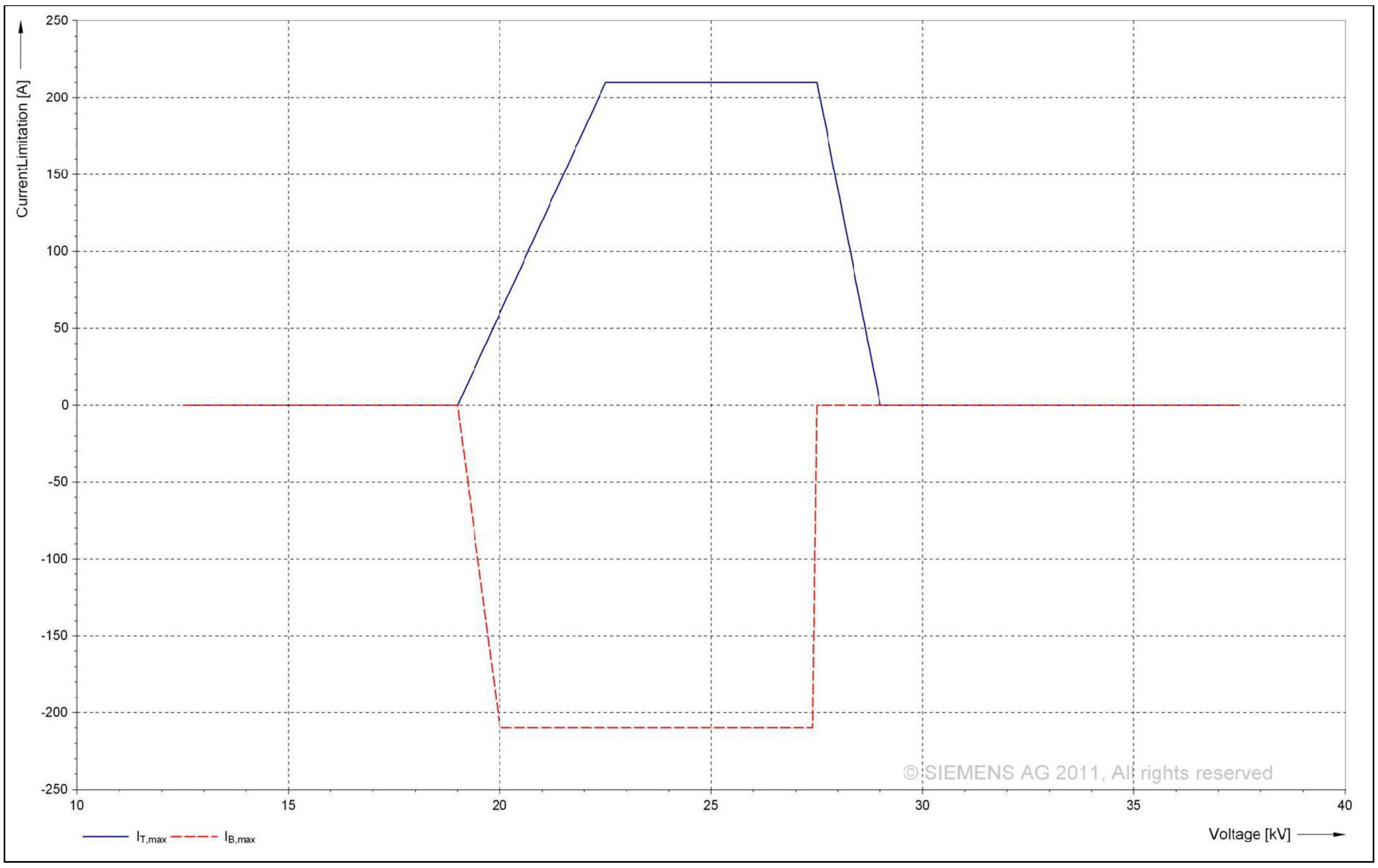

Figure 4-9 Current limit of the traction current – 6car train

Note: The values for the current limitation curve of the 6car train are based on the values of the 4car train. The values for the 6car train are the values for the 4car train multiplied with 1,5.

4.5.9 Train resistance formula for the 6 car train

The train resistance formula, mentioned in [RD 1] for the 4 car train, is multiplied with 1,5 and convert to the international system of units (1 km/h = 3,6 m/s). The data for the 6 car train resistance formula are:

$$F_{w,\,3\text{-car train}} = 5\,534\,\mathrm{N} + 190{,}1 \cdot \frac{\mathrm{kg}}{\mathrm{s}} \cdot v_{\mathrm{train}} + 12{,}7 \cdot \frac{\mathrm{kg}}{\mathrm{m}} \cdot v_{\mathrm{train}}{}^{2} \quad \text{(for a full loaded train)}$$

With F in [N]
v_{train} in [m/s]

4.5.10 Regenerative Braking

Regenerative braking has been considered. Maximum voltage for regenerative braking 27,5 kV. This value is very important for the simulation results of the recuperated power to the utility infeed in chapter 6.9.

5 Calculations

5.1 Simulation Program Sitras® Sidytrac

With Sitras® Sidytrac, scheduled train service on the given route was simulated while taking into account the electrical network.

Using a time step procedure, Sitras Sidytrac determines the speed profile of the trains. In each time step, all voltages and currents in the network are calculated. By means of this calculation procedure, the speed profile and the power intake of the trains are determined, with the effects on the network being taken into account.

The results of the calculations are power levels, energy levels, r.m.s. values, losses etc. which are illustrated in diagrams.

In Figure 5-1 the calculating procedure of Sitras Sidytrac is shown.

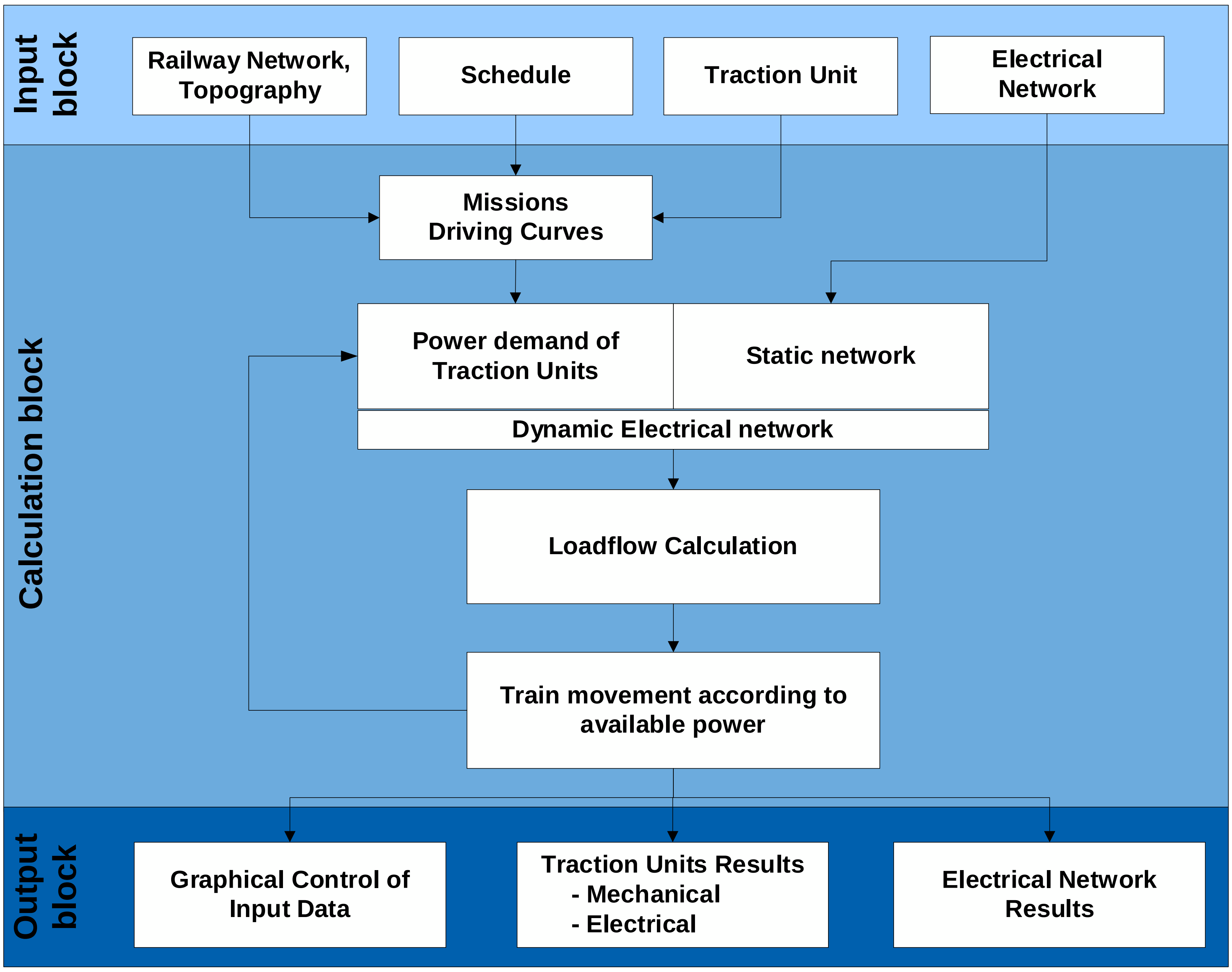

Figure 5-1 Calculating procedure of Sitras SIDYTRAC

5.2 Scope of the calculations

For the assessment of the traction power supply system the following design parameters have been analysed.

