NES NORDIC ELECTRIC POWER CO-OPERATION	TECHNICAL SPECIFICATION FROM THE NES GROUP	TS 02 PAGES: 87 ENCLOSURES: 9 DATE: 01.07.2009

Requirements on rolling stock in Norway and Sweden regarding EMC with the electrical infrastructure and coordination with the power supply and other vehicles

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1 EXECUTIVE SUMMARY

The international standards EN 50 121, EN 50 163, EN 50 238, EN 50 388, and others, define the framework for the electrical compatibility between the rolling stock and the infrastructure systems on electrified railways. However, since the infrastructure systems for historical reasons are not equal in all countries, each national rail administration must define the detailed application of the standards in that country, and specify additional requirements in fields that are not covered by the standards. The present document defines the details of the electrical railway infrastructure in Norway and Sweden, and specifies the electrical compatibility requirements for the rolling stock. In general, these requirements are in accordance with the relevant standards, but certain technical differences exist, also compared to the systems in the other 16.7 Hz countries Germany, Austria, and Switzerland.

1.1 General Characteristics

The following is a prioritized list of the problems and general system characteristics that have typically caused train suppliers the greatest difficulties when introducing a new vehicle in the Norwegian and/or Swedish railway network:

1. Low frequency power oscillations, when supplied from rotating converters
2. High levels of line voltage distortion, in particular the 3rd and 5th voltage harmonics, and high crest voltages
3. Regenerative braking and line voltage limitation
4. Power factor control for improvement of the power capacity of weak supply lines
5. The weak power supply in general, characterized by long feeding distances, single-track lines, small rotating as well as static 50 Hz to 16 2/3 Hz converter stations, and a high number of phase-angle controlled vehicles

1.2 Technical Requirements

1.2.1 Signal interference and telecommunication

Ref.	System	Requirement / interference limit	Details
S1	DC (S only)	25 A, and limits for the DC component at transformer inrush.	*3.2.1*
S2	95 Hz and 105 Hz (N only)	1.00 A. Monitoring required.	*3.2.2*
S3	TI21 track circuits (N only) 16 bands 1532 Hz to 2610 Hz	TBD A	*3.2.3*
S4	FTGS track circuits (N only) 4 bands 4.75 kHz to 6.25 kHz 8 bands 9.5 kHz to 16.5 kHz	1.00 A 0.50 A	*3.2.4*
S5	Psophometric currents	1.50 A	*3.2.5*
S6	Broad-band (N only) TBD-7 kHz 7-9 kHz > 9 kHz	1.00 A 0.50 A 0.33 A	*3.2.6*
S7	Radiated interference	According to EN 50 121-3-1	*3.2.7*
S8	Outside antennas	According to EN and BVS standards.	*3.2.8*
S9	Resistance between wheelsets	< 0.1 Ω.	*3.2.9*

1.2.2 Power supply compatibility

Ref.	System	Characteristics / requirements	Details
P1	Line voltage levels	U_{min2} = 10 kV (N only). Voltage jumps may occur at any level between U_{min2} and U_{max2}.	*4.3.1*
P2	Line voltage frequency	The line frequency is 16 2/3 Hz. The railway power supply is synchronized to the 50 Hz mains.	*4.3.2*
P3	Line voltage distortion	The line voltage may be heavily distorted, with up to 5 kV 3rd and 5th harmonic. The crest voltage may exceed 30 kV.	*4.3.3*
P4	Neutral sections	Procedural requirements for the loco driver.	*4.3.4*
P5	Power factor (cos(φ))	The limits for cos(φ) are more strict, compared to EN 50 388. It is generally only possible to regenerate any significant power back into the weak supply system, if a power factor (cos(φ)) control is applied.	*4.3.5*
P6	Maximum line current limitation	Procedural requirements for the loco driver.	*4.3.6*
P7	Current or power control at low line voltage	The power control specified by EN 50 388 is of particular importance due to the weak supply.	*4.3.7*
P8	Low frequency power oscillations	The rotating converters have a poorly damped eigen-frequency at approximately 1.6 Hz. The vehicles must not cause the system to become unstable at any condition.	*4.3.8*
P9	Electrical resonance stability	The input admittance of the vehicles must be passive at all frequencies > 90 Hz.	*4.3.9*
P10	Current harmonics	The limits for the 3rd, 5th, 7th, and 9th current harmonic are 5.0%, 3.0%, 3.0%, and 3.0%, respectively, of the rated current of the vehicle.	*4.3.10*
P11	Relay coordination	In accordance with EN 50 388.	*4.3.11*
P12	Transformer inrush (AC)	The peak inrush current must be < 2.00 kA.	*4.3.12*
P13	Regenerative braking	The vehicle must not cause the line voltage to increase above 17.5 kV (S) or 18.0 kV (N), in regenerative braking. The vehicle must not cause the voltage locally at other types of vehicles to exceed 17.5 kV to any greater extent than what is seen in the existing system (S only).	*4.3.13*
P14	Train heating	In accordance with UIC standards. Inrush tests required.	*4.3.14*
P15	Energy measurement	The ERESS (European Railway Energy Settlement System) system is used.	*4.3.15*
P16	Other electrical equipment	Certain requirements regarding equipment in the driver's cab.	*4.3.16*
P17	Ice on the overhead line	Significant DC levels have been measured in the primary currents of existing vehicles at OHL ice conditions.	*4.3.17*

1.3 Approval Procedures and Tests

The table below outlines the tests that are required for approval. The time needed for the tests depend on a) the number of different operation modes for the vehicle, and b) the free time on the closed track the actual time periods for testing. Most tests must be performed night-time. Experience shows that the categories T1 and T2 require at least two nights each plus transport time, and category T3 1-2 days. In Sweden, category T4+T5 is generally also one day due to the transport. It is expected that category T6 is performed at the suppliers workshop or similar facilities.

It should be noted that these approximate time indications are valid only for a vehicle that is *in its final and approvable state, with all software functions and all parameters frozen*. Any tests required for the supplier's own purposes (i.e., to make the vehicle approvable, or for fine-tuning of software) come in additional and up front.

The test categories T1, T2, and T4 may be performed in either country. The mixed traffic tests T3 must be performed in the country/countries where the vehicle will operate. Test T5 must be performed in Sweden. The tests T6 may be performed anywhere with 16 2/3 Hz or 16.7 Hz supply. For an approval in Norway, parallel measurements in the substation must be made during test T1.

Three different acceleration-brake operation sequences are defined: LOOP, ABAB, and ARO (please refer to section 3.3.4 and 4.4.4).

Cat.	**Condition**	**Suitable test sites**	**Scope and train operation**	**Max. line speed**
T1	Closed track, rotating converters	Alvesta-Emmaboda (S) Hønefoss-Nesbyen (N)	S1-S6 (LOOP) P1, P2, P5-P10, P13 (ABAB, ARO)	< 130 km/h
T2	Closed track, static converters	Eskilstuna-Södertälje (S) Gardermoen line (N)	S1-S6 (LOOP) P1, P2, P5-P10, P13 (ABAB, ARO, voltage jump)	200 km/h
T3	Mixed traffic	Borlänge area (S) Oslo area (N)	S1-S6, P1-P3, P5-P10, P13 (Normal operation)	
T4	Transformer inrush (peak AC)	Ockelbo (S) Oslo S (N)	P12	
T5	Transformer inrush (DC, S only)	Ockelbo (S)	S1	
T6	Other tests	Any possible	S7, P14	
T7	Non-test approval	N/A	S8, S9, P4, P11, P15-P17	

All vehicles must perform tests up to their speed limit during test category T2. Locomotives must be loaded by a reasonably heavy train (≈ 1-2 t per kN max. tractive effort, or ≈ 50-100 t per MW max. power, whichever is the greater) during all tests T1 and T3, in order to create realistic acceleration times. During tests T2, a somewhat lighter load may be used (some 25% of the values above).

1.4 Deliverables

The supplier must deliver the following documents and other information regarding electrical compatibility.