Supply voltage trains:

- Minimum voltages, which means the train voltage at the overhead catenary system. According to the tender document 20 kV.

Transformer power:

- r.m.s.-values of the complete simulation period
  (representing the continuous load for this operation mode)

Currents of the OCL system:

- 1 - minute r.m.s. (representing short term load)
- r.m.s. - values of the complete simulation period
  (representing the long-term load for this operation mode)

Feeder cable and return feeder currents:

- r.m.s. - values of the complete simulation period
  (representing the long-term load for this operation mode)

Characteristic of the power flow from the utility infeed:

- Recuperated power to the utility infeed

Total energy consumption during the simulation period:

- Total energy consumption - normal operation
- Total energy consumption - outage operation

6 Results

The following chapters show the results of the calculations. The complete simulation period is 35 minutes. According to chapter 4.2 two operation scenarios were taken into account for the simulated train operation.

Note: All results are based on the input data in chapter 4.

6.1 Minimum supply voltages

The minimum supply voltage at the overhead catenary system represents the minimum supply voltage at the pantograph of the train.

Version	Minimum supply voltages [V]
Base	24 969
Out. Chennai C.	25 434
Out. Koyambedu	24 659
Out. Alandur fed Chennai Central	**23 562**
Out. Alandur fed Koyambedu	24 186

Table 6-1: Minimum supply voltages

Above results show that the voltage at the overhead catenary system remains clearly above the minimum 20 kV requirement in chapter 2. Outage of one RSS does not lead to significant changes concerning the minimum voltage.

The following figure 6-1 shows the minimum voltage over the complete OCL in corridor 2 in case of an outage of RSS Alandur fed Chennai Central.

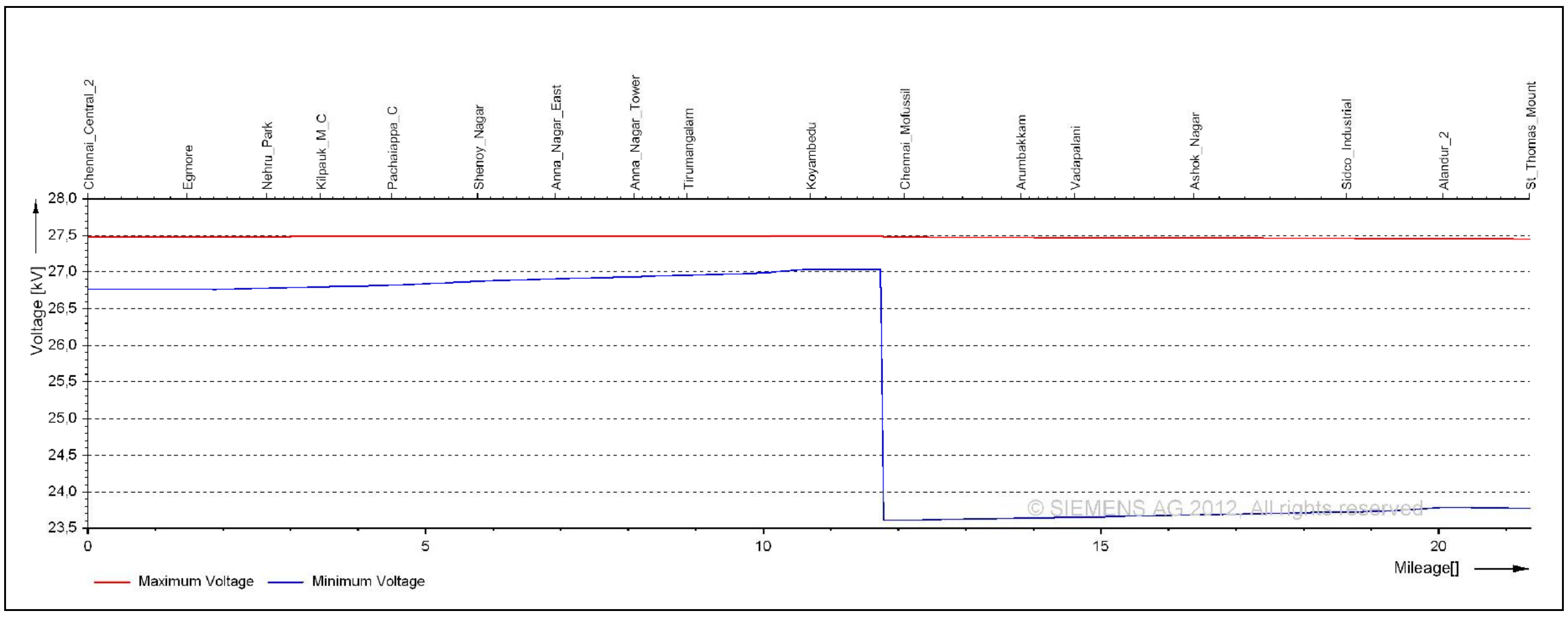

Figure 6-1: Minimum supply voltage of the trains in corridor 2 in case of an outage of one transformer in each RSS

6.2 Transformer power demand

Table 6-2 shows that for all calculated versions the rated transformer power of 31,5 MVA will not be exceeded in case of normal and outage operation. The maximum r.m.s. power is required in the Base-Scenario (One transformer in each substation in operation) and is about 25,7 MVA.

Version	**r.m.s. – power (continuous 35 min.) [kVA]**
Base	**25 734**
Out. Chennai C.	20 325
Out. Koyambedu	21 990
Out. Alandur fed Chennai Central	20 806
Out. Alandur fed Koyambedu	22 152

Table 6-2: Transformer power for normal and outage operation

Note: With the shown results of the minimum supply voltage (chapter 6.1) and the transformer power (chapter 6.2) demand, the system seems to be able to keep a headway of 2,50 min. in case of an outage of one RSS. BUT this is **not** the scope of this study. Such a operation (2,50 min headway and outage of one RSS) could be analysed in detail in a separate study with respect to all components of the traction power supply system and the protection schematic.

With respect to the minimum short circuit power of the three-phase supplying network (listed in chapter 4.4.5) the r.m.s. mean (long term) unbalance (caused by the traction power supply) is calculated to:

Unbalance at RSS Alandur: 0,772 % (Base)

Unbalance at RSS Chennai Central: 0,388 % (Out. RSS Alandur fed Chennai C.)

Unbalance at RSS Koyambedu: 0483 % (Out. RSS Alandur fed Koyambedu)

6.3 Overhead contact line system

6.3.1 Overhead contact line operation current

The maximum 1 min.-r.m.s. overhead contact line current and the maximum long time-r.m.s.-value are listed in Table 6-3.

Version	Maximum current (1 min.) short term [A]	r.m.s. – current (long term 35 min.) [A]
Base	409	332
Out. Chennai C.	254	210
Out. Koyambedu	**547**	**376**
Out. Alandur fed Chennai Central	478	343
Out. Alandur fed Koyambedu	401	254

Table 6-3: Maximum current and maximum long time-r.m.s. current of the overhead contact line system for normal and outage operation

The long term current carrying capacity at 46,1°C ambient temperature of the overhead catenary system is approx. 689 A, including 20% wear of the contact wire, see chapter 4.4.

Above values show that the calculated long term load is well within its current carrying capacity. Same applies for the short term currents.

Accordingly the design of the overhead contact line fulfils the criterions to supply the vehicles with the required power for all simulated operational states.

Version	Maximum current (1 min.) short term [A]		r.m.s. – current (long term 35 min.) [A]	
	Contact Wire	Messenger Wire	Contact Wire	Messenger Wire
Base	236	173	192	140
Out. Chennai C.	147	107	121	89
Out. Koyambedu	**316**	**231**	**212**	**164**
Out. Alandur fed Chennai Central	276	202	198	145
Out. Alandur fed Koyambedu	231	170	147	107

Table 6-4: Contact wire and messenger wire distribution according to chapter 4.4.3 (sharing ratio applied at values of Table 6-3)

6.3.2 Overhead contact line sizing – fault condition

The short-circuit capability of the cables depends on the short-circuit current and on the fault clearing time of the network protection. The typical rated short-circuit current of the used copper conductors are as follows:

Cross section	rated short-circuit current (for a fault clearing time of = 1 s)
150 m² copper	21,45 kA
65 mm² copper	9,3 kA

Note: The rated short-circuit currents of the both conductors above are for cable components. In case of wire applications without insulation, the rated short-circuit current values are clearly higher.

The maximum short circuit current of 8,73 kA is lower than the rated short-circuit current of the chosen copper conductors.