Before testing:

- Clause-by-clause comments to the present specification section 3 and 4, explaining how the technical requirements are met
- Calculated, previously measured, or otherwise estimated signaling interference and psophometric current levels
- The input admittance versus frequency characteristics
- A simulation study regarding low frequency power oscillations
- Descriptions and characteristics of key functions, such as the current or power control at low line voltages, voltage limitation at regenerative braking, cos(φ)-control, etc.
- Calculations regarding the voltages locally at other types of vehicles (S only)
- Design descriptions, main circuit diagrams, data sheets, and other relevant general information
- Test reports and other documentation showing that the vehicle meets the radiated interference requirements of EN 50 121-3
- Documentation that the vehicle is compatible with relevant requirements outside the field of EMC (such as running dynamics, kinematic envelope, braking performance, etc.), to obtain track access for the EMC tests
- A test plan, including descriptions of the instrumentation and data analysis

After testing:

- The test report, including individual conformity statements for each requirement S1-S9 and P1-P16, and including explanations, references to the detailed test results and printouts, and so on.

Before operation:

- Vehicle data for power system studies

2 INTRODUCTION

2.1 Abstract

The international standards (EN, IEC, UIC, etc.) that deal with electromagnetic and functional compatibility between railway vehicles and infrastructure, are kept on a quite general level and do not cover all aspects of relevance for each individual country and national rail administration. Typically, different signalling systems are used in different countries, meaning that specific national requirements apply in addition to the common standards.

In Norway and Sweden, not only the signalling systems, but also the power supply differs significantly in comparison with other 16.7 Hz countries.

It is the objective of the present document to compile all relevant information and all requirements that apply to rolling stock used in Norway and Sweden, with respect to compatibility with the electrical infrastructure and other vehicles; i.e. the power supply, existing rolling stock, and infrastructure systems such as track signalling circuits, telecommunication lines, etc.

Jernbaneverket and Banverket are committed to harmonize, as far as possible, not only their technical requirements, but also their requirements regarding approval procedures and tests. It must be noted, however, that due to a number of technical differences between the two countries, this objective cannot be fulfilled for all requirements.

The document is first and foremost based on the standards EN 50 121 part 1 to 5, EN 50 163, EN 50 238 and EN 50 388. This however does not imply that other standards are not valid.

The document concentrates on the special national conditions that are valid for Norway or Sweden, and on topics that are not completely covered by international standards.

The tests described in the document are considered being type tests. This means that if tests are performed in one country, and the test procedures and conditions are representative also for the other country, then the tests, the recorded data, and the results may also be used for the performance evaluation and approval in the other country, even if the limits are different (i.e., tests in one country can provide data also for the other country).

Requirements regarding the mechanical interaction between the pantograph and the contact line are presented in other documents. Furthermore, the requirements on train control systems, such as ATC (= Automatic Train Control) or ERTMS, and interference with train radio and digital systems such as PCM, ISDN, etc., are not included in this document.

2.2 About this document

2.2.1 Structure

This document exists in three versions:

- One full version with all sections 1-4. This version is an appendix to Banverkets document BVS 543:19300.
- One version with the sections 1-3 only, and section 4 left unused. This version is an appendix to chapter 5 in Jernbaneverkets document JD 590.
- One version with the sections 1, 2, and 4 only, and section 3 left unused. This version is an appendix to chapter 4 in Jernbaneverkets document JD 590.

2.2.2 Validity

Section 1 and 2 of this document are for information only. The formal and valid requirements are given in section 3 and 4. In case of any conflicts, section 3 and 4 take precedence over section 1 and 2.

2.2.3 Responsibility

Section 3 of this document is under the responsibility of the signalling departments at Jernbaneverket and Banverket, while the power supply departments are responsible for section 4.

2.2.4 Coordination between sections and document versions

Certain parts of section 3 and 4 are harmonised and to some extent equal, in particular the requirements regarding testing. These sections are marked with a vertical line in the left margin, as shown here. Any changes to these sections should be coordinated between the signalling and the power supply departments.

2.2.5 National differences

Most requirements apply equally in the two countries. If a requirement is valid solely in one country, this is highlighted with a (Norway only) or (Sweden only) in the level three header for that requirement. Sometimes (e.g., in tables), the shorter (N only) or (S only) is used.

If a requirement is different in the two countries, the following identification is made:

NORWAY AND SWEDEN:

Here the parts of the requirement that are common to the two countries are listed. If there are no common requirements, this heading is not used.

NORWAY:

Here the requirements that are specific to Norway are listed.

SWEDEN:

Here the requirements that are specific to Sweden are listed. The “Sweden only”-section goes on until the next level two, level three, or level four heading, whichever is first.

2.2.6 Accuracy

If a requirement is quantitative, i.e. there is a numerical limit; the accuracy of the limit is given by the number of digits used for the requirement.

2.3 Abbreviations and Definitions

2.3.1 Abbreviations

ABAB	Operation sequence (see 4.4.4)
ABS	Absolute value
AC	Alternating current
A/D	Analog to digital conversion
ARO	Operation sequence (see 4.4.4)
AT	Autotransformer
ATC	Automatic train control (called ATP in most countries)
ATP	Automatic train protection (called ATC in the Nordic countries)
BP	Band-pass
BT	Booster transformer
BW	Butterworth
bw	Bandwidth
DAT	Digital audio tape
DC	Direct current
EMC	Electromagnetic compatibility
EMI	Electromagnetic interference
f_C	Centre frequency
FFT	Fast fourier transform
FTGS	Type of track circuit
GPS	Global positioning system
ID	(Data recording) idendity
IIR	Infinite impulse response
I_N	Rated current
LOOP	Operation sequence (see 3.3.4)
N	Norway
N/A	Not applicable
OHL	Overhead (contact) line
P1-P17	Compatibility requirements, power supply systems

PWM	Pulse width modulation
RMS	Root-mean-square
RSS	Root-sum-square
S	Sweden
S1-S9	Compatibility requirements, signalling and telecommunication systems
T1-T7	Test categories
TBD	To be defined
THD	Total harmonic distortion
TI 21	Type of track circuit

2.3.2 Definitions

Bandwidth	In accordance with EN 50 238
Bin	Output from a FFT. For example, a FFT with a 1 s window length produces bins at the frequencies 0 Hz (DC), 1 Hz, 2 Hz, . . .
Closed track	A line section that is single-end fed, and where no other rail vehicles are activated or in operation
Crest voltage	The highest value within one period of the rectified AC voltage. For an ideal sinusoidal voltage, the crest value equals √2 times the RMS value.
Fault mode	Degraded vehicle operation mode with one or more subsystems (converter, filter, or similar) cut-out
Hanning	Weight function used in combination with the FFT, in order to reduce the effect of transients
Normal operation	Vehicle operation mode with all subsystems in intended operation
Quasi-stationary	An operation condition where the variables (e.g., RMS voltage or current) vary so slowly that no oscillations or other dynamic effects are triggered
Rated current	The line current drawn by the vehicle when operating at full power at the nominal voltage of 15.0 kV
RMS	Root-Mean-Square. Please notice that different window lengths are used for different purposes. Generally, the window length is defined as a part of each specific requirement
Spectral leakage	The phenomenon that a FFT bin at a certain frequency is “contaminated” with energy originating from signal components at the frequencies of the neighbouring bins. This is an effect of the Hanning window
Window	Time duration over which data is analysed, e.g., 60 ms or 1 s

2.4 Scope

NORWAY AND SWEDEN:

This document is foremost intended for manufacturers or operators who plan:

A) to specify and design new vehicles for operation in Norway and/or Sweden,
B) to modify or rebuild already existing vehicles, or
C) to introduce already existing vehicles that have not previously been operating in Norway or Sweden.

For this purpose, the document provides detailed information about the infrastructure in the two countries. Some of this information is found in connection with the various requirements, but most is given in the attached appendices.