6.4 Earth cable currents – during operation

6.4.1 Buried earth cable currents

The maximum long time-r.m.s. values of the buried earth cable current are listed in Table 6-5.

Version	r.m.s. – current (long term 35 min.) [A]
Base	**61**
Out. Chennai C.	40
Out. Koyambedu	54
Out. Alandur fed Chennai Central	45
Out. Alandur fed Koyambedu	58

Table 6-5: Maximum current and maximum long time-r.m.s. current of the buried earth cable for normal and outage operation

A long term current load of the buried earth cable under 1,8 A/mm² is well within its limits for the current carrying capacity of the conductor.

6.4.2 Aerial earth conductor currents (in tunnel)

The maximum long time-r.m.s. values of the aerial earth conductor (in tunnel) current are listed in Table 6-6.

Version	r.m.s. – current (long term 35 min.) [A]
Base	104
Out. Chennai C.	55
Out. Koyambedu	55
Out. Alandur fed Chennai Central	**124**
Out. Alandur fed Koyambedu	55

Table 6-6: Maximum current and maximum long time-r.m.s. current of the aerial earth conductor (in tunnel) for normal and outage operation

The long term current carrying capacity at 46,1°C ambient temperature of the AEC (in tunnel) is approx. 300 A, see chapter 4.4..

Above values show that the calculated long term load is well within its current carrying capacity.

6.5 Earth cable currents – fault conditions

The BEC and the AEC are connected on both sides to the earth structure and to other parts of the return conductor structure. In case of a short circuit, the short circuit current flows throw both sides of the conductor. The maximum short circuit current of 8,73 kA is deduce in chapter 4.4.5.1.

The short-circuit capability of the cables depends on the short-circuit current and on the fault clearing time of the network protection.

6.5.1 Buried earth cable sizing – fault condition

The effective cross section for the short circuit current is 2 x 35 mm² (Copper) = 70 mm² (Copper). The typical rated short-circuit current of a 70 mm² copper cable is as follows:

Cross section	rated short-circuit current (for a fault clearing time of = 1 s)
70 mm² copper	10,0 kA

The maximum short circuit current of 8,73 kA is lower than the rated short-circuit current of the chosen cables.

6.5.2 Aerial earth conductor sizing – fault condition

The effective cross section for the short circuit current is 2 x 93 mm² (Aluminium) = 186 mm² (Aluminium). The typical rated short-circuit current of a 186 mm² Aluminium cable is as follows:

Cross section rated short-circuit current (for a fault clearing time of = 1 s)

186 mm² aluminum 17,5 kA

The maximum short circuit current of 8,73 kA is clearly lower than the rated short-circuit current of the chosen cables.

6.6 Feeder cable and return feeder cable operation current

A 240 mm² cable of type 2XS2Y 1x240 RM/25 26/45kV (XLPE insulated cable with copper conductor, copper screen and PE outer sheath) was assumed as feeder cable [RD 9]. The continuous current carrying capacity is:

- approx. 605 A in air
- approx. 470 A in earth

by considering:

- ambient temperature air 40°C
- ambient temperature earth 30°C
- max. operating temperature 90°C
- thermal soil resistivity 1,0 Km/W
- Load factor 0,7

6.6.1 Switchgear feeding cable currents

The maximum long time-r.m.s. value of the switchgear feeding cable (cable connection between transformer and switchgear) current are listed in Table 6-7.

Version	**Maximum current (1 min.) short term [A]**	**r.m.s. – current (long term 35 min.) [A]**
Base	**1 374**	**935**
Out. Chennai C.	986	738
Out. Koyambedu	1 132	799
Out. Alandur fed Chennai Central	1 025	756
Out. Alandur fed Koyambedu	1 137	805

Table 6-7: Maximum long and short time-r.m.s. current of the switchgear feeding cables for normal and outage operation

The assumed cable connection (4x240mm² copper) between the transformer and the switchgear is sufficient.
I.e. the currents listed in Table 6-7 are well within the continuous current carrying capacity of the assumed cable for laying in air as well as in earth (with a worst case reduction factor of 0,54, for some cable laying condition with a safety margin).

6.6.2 Return cable currents

The maximum return cable (cable connection between rails of one track and return bus bar) current and the maximum long time-r.m.s. value are listed in Table 6-8.

Version	Maximum current (1 min.) short term [A]	r.m.s. – current (long term 35 min.) [A]
Base	**763**	517
Out. Chennai C.	559	452
Out. Koyambedu	745	**544**
Out. Alandur fed Chennai Central	479	353
Out. Alandur fed Koyambedu	509	353

Table 6-8: Maximum long and short time-r.m.s. current of the return cables for normal and outage operation

The assumed cable connection (4x240mm² copper) between the rails of one track and return bus bar is sufficient.

I.e. the currents listed in Table 6-8 are well within the continuous current carrying capacity of the assumed cable for laying in air as well as in earth (with a worst case reduction factor of 0,54, for some cable laying condition with a safety margin).

6.6.3 Track feeding cable currents

The maximum track feeding cable (cable connection between 25 kV switchgear and track) current and the maximum long time-r.m.s. value are listed in Table 6-9.

Version	Maximum current (1 min.) short term [A]	r.m.s. – current (long term 35 min.) [A]
Base	450	302
Out. Chennai C.	338	263
Out. Koyambedu	**558**	**391**
Out. Alandur fed Chennai Central	479	344
Out. Alandur fed Koyambedu	409	261

Table 6-9: Maximum long and short time-r.m.s. current of the track feeding cables for normal and outage operation

The assumed cable connection (2x240mm² copper) between the switchgear and the corresponding overhead contact line system is sufficient.

I.e. the currents listed in Table 6-9 are well within the continuous current carrying capacity of the assumed cable for laying in air as well as in earth (with a worst case reduction factor of 0,54, for some cable laying condition with a safety margin).

6.7 Feeder, return feeder and track feeder cable sizing – fault conditions

One cable of the 240 mm² copper cable should be able to carry the short circuit current during fault conditions. The rated short-circuit current of the chosen 240 mm² copper cables are as follows:

Cross section	rated short-circuit current (for a fault clearing time of = 1 s)
240 mm² copper	34,3 kA

The maximum short circuit current of 8,73 kA is clearly lower than the rated short-circuit current of the chosen cables.

6.8 Energy consumption

The following energy consumptions represent the total values of all three substations at 110 kV-level, supplying the traction power system. The recuperated energy into the 110 kV network is in all simulated scenarios **zero**. The listed recuperated energy is the energy recuperated by the trains into the contact line system (25 kV traction network) at the pantograph.

Version	Total Energy (110 kV) [kWh]	Recuperated Energy (25 kV) [kWh]
Base	**32 209**	**9 330**
Out. Chennai C.	16 449	4 918
Out. Koyambedu	16 627	4 835
Out. Alandur fed Chennai Central	16 481	4 997
Out. Alandur fed Koyambedu	16 833	4 576

Table 6-10: Total energy consumption for 35 min. of operation

The maximum energy consumption with 32,2 MWh is during the base simulation.

Annotation recuperated energy:

During braking mode of a train, energy will be recuperated. This energy is used for the auxiliary loads (e.g. lighting and air conditioning) of the train. The remaining energy is fed into the contact line system and supplies other trains. In case of a voltage limit on the contact line is exceeded, the remaining energy will be absorbed by the mechanical breaks of the train. In the calculation model for the recuperated energy the respective efficiency factors are considered.

6.9 Power fluctuation to the 110 kV network

In the simulated variants, no energy will be recuperated to the utility network. Due to the fact, that the transformer power will not be minus when trains were operated in both schedule headway of 2:30 min. and 5 min. Refer to the simulation result of each condition, it is shown that the trend of active power in each condition don't have any minus in graph as follows:

- Schedule 2:30 minutes headway in condition of normal operation and outage of one transformer refer to Figure 7-5 to Figure 7-9.
- Schedule 5 minutes headway in condition of outage of one RSS refer to Figure 7-10 to Figure 7-22.

7 Appendices

7.1 Schedule 2,5 minutes headway

The following figure shows the schedule for the 2,5 minutes headway in corridor 1.