NORWAY:

The validity and the application of the requirements in this document are defined in the JD 590 "Characteristics of the infrastructure" chapter 1 section 1.4.2. The document JD 590 is an overall document that describes the infrastructure and the compatibility requirements in Norway for all relevant fields. This present document concerning electric compatibility is hence a part of JD 590 as:

- Signal interference is treated in JD 590 chapter 5 "Signalling and train control systems"
- Telecommunication is treated in JD 590 chapter 6 "Telematic applications"
- Power supply is treated in JD 590 chapter 4 "Energy"

SWEDEN:

The requirements in this document are valid for:

- First time use of rolling stock or reintroduction of rolling stock that have been considered out of use permanently.
- Rolling stock that is going to be introduced on sections of track not included in current acceptance.
- Changes, both in hardware and software, in rolling stock usage not in compliance with current acceptance.
- Modifications of rolling stock in a way that may affect the compliance with the current acceptance.

This means that the requirements in this document are valid for new electrical traction vehicle and old used vehicles that have not been used in normal operation in Norway or Sweden before. An old vehicle used in Norway is not automatically accepted in Sweden.

The requirements in this document can however be discussed when applied on imported old vehicles, except for the Electrical Safety and requirements regarding signalling circuits and psophometric currents. Requirements regarding signalling circuits are always valid due to safety aspects. Requirements regarding psophometric currents are valid due to effects for third party.

A summary of how and for which rolling stock the requirements are valid is given in the table below:

Category of rolling stock	**Age of the rolling stock**	
	Vehicle design started after 2007-01-01	**Vehicles designed before 2007-01-01**
Vehicles specifically designed for use in Sweden only	All requirements are mandatory.	Already accepted, but any rebuilds or modifications should aim for improving compatibility, and must not reduce compatibility. For already accepted vehicles, which are to be put in operation on new lines for which the acceptance is not valid, relevant requirements are valid in order to maintain traffic and not to disturb the electrical infrastructure. Relevant requirement are decided on a case-to-case basis.
Vehicles designed for cross border operation, or for use also in other countries	Safety requirements and requirements regarding signalling systems and telecommunications are mandatory. Non-compatibilities with other requirements might be accepted on a case-to-case basis, but only if it can be demonstrated that the requirements are in fundamental conflict with technical requirements from other countries of operation.	Safety requirements and requirements regarding signalling systems and telecommunications are mandatory. Non-compatibilities with other requirements might be accepted on a case-to-case basis, but only if it can be demonstrated that a rebuild would be in fundamental conflict with technical requirements from other countries of operation, or if it can be demonstrated that the cost of a rebuild is out of proportion.
Vehicles originally designed for use in other countries, but imported for future use solely in Sweden	Safety requirements and requirements regarding signalling systems and telecommunications are mandatory. Non-compatibilities with other requirements might be accepted on a case-to-case basis, but only if it can be demonstrated that the cost of a rebuild is out of proportion.	Safety requirements and requirements regarding signalling systems and telecommunications are mandatory. Non-compatibilities with other requirements might be accepted on a case-to-case basis, but only if it can be demonstrated that the cost of a rebuild is out of proportion.

Table 1. Use of the requirements (Sweden only).

2.5 General information about the infrastructure

This chapter gives a short introduction to traction power supply systems and track signalling circuits in Norway and Sweden. More specific data about the infrastructure is given as information in APPENDIX 1: Infrastructure data and related information.

2.5.1 General

In Norway and Sweden the earth resistivity is high in comparison to most of the rest of Europe. This has direct an effect on traction power supply design to avoid disturbing other electrical systems.

2.5.2 Norway

In Norway there are 2500 km of electrified railway (2004). The network around the capital Oslo is meshed with both double and single-track lines. Around this centre there are long (> 500 km) single-track lines to other parts of the country. The Norwegian single-phase network is much weaker than in rest of Europe. In some areas the overhead contact line impedance is so large that changes in the power demand from one train may cause voltage variations up to some kilovolts. Both tap changer vehicles, phase controlled vehicles and inverter vehicles with and without filters operate in the network.

The power supply system is of the type 15 kV, 16.7 Hz. It is synchronized with the 50 Hz national grid, i.e. a decentralized system. There is however a small centralized system in the Oslo area consisting of a 55 kV, 16 2/3 Hz single-phase high voltage transmission line fed by one small hydro power station. This system is connected to the contact lines system via 5 substations (which can be located together with rotary converters).

Apart from the small centralized system the power is fed into the traction power supply system by rotary and static (power electronic) converter stations, which convert the energy from 50 Hz, three-phase, to 16 2/3 Hz, single-phase. The number of active converter units in each converter station is adapted to the hourly variation in load demand to allow maintenance and reduce the losses. There is one small hydro power station feeding directly to the overhead contact line system. In normal operation there is often a one-to-one relation between one converter station capacity and load demand form one train. Due to this, low frequency oscillations have often caused severe problems when new vehicles have been introduced.

In normal operation the system is interconnected between the feeding points, but in order to maintain both rail tracks and contact line, sectioning of the system is a common operation mode.

At present, the booster transformer (BT) system, with or without return conductors, is the main feeding system for contact lines in Norway. However, Jernbaneverket plans to build autotransformer (AT) systems for main long distances lines. There are also some series capacitances and one shunt capacitor in the single-phase network in order to reduce inductive contact line impedance, strengthening the voltage and feeding reactive power. The return path for the traction current, regardless of system and apart from return conductors or any extra earth conductors, always comprise both rails, with exception of stations where single rail track signalling circuits occurs.

On electrified lines AC track signalling circuits are used, either double rail or jointless. Most common are 95 and 105 Hz uncoded track signalling circuits.

ATC equipment type EBICAB 700 is used on most lines.

2.5.3 Sweden

In Sweden there are 9 543 km of electrified railway (2004). The railway network is meshed except for the northern part of Sweden. Most of the lines are single track lines except for lines close to Stockholm and the lines between the cities Stockholm, Gothenburg and Malmö.

The power supply system is of the type 15 kV, 16.7 Hz. The system is decentralized and synchronized with the 50 Hz national grid. The power is fed into the traction power supply system by converter stations, which convert the energy from 50 Hz, three-phase, to 16 2/3 Hz, single-phase. The converters are of both rotary and static (power electronic) type. The number of active converter units in each converter station is adapted to the load.

In order to reduce the number of converter stations, the contact overhead line system is also fed by a 132 kV system (a two-phase 2 x 66 kV system with directly earthed midpoint) with transformer substations. This system is used from the middle to the northern parts of Sweden. There is no power generation connected directly to the 132 kV system. The system is fed from transformers connected to the 15 kV 16,7 Hz busbars at the converter stations.

The two feeding systems for contact lines in Sweden are; BT-system (booster-transformer system) with one or two return conductors and AT-system (auto-transformer system). Sometimes also a strengthening wire (reinforcement wire, booster wire) occurs. This is more common in the northern part of Sweden, and this type of reinforcement wire is always used on AT-systems. Its objective is to lower the impedance. Sometimes an additional earth wire is used. This type of earth wire is planned to become standard on AT-system lines. A combined AT/BT-system is currently under investigation for introduction (a first small installation is made).

Most of the railway lines are fed from both ends (double sided feeding). Due to the high earth resistivity booster transformer systems with return conductors are mainly used, when not autotransformer systems are implemented, due to EMC requirements. This causes normally higher line impedance than in the central and south of Europe, where the return current can use the rails and earth all the way to the feeding point. The system is relatively weak with rather high voltage drops.
Only DC track signalling circuits exist on electrified lines in Sweden. At some non-electrified low traffic lines, radio block systems are used.

Only one of the rails, the S-rail, is used for the return path of the traction current. This is regardless of what type of feeding system that is being used (BT- or AT-system). The other rail is always isolated, I-rail, and is used for the DC track signalling circuits.

ATC equipment type EBICAB 700 is used on most lines.

2.6 Revision history

05-01-2007: First version, based on the NIM NES-R10 report with the same title as this document, from 27.11.2006.

07-01-2009: Second version

3 SIGNALLING SYSTEMS AND TELECOMMUNICATION

(Applies to “Signal interference and telecommunication” only. Please see JD590 chapter 5 and 6)

4 POWER SUPPLY

4.1 REFERENCES

4.1.1 Normative references

No.	**Standard**	**Applicable to**	
		Signalling	**Power**
1.1	EN 50 110-1: Operation of electrical installations. CENELEC, European Standard.		X
1.2	EN 50 121: Railway applications – Electromagnetic compatibility (relevant parts in this context). Part 1: General Part 2: Emission of the whole system to the outside world Part 3-1: Rolling stock – Train and complete vehicle Part 3-2: Rolling stock – Apparatus Part 4: Emission and immunity of the signalling and telecommunication apparatus Part 5: Emission and immunity of fixed power supply installations and apparatus CENELEC, European Standard.	X	X
1.3	EN 50 122-1 Railway applications- Fixed installations Part 1: Protective provisions relating to electrical safety and earthing. CENELEC, European Standard.		X
1.4	EN 50 128: Railway applications – Communications, signalling and processing systems – Sofware for control and protection systems. CENELEC, European Standard.	X	
1.5	EN 50 153: Railway applications – Protective provisions relating to electrical harzards. CENELEC, European Standard.		X
1.6	EN 50 155: Railway applications Electronic equipment used on rolling stock. CENELEC, European Standard.	X	
1.7	EN 50 163: Railway applications – Supply voltages of traction systems. CENELEC, European Standard.		X
1.8	EN 50 207: Railway applications – Electronic power converters for rolling stock. CENELEC, European Standard.		X
1.9	EN 50 215: Railway applications – Test of rolling stock after completion of construction and before entry into service. CENELEC, European Standard.	X	X
1.10	EN 50 238: Railway applications – Compatibility between rolling stock and train detection systems. CENELEC, European Standard.	X	
1.11	EN 50 388: Railway applications – Power supply and rolling stock – Technical criteria for the coordination between power supply (substation) and rolling stock to achieve interoperability. CENELEC, European Standard.		X

1.12	UIC 550, 550-1, 550-2, 550-3: Power supply installations for passenger stock.		X
1.13	UIC 552: Electrical power supply for trains – Standard technical characteristics of the train line.		X
1.14	UIC 554-1: Power supply to electrical equipment on stationary vehicles from local mains system or another source of energy at 220 V or 380 V, 50 Hz.	X	
1.15	UIC 512: Conditions to be fulfilled in order to avoid difficulties in the operation of track circuits and treadles.	X	
1.16	BVS 545.43501: Requirements on external antennas for railway vehicles (only published in Swedish: ”Krav på yttre antenner för järnvägsfordon”). Banverket. Only normative for Sweden.	X	
1.17	ITU-T Recommendation O.41: Psophometer for use on telephone-type circuits.	X	

4.1.2 Other references

No.	Standard	Applicable to	
		Signalling	Power
2.1	HS TSI: Directive 96/48/EC – Interoperability of the trans-European high speed rail system, 96/48 ST14EN03 ENE part 2, Draft from 22.06.2006.	X	X
2.2	Characteristics of infrastructure. Document JD 590. Jernbaneverket, 01.02.2005.	X	X
2.3	Electro-technical requirements on new electrical vehicles regarding compatibility with the power supply system and other electrical vehicles, BKE 00/14, rev. H. Banverket, July 2004.	X	X
2.4	Rotating converters BV/JBV: Description of simulation model. emkamatik document 06-0132, ver. 1. Stefan Menth, emkamatik, 18.9.2006.		X
2.5	EN 61000-4-7, March 1993. Electromagnetic compatibility (EMC). Part 4: Testing and measurement techniques. Section 7: General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto. IEC, CENELEC.		X

4.2 Safety with respect to electricity

4.2.1.1 Information

SWEDEN:

If the vehicle is designed such that it is possible to climb up on the roof of the vehicle without difficulty and without additional means, Banverket will define restrictions for parking the vehicle under live overhead contact line.

4.2.1.2 Requirements

Requirements are in accordance with EN 50 153:
The rolling stock shall be designed such that it is possible to operate the electrical installations in accordance with the following regulations:

NORWAY:

Any valid regulation from the Directorate for Civil Protection and Emergency planning (Direktoratet for Samfunnssikkerhet og Beredskap) must be followed. Information can be found at http://www.dsb.no/

SWEDEN:

Any valid regulation from the National Electrical Safety Board (Elsäkerhetsverket) for operations of electrical installations must be followed. Information can be found at http://www.elsakerhetsverket.se/

If there is any accessible electrical equipment on the roof of the vehicle, it shall be possible to connect the grounding and short-circuiting tools used by Banverket to earth points on the electrical equipment. Otherwise the vehicle must have own grounding tools. According to Elsäkerhetsverket, grounding via a transformer is not allowed.

EN 50 110-1 *Operation of electrical installations* is applicable to work activity on Swedish railway electrical installations with some exceptions and applications to overhead contact line.

NORWAY AND SWEDEN:

Necessary information about disconnection and grounding of rolling stock either as labels on vehicles or as readily understandable manuals in each vehicle is required in order to handle deviation situations. This requirement does not apply to information which is obvious or can be assumed to be common knowledge for those who do the specific tasks.

4.2.1.3 Verification

Verification shall be made by conformity statements that the rolling stock fulfils standards and regulations.

4.2.1.4 Documentation

The conformity statements shall be presented in a report.

4.3 Compatibility requirements

In this chapter all requirements regarding compatibility between vehicles and the power supply are compiled. All requirements, when applicable, are valid for one vehicle and for the maximum configuration of vehicles (i.e. multiple units) for which the approval must be valid.

This document describes requirements and infrastructure as is. The infrastructure managers are continuously trying to improve the infrastructure in Norway and Sweden. New or newly imported old rolling stock must not however require changes in the existing infrastructure and rolling stock in order to operate properly.

4.3.1 P1: Line voltage levels

4.3.1.1 Information

The values in this section refer foremost to stationary or quasi-stationary conditions. For dynamic effects see also section 4.3.8 *P8: Low frequency power oscillations* and 4.3.9 *P9: Electrical resonance stability*.

NORWAY AND SWEDEN:

Under normal operating conditions (in accordance with the definition in clause 3.16 in EN 50 163:2004), the traction power supply complies with the requirements for minimum and maximum voltage given in clause 4.1 in EN 50 163:2004, and for $U_{\text{mean useful}}$(zone) and $U_{\text{mean useful}}$(train) for conventional TSI lines and classical lines given in clause 8 of EN 50 388:2005. Exceptions and specifications are given below.

The nominal voltage is 15.0 kV RMS. The voltage at the feeder station busbar is usually adjusted to 16.5 kV RMS independent of load (below max load), or to 16.5 kV RMS with a gently declining characteristic as a function of inductive current in order to improve load-sharing of reactive power between converter stations. Declining characteristic means that the voltage is controlled in such a way that the voltage will drop linearly as a function of the inductive load, and such that the voltage will decrease about 2-5% from 16.5 kV RMS at full and purely inductive load.

There are no requirements for the unspecified period in time in clause 4.1 in EN 50 163:2004 for maximum voltage, if the increased contact line voltage is caused by regenerative braking of rolling stock. This implies that a train may continuously generate up to U_{max2} during regenerative braking.

The instantaneous values for the line voltage can be very high. Due to the high harmonic content, a crest factor above 1.8 can occur giving crest values of up to about 32 kV. Please also refer to section 4.3.3 *P3: Line voltage distortion*.

The line voltage level may change abruptly, due to cut-in or cut-out of substations or feeding points. The jumps may be from any value to any other value within the line voltage interval 10.0 kV to 18.0 kV RMS.

NORWAY:

Existing older rolling stock may not have an efficient current limitation as a function of pantograph voltage and can therefore force the line voltage to be low at sections where the distances between traction power supply feeding points are long. Hence it must be expected minimum train voltages of U_{min2} = 10.0 kV RMS and U_{min1} = 11.0 kV RMS in accordance with definitions in clause 4.1 in EN 50 163:2004.

SWEDEN:

Existing Swedish vehicles have not been designed to U_{max2} = 18.0 kV RMS, and cannot be expected to withstand voltages higher than 17.5 kV RMS.