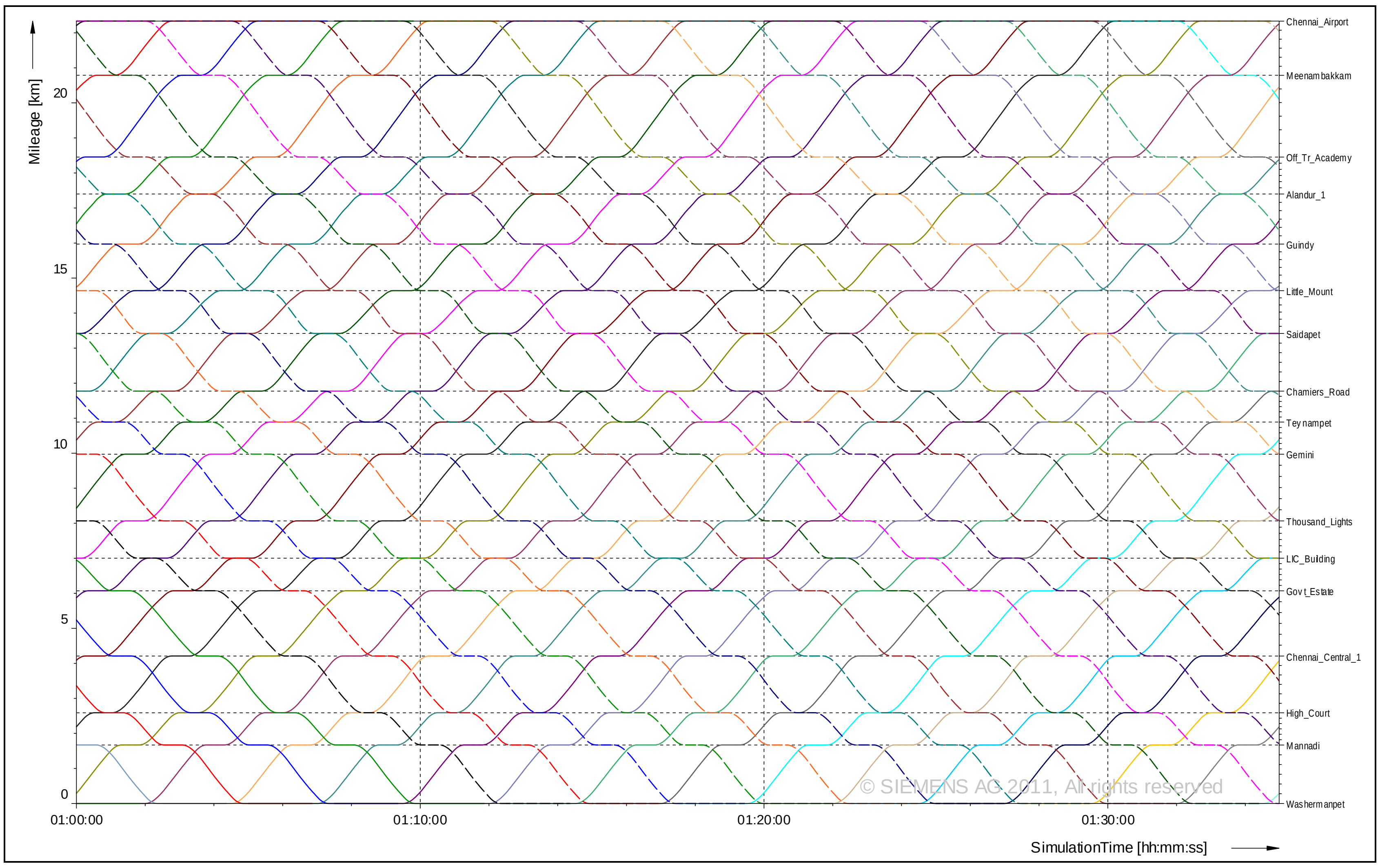

Figure 7-1: Train schedule 2,5 minutes headway – corridor 1

Description of the schedule table in Figure 7-1 with explanation to the trip time (travelling from "Chennai Airport" to "Washermanpet") of one train: The train, which leave the station "Chennai Airport" at simulation time 1:02:00 is referenced with the dashed magenta line. The train leaves the station "Chennai Airport" at after 120s of waiting and arrives at station "Washermanpet" at simulation time 1:35:00. The corresponding train (see dark magenta trace) leaves the station "Washermanpet" at simulation time 1:02:00 (also after 120s of waiting) and arrives at station "Chennai Airport" at simulation time 1:35:00. Hence, the complete turn around time of one train is 70 min.

The following figure shows the schedule for the 2,5 minutes headway in corridor 2.

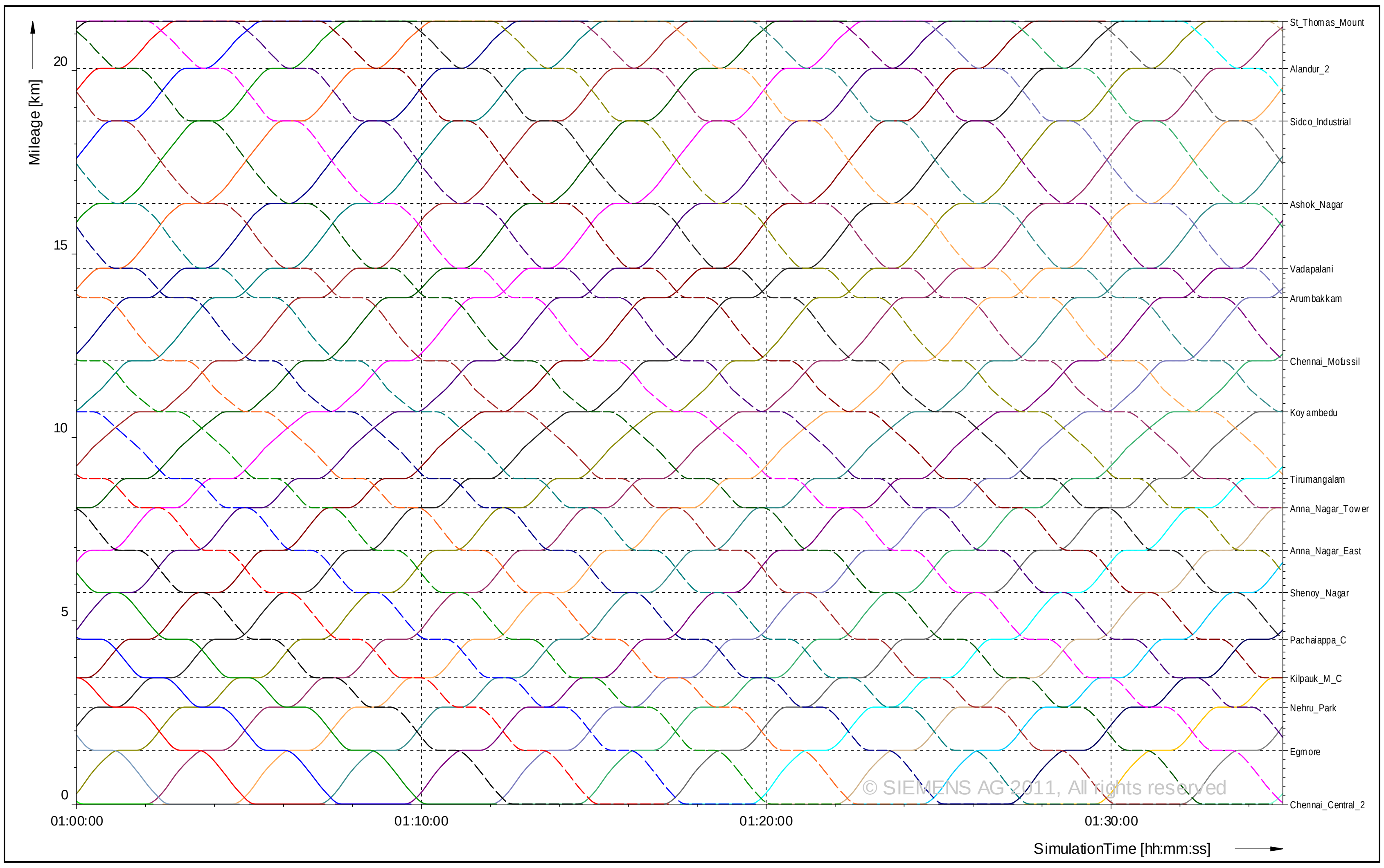

Figure 7-2: Train schedule 2,5 minutes headway – corridor 2

7.2 Schedule 5 minutes headway

The following figure shows the schedule for the 5 minutes headway in corridor 1.

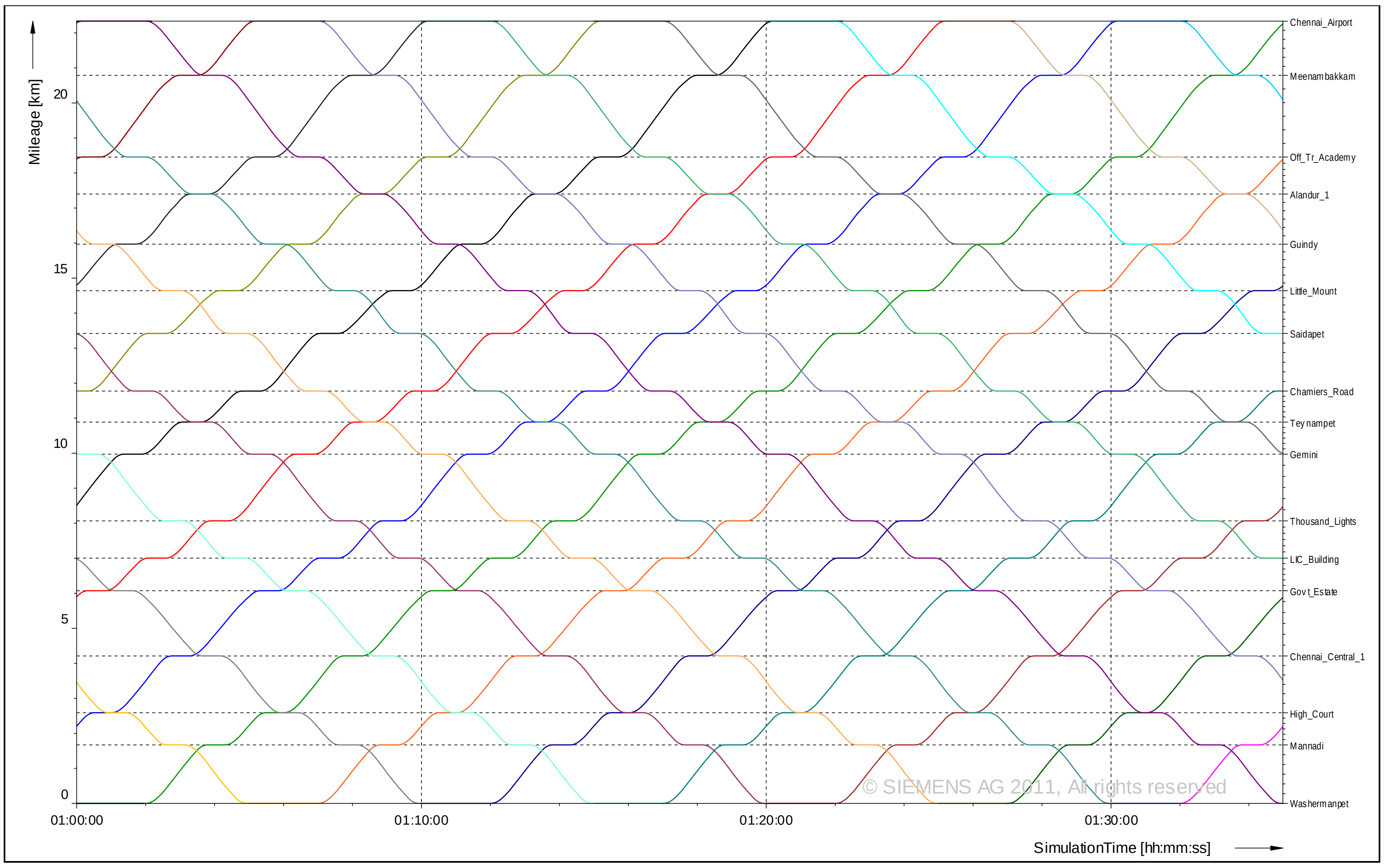

Figure 7-3: Train schedule 5 minutes headway – corridor 1

The following figure shows the schedule for the 5 minutes headway in corridor 2.

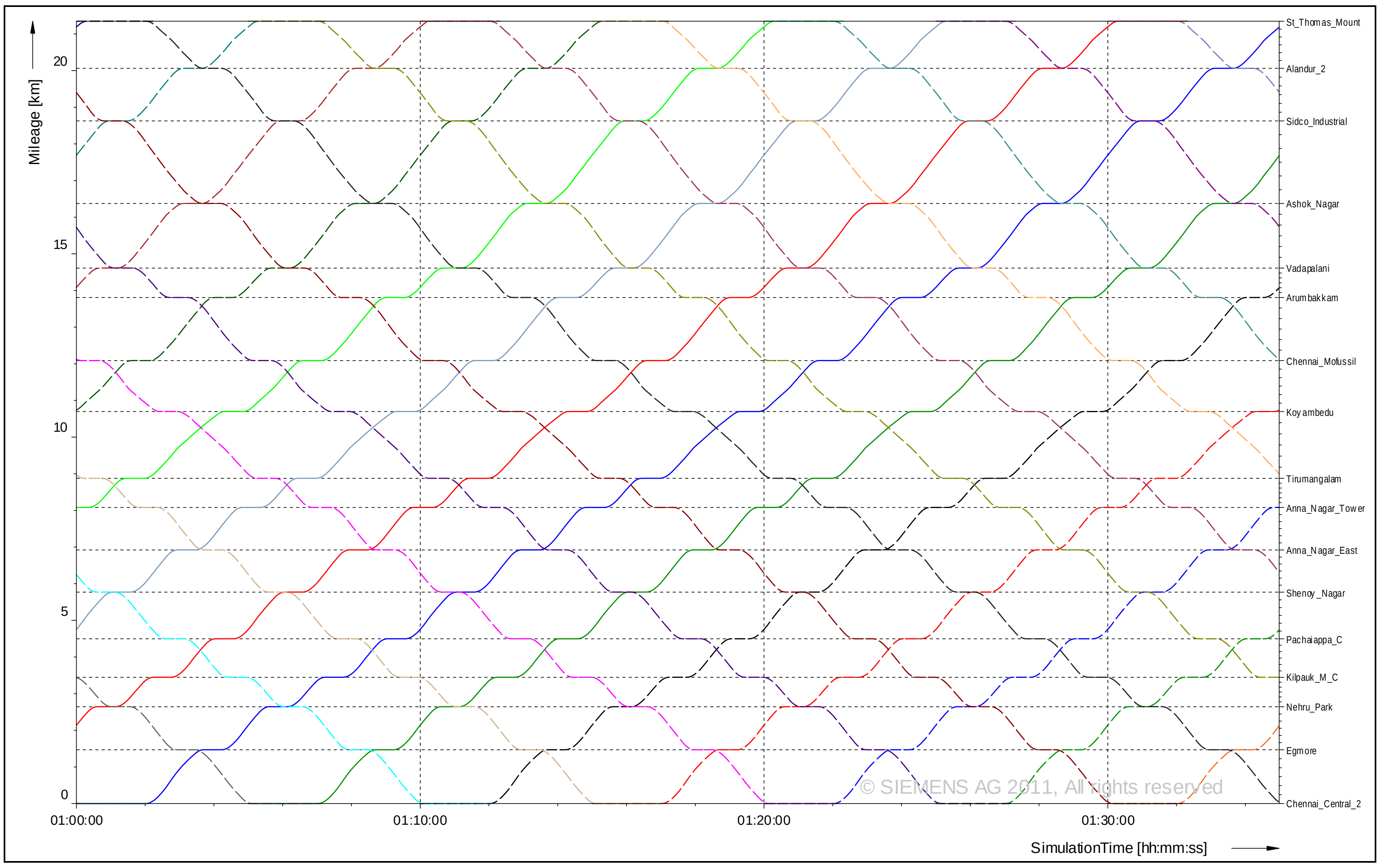

Figure 7-4: Train schedule 5 minutes headway – corridor 2

7.3 Traction transformer power flow

The following figures show the power flow of traction transformer at following locations:

- Chennai Central RSS
- Alandur RSS
- Koyambedu RSS

In detail, the following figures show three graphs with instantaneous values of:

- Total Power (represent the total Power at the high voltage side of the traction transformer)
- Power (represent the total power at the medium voltage side of the traction transformer)
- Losses (represent the losses in the power transformer)

7.3.1 Normal operation (one transformer in each RSS in operation)

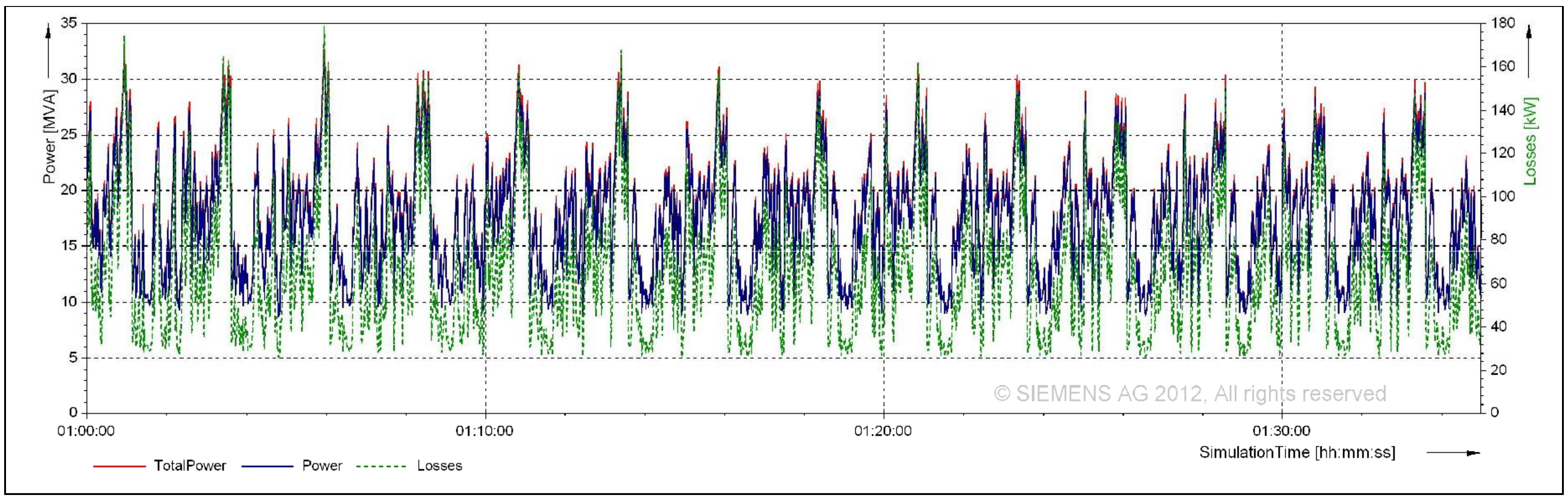

Figure 7-5: Power flow traction transformer (high voltage side) at Chennai Central RSS