4.3.1.2 Requirements

NORWAY AND SWEDEN:

Rolling stock must be able to operate under voltage conditions given above.

NORWAY:

Rolling stock is not allowed to cause voltages outside the limits in EN 50 163:2004. See also section 4.3.7 *P7: Current or power control at low line voltage* and 4.3.13 *P13: Regenerative braking*.

SWEDEN:

Rolling stock is not allowed to cause voltages below the limits in EN 50 163:2004.
New rolling stock must not cause the line voltage locally at any existing vehicle to increase above 17.5 kV to any greater extent (amplitude and time duration limited to approximately 5 seconds) than what is already seen in the existing system. A compatibility study according to EN 50 388 must be made, showing that this requirement is met. A train may continuously generate up to 17.5 kV RMS during regenerative braking.
See also section 4.3.7 *P7: Current or power control at low line voltage* and 4.3.13 *P13: Regenerative braking*.

4.3.1.3 Verification

NORWAY AND SWEDEN:

Rolling stock ability to withstand the voltage levels must be tested in accordance with EN 50 215:1999, clause 9.15.

Practical short circuit tests on a line as described in EN 50 215:1999, clause 9.15.4 shall not be performed. These tests are to be performed as factory tests instead. See also chapter 4.3.13 *P13: Regenerative braking*, and its reference to EN 50 388:2005, clause 12, regarding regeneration to a neutral section or a short circuit.

For more details about tests see chapter 4.4. The line voltage must be continuously recorded throughout all test runs, and the correct operation of the train must be documented.

Voltage jump tests must be performed according to chapter 4.4.4.8.

4.3.1.4 Documentation

NORWAY AND SWEDEN:
Conformity statement and test report.

4.3.2 P2: Line voltage frequency

4.3.2.1 Information

The values in this section refer foremost to stationary or quasi-stationary conditions. For dynamic effects see also section 4.3.8 *P8: Low frequency power oscillations*.

Synchronous frequency is within the variation given by EN 50 163:2004, clause 4.2.

The traction power system frequency is synchronous with the national grid in Norway and Sweden, hence is then also dependent on variation in three-phase network frequency.

$f_n = 16 \frac{2}{3}$ Hz

Normally the frequency variation is ± 0.033 Hz and under special conditions the variation is ± 0.166 Hz due to frequency variations in three-phase network.

4.3.2.2 Requirements

Rolling stock shall be able to operate under frequency variations in accordance with EN 50 163:2004, clause 4.2.

4.3.2.3 Verification

Conformity statement.

4.3.2.4 Documentation

Conformity statement.

4.3.3 P3: Line voltage distortion

4.3.3.1 Information

THD (total harmonic distortion) is defined as:

$$THD_U = \frac{\sqrt{U_2^2 + U_3^2 + \ldots + U_n^2}}{U_1}, \; n = 4, 5, 6, \ldots$$

U_1 = fundamental harmonic voltage
U_n = various higher-order harmonics

The line voltage THD may exceed 0.3 p.u. or 30%. Table 4 below gives a typical example of the statistical distribution of the voltage distortion parameters.

Parameter	Percentile		
	90.0%	99.0%	99.95%
Crest voltage	*29.5 kV*	*31.2 kV*	*32.4 kV*
Total RMS voltage	*16.7 kV*	*17.0 kV*	*17.2 kV*
16 ⅔ Hz fundamental, RMS	*16.4 kV*	*16.7 kV*	*16.9 kV*
3rd harmonic, RMS	*3.4 kV*	*4.0 kV*	*4.7 kV*
5th harmonic, RMS	*1.8 kV*	*2.7 kV*	*3.6 kV*
7th harmonic, RMS	*0.4 kV*	*0.7 kV*	*1.3 kV*
THD_U	*23%*	*30%*	*34%*

The values of this table are based on approximately 20 hours of recordings made during tests with a locomotive on the Borlänge-Ludvika/Krylbo-Frövi-Eskilstuna line sections in Central Sweden, October 2005. Recordings and analysis by L. Buhrkall.

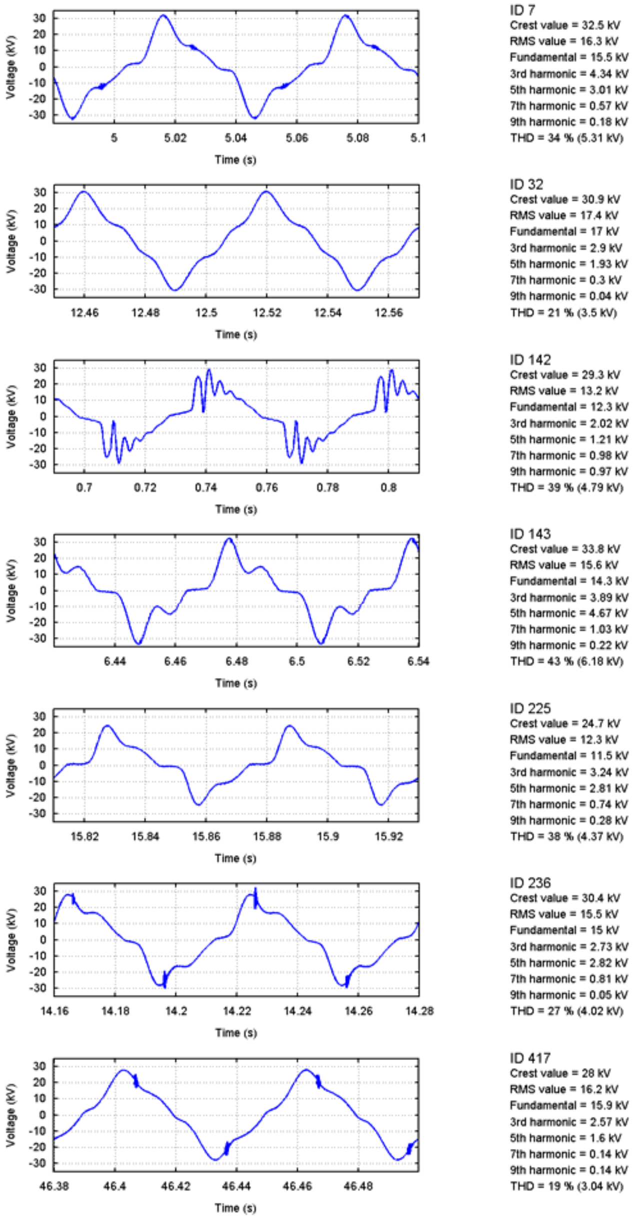
Table 4. Line voltage distortion parameters.

The values at the 99.95% percentile may be taken as worst-case, excluding short transients etc. Please notice that the highest levels of the low-order harmonics (3rd, 5th, and 7th) do not necessarily occur simultaneously.

Higher-order harmonic voltages exist, typically generated by vehicles without any interference filter.

The harmonics specified above may have all possible angles. Typically, the phase angle of the 3rd harmonic is the opposite of that of the fundamental, such that the crest value of the line voltage becomes the highest possible. To a lesser extend, this is also the case with the 5th harmonic.

Figure 7 below shows examples of measured line voltage waveshapes.