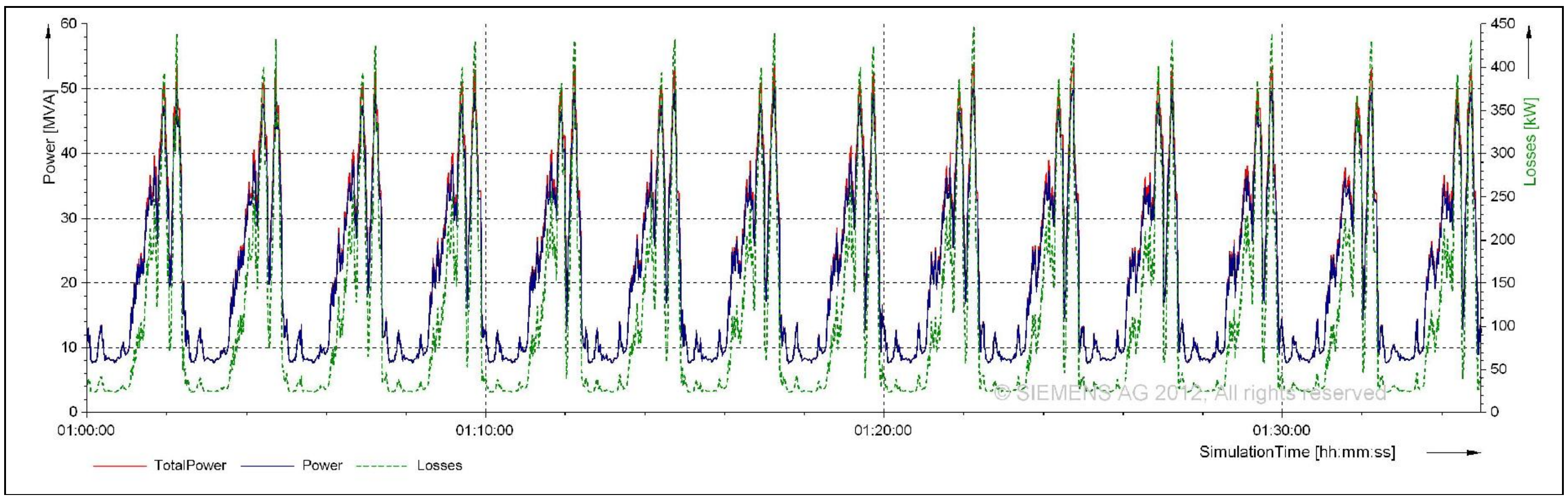

Figure 7-6: Power flow of traction transformer (high voltage side) at Alandur RSS

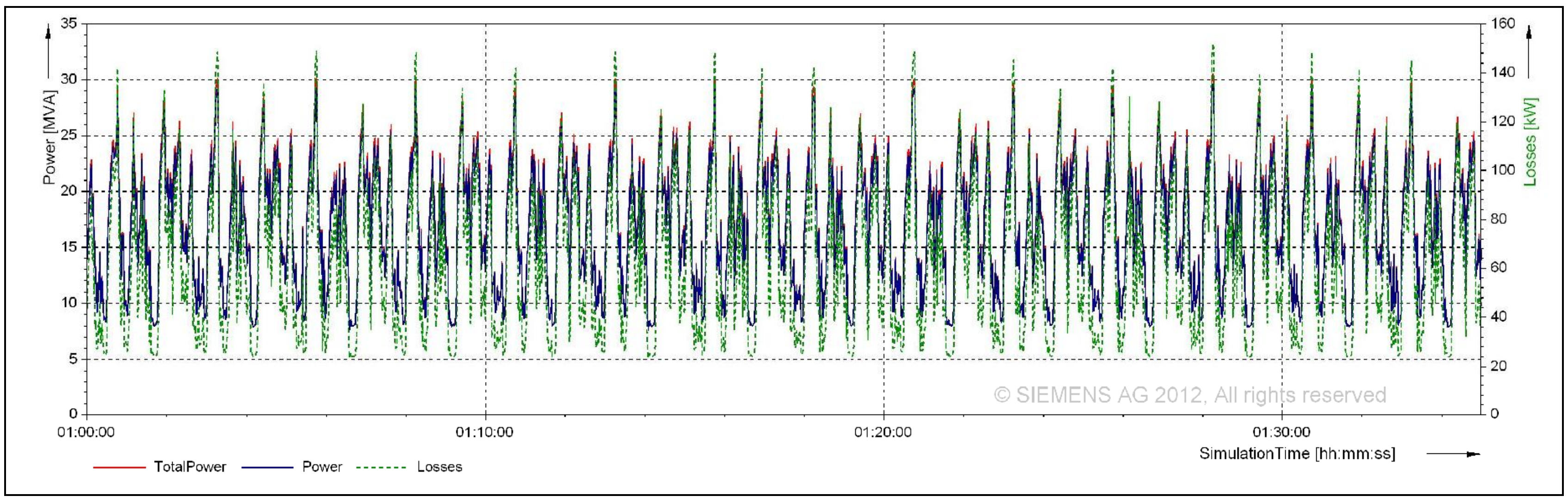

Figure 7-7: Power flow of traction transformer (high voltage side) at Koyambedu RSS

7.3.2 Outage of one RSS

7.3.2.1 Outage of Chennai Central RSS

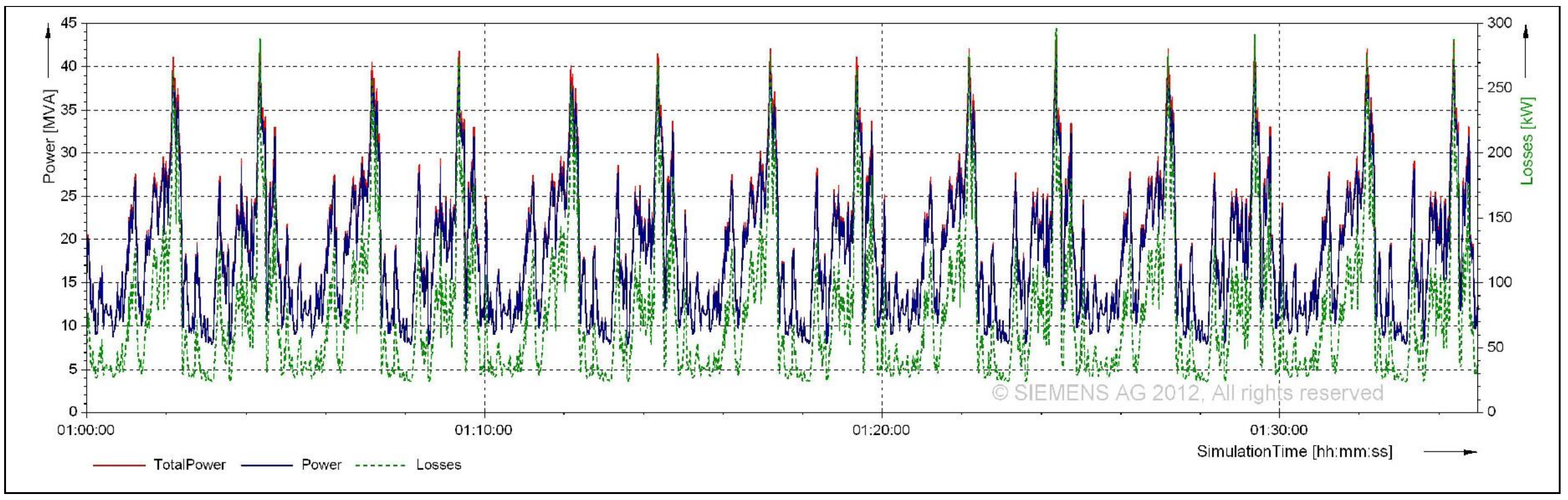

Figure 7-8: Power flow traction transformer (high voltage side) at Alandur RSS (Outage of Chennai Central RSS)