ID 7
Crest value = 32.5 kV
RMS value = 16.3 kV
Fundamental = 15.5 kV
3rd harmonic = 4.34 kV
5th harmonic = 3.01 kV
7th harmonic = 0.57 kV
9th harmonic = 0.18 kV
THD = 34 % (5.31 kV)

ID 32
Crest value = 30.9 kV
RMS value = 17.4 kV
Fundamental = 17 kV
3rd harmonic = 2.9 kV
5th harmonic = 1.93 kV
7th harmonic = 0.3 kV
9th harmonic = 0.04 kV
THD = 21 % (3.5 kV)

ID 142
Crest value = 29.3 kV
RMS value = 13.2 kV
Fundamental = 12.3 kV
3rd harmonic = 2.02 kV
5th harmonic = 1.21 kV
7th harmonic = 0.98 kV
9th harmonic = 0.97 kV
THD = 39 % (4.79 kV)

ID 143
Crest value = 33.8 kV
RMS value = 15.6 kV
Fundamental = 14.3 kV
3rd harmonic = 3.89 kV
5th harmonic = 4.67 kV
7th harmonic = 1.03 kV
9th harmonic = 0.22 kV
THD = 43 % (6.18 kV)

ID 225
Crest value = 24.7 kV
RMS value = 12.3 kV
Fundamental = 11.5 kV
3rd harmonic = 3.24 kV
5th harmonic = 2.81 kV
7th harmonic = 0.74 kV
9th harmonic = 0.28 kV
THD = 38 % (4.37 kV)

ID 236
Crest value = 30.4 kV
RMS value = 15.5 kV
Fundamental = 15 kV
3rd harmonic = 2.73 kV
5th harmonic = 2.82 kV
7th harmonic = 0.81 kV
9th harmonic = 0.05 kV
THD = 27 % (4.02 kV)

ID 417
Crest value = 28 kV
RMS value = 16.2 kV
Fundamental = 15.9 kV
3rd harmonic = 2.57 kV
5th harmonic = 1.6 kV
7th harmonic = 0.14 kV
9th harmonic = 0.14 kV
THD = 19 % (3.04 kV)

Figure 7. Examples of measured line voltage waveshapes.

4.3.3.2 Requirements

Rolling stock must be able to function satisfactory when the contact line voltage includes harmonic distortion as described above.

Limit values for generated and conducted current harmonics are specified in section 0

P10: Current harmonics.

4.3.3.3 Verification

Conformity statement and tests. Tests are specified in chapter 4.4.

4.3.3.4 Documentation

The conformity statement and the results of the tests and documented function shall be presented in a technical report.

4.3.4 P4: Neutral sections

4.3.4.1 Information

NORWAY AND SWEDEN:

Neutral sections (A.C. phase separation sections) are arranged at:
- most feeding points/stations – normally unenergized and floating
- most switching posts – normally unenergized and floating
- all coupling posts – normally energized if network is interconnected, otherwise unenergized and floating
- all series capacitances – normally unenergized and floating, (series capacitances exists only in Norway)

Temporarily sectioning of overhead contact line network is necessary in order to do maintenance and is consequently a frequent mode of operation. In case of short circuit in a railway line, or special operation of the utility grid, sectioning of the network is also used.

Infrastructure is not equipped with automatic information about neutral sections. Information about the state of the neutral sections is given to driver by optical signals along the line. Manual on board operation is hence permitted.

NORWAY:

The normal length is 90 m, but length down to 40 m and up to 350 m exists. In Norway neutral sections of 402 m length is planned for the future to avoid bridging by train with two current collectors.

System separation sections do not exist.

SWEDEN:

The normal length is 180 m, but length down to 60 m exists. In railway yards neutral sections with lengths of down to 2 m can occur. The neutral sections are normally not earthed, but at narrow bridges and at construction or big maintenance work this may occur.

4.3.4.2 Requirements

NORWAY AND SWEDEN:

Requirements are in accordance with EN 50 388:2005, clause 5. Feedback of regenerative braking power should also be brought to zero when entering a neutral section.

4.3.4.3 Verification

NORWAY:

Verification shall be made by means of a technical description on how the vehicle behaves when entering neutral sections. The description can include calculations and functional diagrams.

SWEDEN:

Verification shall be made by means of a technical description on how the vehicle behaves and how the driver shall behave when entering neutral sections. The description can include calculations and functional diagrams.

4.3.4.4 Documentation

NORWAY AND SWEDEN:

The conformity statement and verification shall be presented in a technical report.

4.3.5 P5: Power factor

4.3.5.1 Information

The power factor, λ, in this section is defined as:

$$\lambda = \frac{P}{S}$$

Where

$$P = U_1 \cdot I_1 \cdot \cos(\varphi_1)$$
$$S = U_1 \cdot I_1$$

Hence, in this document:

$$\lambda = \cos(\varphi_1)$$

and concerns only the fundamental.

In many other cases apparent power is defined or measured as:

$$S = U_{RMS} \cdot I_{RMS}$$

which can give very misleading results if harmonics are present, and hence shall not be used.

4.3.5.2 Requirements

Requirements are in accordance with EN 50 388:2005, clause 6.

NOTE 1: At very long feeding distances, the application of a capacitive cos(φ) can lead to network breakdown, over voltages, exceedance of power transfer stability limits, or other dynamic effects, within the normal operation range of line voltage and active power. At lower voltages, however, it could be beneficial from a power transfer point of view to let cos(φ) go even lower than 0.95 (cap), but in case this possibility is utilized, it must be treated in accordance with clause 10 in EN 50 388:2005 (section 4.3.8 and 4.3.9 in this document). I.e., a stability study must be performed in order to document that the vehicle is stable at these conditions. Please also refer to the section 4.3.7 *P7: Current or power control at low voltage*.

NOTE 2: Even if the power factor is allowed to decrease freely (inductively) during regeneration (electrical braking), according to EN 50 388:2005, clause 6, in order to keep the voltage within limits, it is required that the power factor is not inductive (below 0.95) when the voltage goes below 16.5 kV. Please also refer to section 4.3.13 *P13: Regenerative braking*.

As an alternative to the requirements in EN 50 388:2005, it is recommended that the limits defined in figure 8 below are used (also in this figure, the power factor refers to the fundamental, as in EN 50 388:2005).

The figure is valid for all possible situations (all instantaneous RMS-values, but transients excluded) with the restrictions mentioned above.

Using the figure means that the applicant does not have to perform the calculations given in EN 50 388:2005, clause 6.2. The verification can be made by measurements, see section 4.4.

NOTE: It is acceptable that the requirement for cos(φ) ≥ 0.95 in driving mode is violated when operating at conditions with ice or frost on the overhead contact line. Under these conditions, a higher reactive current may be used at no or low power in order to maintain a continuous current for the traction and auxiliary converters. Approximately 15 A rms inductive reactive current per current collector is allowed.

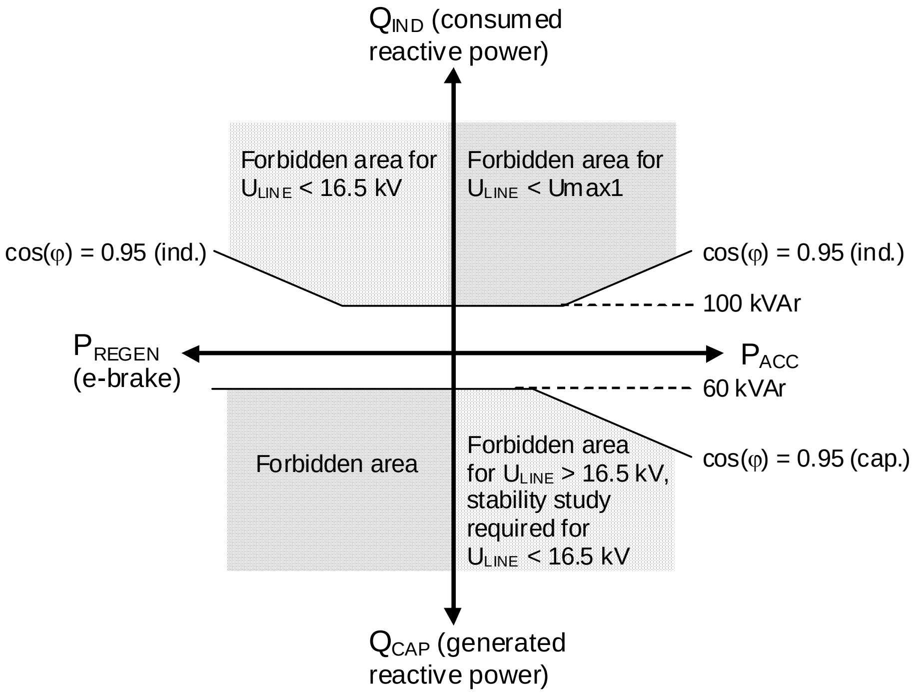


Figure 8. Allowed power factor for the fundamental. For the area that requires stability investigations see also chapter 4.3.8 and 4.3.9.

Both Norway and Sweden have exceptions from the general requirements stipulated in EN 50 388:2005 and in the draft of the High Speed TSI from June 2006:

1) Capacitive power factor (below 0.95 cap.) is not allowed at voltages over 16.5 kV in Norway and Sweden, due to the risk that it becomes difficult or impossible for other vehicles to use regenerative braking because of high voltage on the overhead line.

   (This exception is stipulated for Sweden in both EN 50 388:2005 and the HS TSI and for Norway in the draft of the HS TSI.)

2) In regeneration mode (electrical braking) the train shall not behave like a capacitor greater than 60 kVAr at any regenerative power, i.e. capacitive power factor is prohibited during regeneration. The exception of 60 kVAr capacitive reactive power is to allow the possibility to have filters on the high voltage side of the train/traction unit. These filters shall not exceed 60 kVAr capacitive reactive power at the fundamental.

   (This exception is stipulated for Sweden and Norway in both EN 50 388:2005 and in the draft of the HS TSI.)

NOTE: The value 0.95 in the figure above is expected to be improved to 0.98 in the future for inductive power factor, as stated in EN 50 388:2005.

4.3.5.3 Verification

The requirements shall be verified by calculations, using measured power factors at different operating conditions, in accordance with EN 50 388:2005, clause 6, 13 and 14. As an alternative, the verification can be made by tests and the use of figure 8. The conditions for measurements and tests are specified in chapter 4.4.

4.3.5.4 Documentation

The conformity statement and verification shall be presented in a technical report. The report shall include the calculations or a description of the calculations when calculations in accordance with EN 50 388:2005 have been made. Also measured values shall be presented in the report.

If the alternative method of the requirements and verification is being used the report shall include figures presenting the measured results. A description of the used instrumentation shall be included.

If cos(φ) control is used in the vehicle, the corresponding control characteristics shall be documented. If capacitive cos(φ) is applied in traction, line power versus voltage diagrams shall be included for lines with various line lengths / impedances.

4.3.6 P6: Maximum current limitation

4.3.6.1 Information

NORWAY AND SWEDEN

Maximum allowable train current is given in EN 50 388:2005 Table 2 with specifications and exceptions as given below.

NORWAY:

Due to the mixture of line having different power supply capacity, the Norwegian lines are divided into classes of maximum allowable train current (I_{max}). These classes and where they apply is given in register of infrastructure (*Network Statement*).

NOTE: There are additional limitations of the maximum line current in regenerative braking, see section 4.3.13 *P13: Regenerative braking*.

For older rolling stock without automatic current limitation, maximum allowable train current (I_{max}) must however be considered in each individual case.

Norwegian infrastructure is not prepared for automatic current selection. An on board installed technical current or power selector which limit the current or power demand of the train to the given electrical capacity of the line is not required. In case such a selector is not installed, the maximum current limiting must be carried out manually by the driver.

Note that if voltage dependent current limitation is not used, voltages below the line voltage level requirements given in EN 50 163:2004 (see 4.3.1 *P1: Line voltage levels*) may occur when collecting I_{max} on some sections, even when no other trains are present in the section.

SWEDEN:
The value for Sweden in Table 2 in EN 50 388:2005, clause 7, is valid for vehicle drawing current in tractive mode. During regenerative braking the current can exceed this value, due to cos(φ)-control (if present) in order to keep the voltage within limits.

4.3.6.2 Requirements

NORWAY AND SWEDEN:
Requirements are in accordance with EN 50 388:2005, clause 7.

4.3.6.3 Verification

NORWAY AND SWEDEN:
No specific verification needed.

4.3.6.4 Documentation

NORWAY AND SWEDEN:
No specific documentation needed.

4.3.7 P7: Current or power control at low voltage

4.3.7.1 Information

Due to long feeding distances and consequently large voltage drops, it is necessary to adapt the level of power consumption depending on the line voltage.

NOTE: Application of such a voltage dependent current or power limiting device may increase the risk for low frequency oscillations. See section 4.3.8 *P8: Low frequency power oscillations*.

NOTE: Application of a capacitive cos(φ) at low line voltages may increase the power that can be transferred at long feeding distances, but may also lead to instabilities due to line voltage collapse or feedback effects. See section 4.3.5 *P5: Power factor* and 4.3.8 *P8: Low frequency power oscillations*.

4.3.7.2 Requirements

Requirements are in accordance with EN 50 388:2005, clause 7.

NOTE: The requirements in EN 50 388:2005, clause 7, are based on line current. Control based on power can be easier to realize and fulfils the basic requirements (avoid breakdown of voltage and let the vehicle find a stable working point) as well. Hence it is allowed for the applicant or manufacturer to design this control as a power limitation control, even though it is not strictly according to the standard. If the limitation is designed as a power control, the current shall not exceed the limits given in EN 50 388:2005, clause 7.2. It must however be stated how the limitation is designed.

4.3.7.3 Verification

Verification shall be made by a technical description of how the requirements are fulfilled. Verification shall also be performed by tests on a weak single fed line by measuring the voltage and current. The tests are specified in chapter 4.4.

4.3.7.4 Documentation

The conformity statement and verification shall be presented in a technical report. The tests shall at least be presented in a U-I-diagram with the limits drawn in the diagram for both traction and braking. As additional information, a U-P-diagram should be given.

4.3.8 P8: Low frequency power oscillations

NOTE: The whole subject of low frequency power oscillations is currently under investigation, and the requirements in section 4.3.8 reflect present (mid-2009) knowledge. A thorough update of the section is expected within the next two years.

4.3.8.1 Information

NORWAY AND SWEDEN:
See also Appendix A4.1.1 for the background of low frequency oscillations.

Both Norway and Sweden have a large number of rotary frequency converters feeding the railway network with 16 2/3 Hz from the public 50 Hz grid. These converters are synchronous-to-synchronous machines and have no damping windings on the motor side. Hence the pole angle oscillations – which have an eigen-frequency of about 1.6 … 1.9 Hz – are poorly damped. This characteristic is very specific for both countries and leads to special requirements which may not exist in other networks. However, it is possible to meet these requirements as various projects have shown.

If an oscillation is excited, the rotor in the synchronous-to-synchronous converter oscillates relative to the synchronous frequency (rotates faster and slower than the synchronous speed in a cycle with the oscillation frequency), and the single phase voltage and frequency may vary from the stationary value (frequency oscillations up to and possibly above 3% of f_n can be used as indicative values). This means that the zero crossings of the voltage may not be as predictable as indicated by the specified stationary frequency variation. Experience has showed that vehicles may have problems to work properly or at all when this type of oscillations occurs.

Periodic changes in active power in the single-phase network occurring at the eigen-frequency of the converter can be greatly amplified, typically 10 times, through the converter unit. This means that periodic changes in the active power at the single-phase side can cause 10 times higher power oscillations on three-phase side of converter. This may cause noticeable voltage fluctuations and power oscillations in public utility grid. The eigen-frequency of the converters depends on the size of the converter unit, the number of units running in parallel, the characteristics of the utility network feeding the station, etc.

Figure 9 below shows an example of an unstable vehicle (an example from Norway including measurements in the substation).