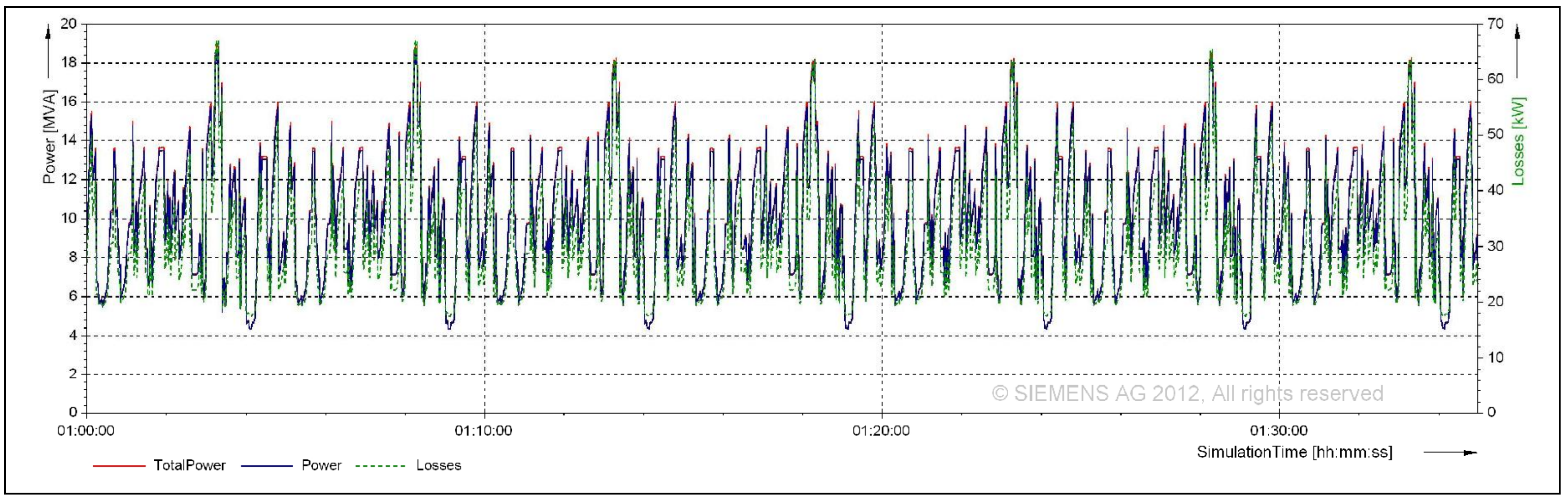

Figure 7-9: Power flow traction transformer (high voltage side) at Koyambedu RSS (Outage of Chennai Central RSS)

7.3.2.2 Outage of Koyumbedu RSS

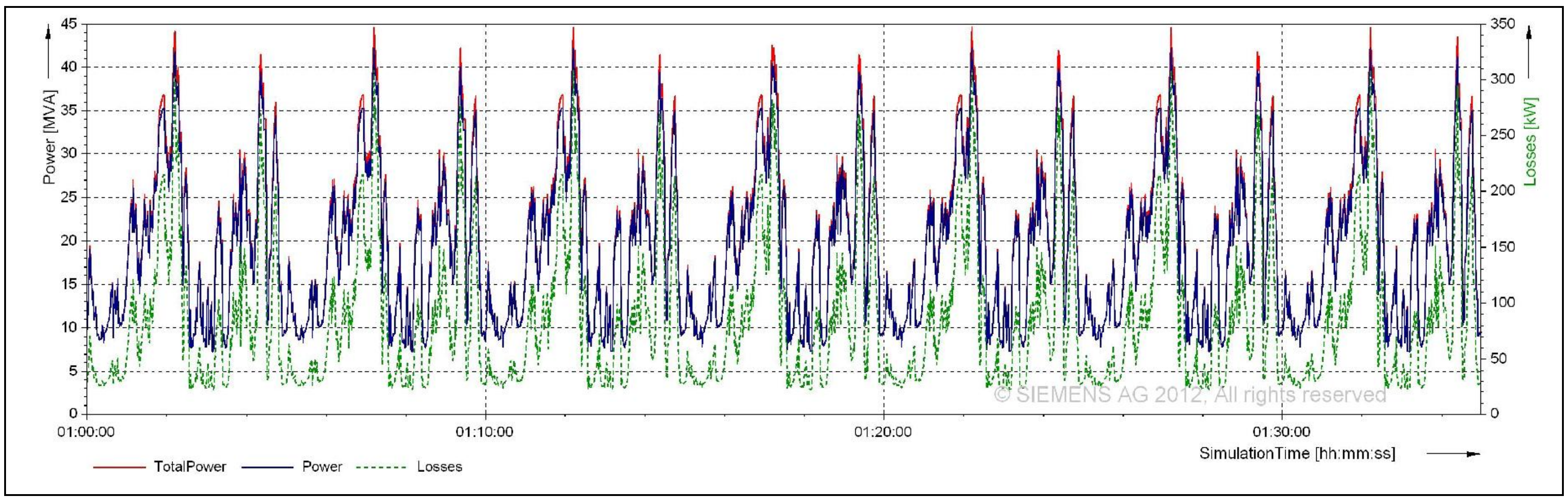

Figure 7-10: Power flow traction transformer (high voltage side) at Alandur RSS (Outage of Koyumbedu RSS)

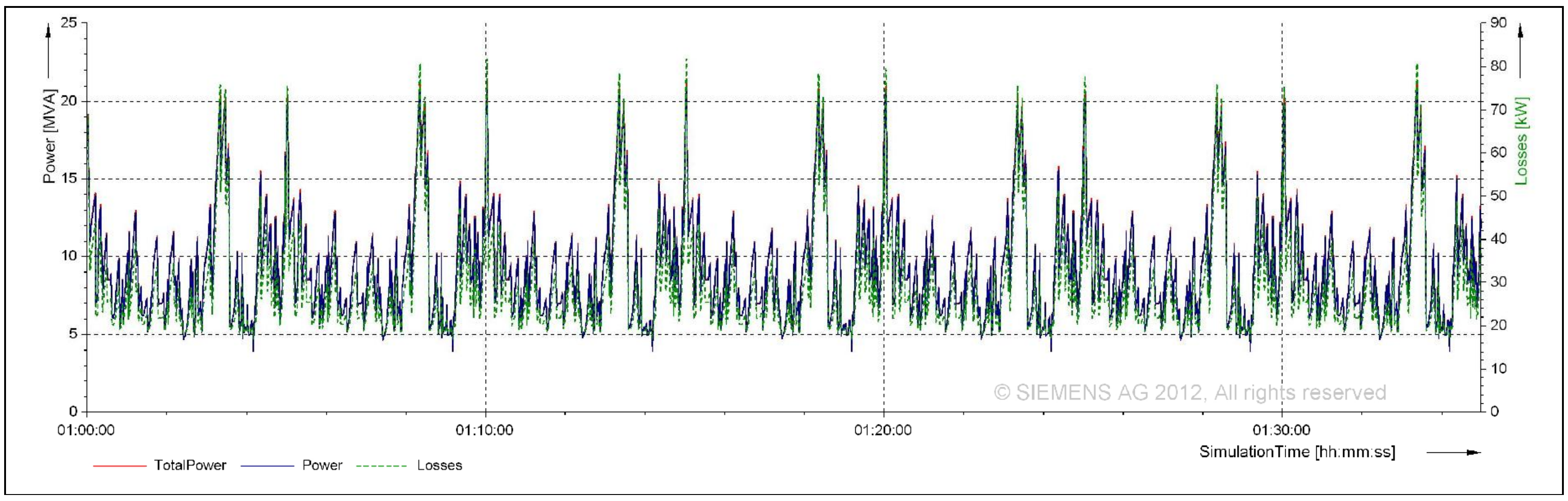

Figure 7-11: Power flow traction transformer (high voltage side) at Chennai RSS (Outage of Koyumbedu RSS)

7.3.2.3 Outage of Alandur RSS fed Chennai Central

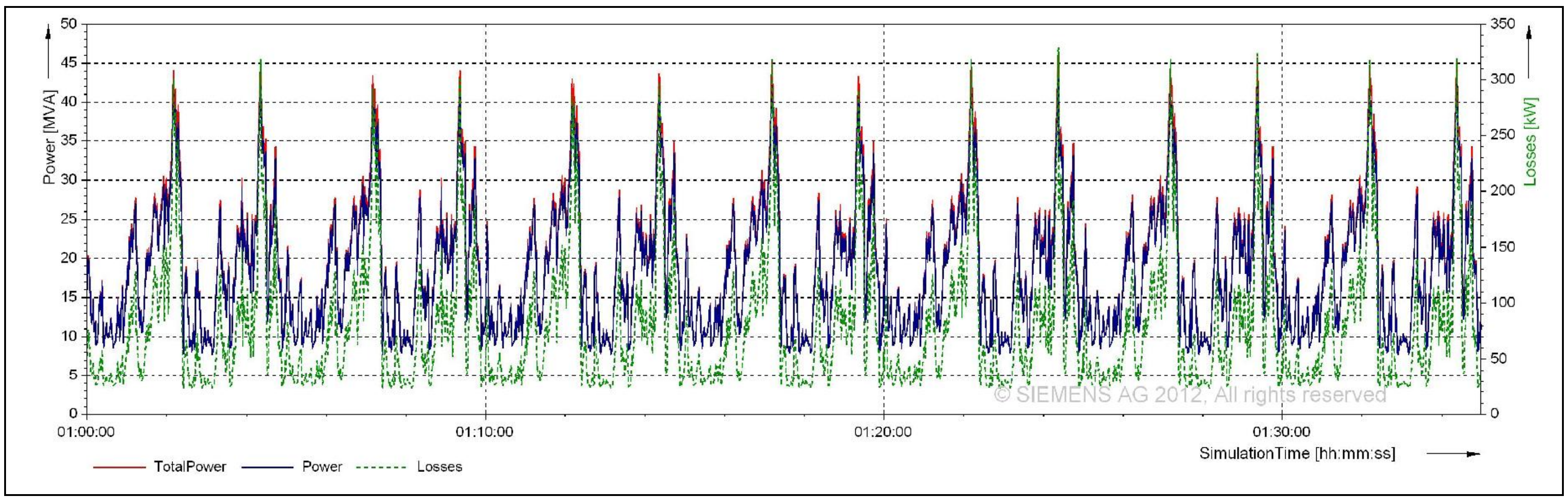

Figure 7-12: Power flow traction transformer (high voltage side) at Chennai RSS (Outage of Alandur RSS)

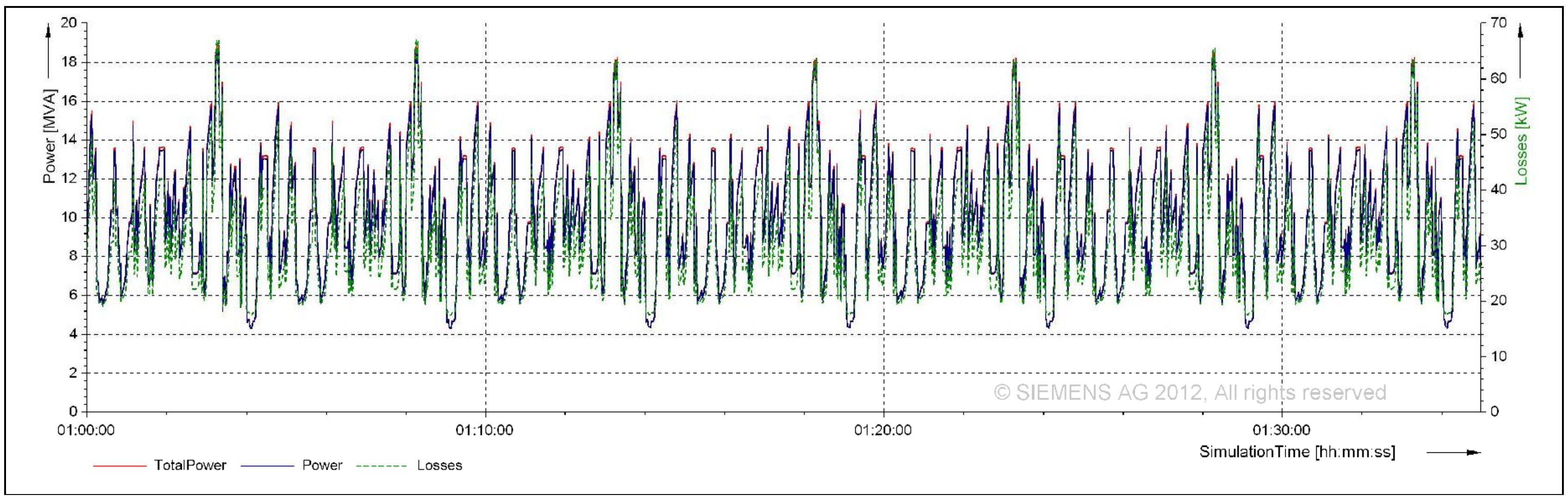

Figure 7-13: Power flow traction transformer (high voltage side) at Koyambedu RSS (Outage of Alandur RSS)

7.3.2.4 Outage of Alandur RSS fed Koyambedu

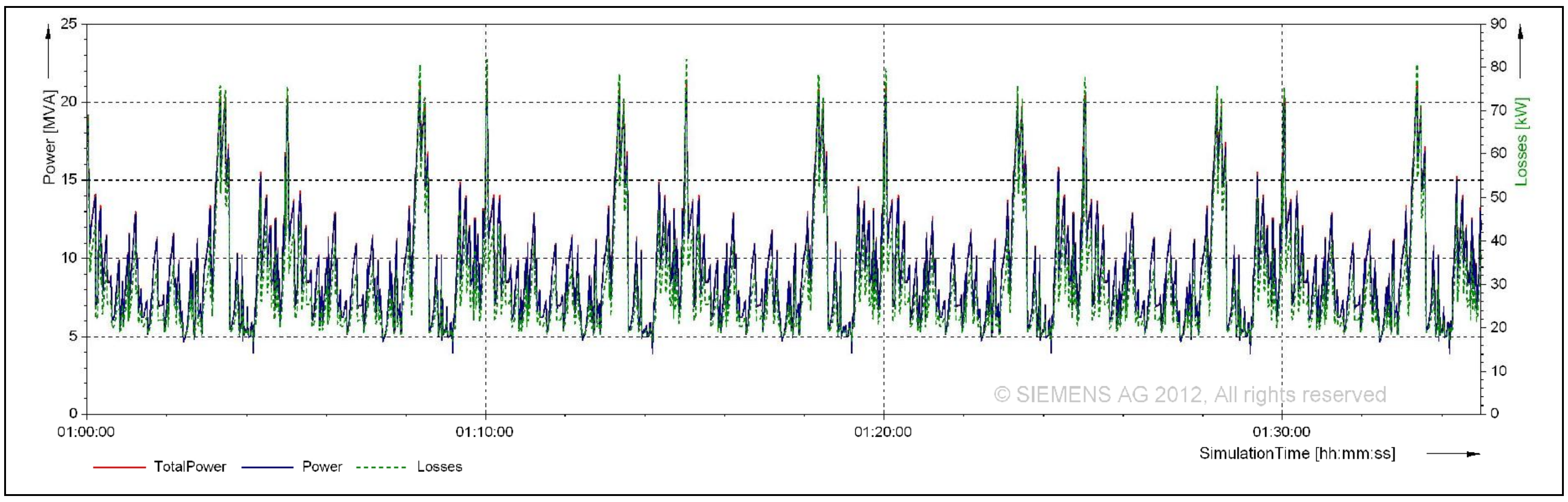

Figure 7-14: Power flow traction transformer (high voltage side) at Chennai RSS (Outage of Alandur RSS)

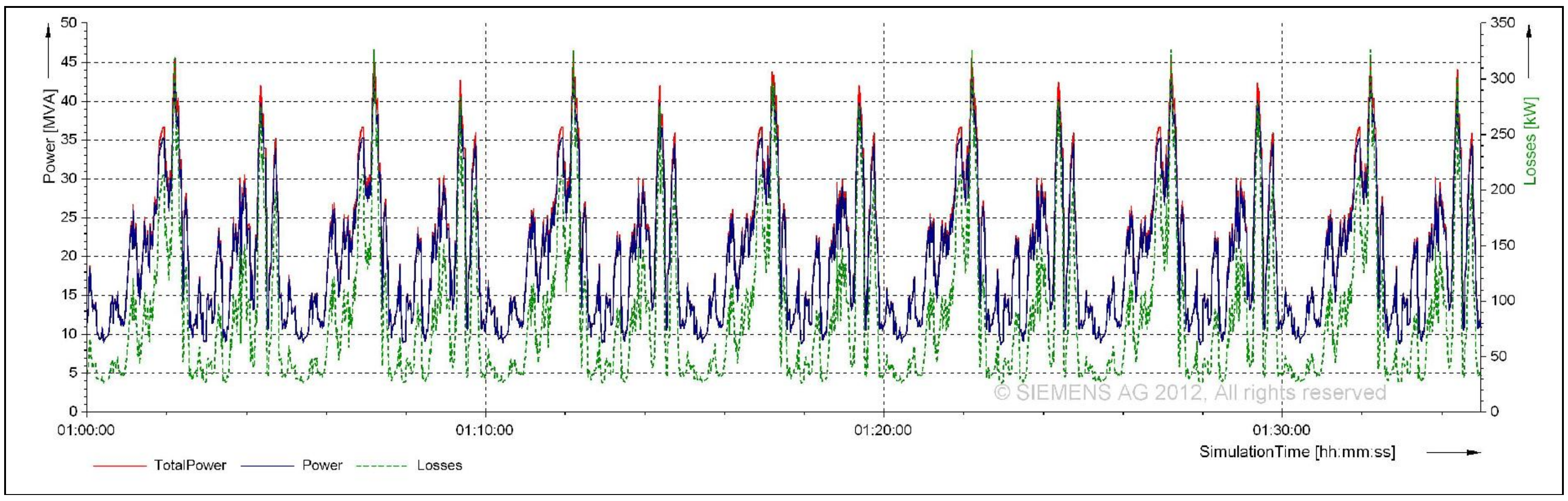

Figure 7-15: Power flow traction transformer (high voltage side) at Koyambedu RSS (Outage of Alandur RSS)