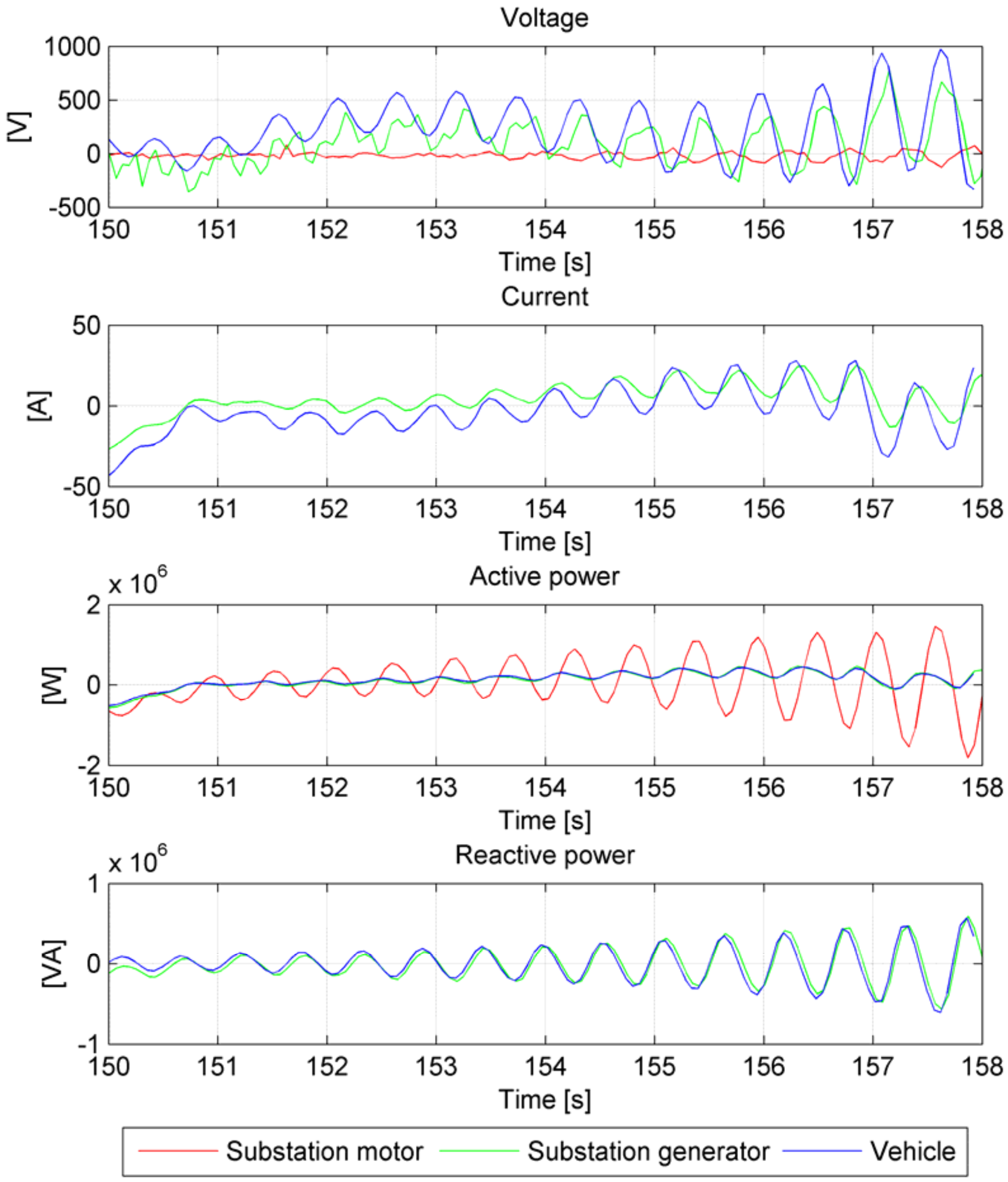


Figure 9. Example of an unstable vehicle, low frequency power oscillations.

The figure shows measured voltage and current together with calculated active and reactive power in a situation when a vehicle makes the power system unstable.
All values are referred to their respective quasi-stationary values. It is important to notice that the vehicle active power, reactive power and hence current oscillates more or less 180 degrees phase shifted relative the line voltage amplitude oscillation. This has a de-stabilizing impact on the system and should be avoided.

Oscillations are also expected to cause mechanical stress and degeneration of the converter units.

More information on dynamic behaviour of rotary converters is given in Appendix A5.

It is important to notice that the installed power of a train may in some cases reach or even exceed the rated power of a rotary or static converter. Low traffic density implies that the voltage controller in a vehicle and in the converter unit can work directly against each other in a one to one relation. Hence low frequency oscillations of about 3-4 Hz have also been observed together with static converters in some cases.

Long feeding distances and the correspondingly high line impedance can also lead to low frequency oscillations if the vehicle controllers are inadequately structured and parameterised.

By generating or consuming reactive power (cos(φ)-control), the line voltage at the location of the vehicle can be lowered or raised in a controlled manner, hence reducing the voltage drop along the line. However, this control strategy has the potential of creating low frequency oscillations in the feedback loop line voltage → reactive power → line voltage. The line impedance as well as the number of vehicles in a feeding section acts as gain factors in this loop.

A simple time domain simulation model of the oscillatory rotary converter has been developed. The aim is to provide an impression of how the rotary converter behaves. This model can be used by railway vehicle manufacturers for compatibility studies prior to the first test with new vehicles. However, experience has shown that the model due to its simplicity gives more optimistic results regarding stability than real life measurements. Description of the model can be found in Appendix A5.4.

NORWAY:
It is possible that the rail network in future will be divided into different classes based on low frequency oscillations and each class with different requirement.

4.3.8.2 Requirements

NORWAY AND SWEDEN:

The vehicles shall not cause low frequency oscillations, neither by feedback effects (including cos(φ)-control) nor by repetitive controller action. Furthermore, the vehicles must not obstruct damping of low frequency oscillations that have been excited by other vehicles or events in the network. Any already excited oscillation, e.g., due to a sudden load change, shall be well damped. This means that the damping of the ≈ 1.6 Hz oscillation that is seen in the load step response of an isolated rotating converter (see figure 10 below) must not be reduced when a vehicle is present on the line, compared to the damping (time constant ≈ 3 s) of the converter itself.

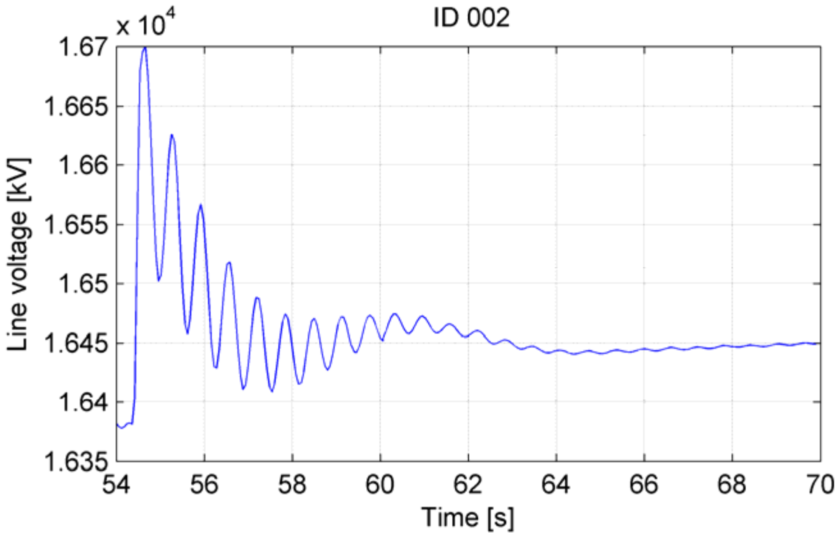


Figure 10. Load step response of an isolated rotating converter (load step to zero).

These requirements must be assured for all relevant operational conditions, including maximum number of vehicles in a feeding section, and outage of a substation and single-side feeding. The precise conditions and consequently the parameters depend on the application of the vehicle (e.g. freight locomotives or rapid mass transit).

A train must have a stable behaviour close to a converter station with an installed power equal to or lower than the rated power of the train. The same train shall be stable at 60 km distance from the same substation on a line with single-side feeding.

The vehicle must be immune against the oscillations in such a way that its operation is not improperly influenced by oscillations caused by the vehicle itself, or by other vehicles or events in the network.

Repetitive controller action (e.g. in the adhesion control or line current limitation) must not take place with deterministic intervention frequencies between 1.0 and 2.0 Hz.

Feedback loop effects must not cause oscillations within the frequency range of 1.0 to 5.0 Hz. Such effects should in general also be avoided for other frequency ranges.

For new vehicles, a stability study according to EN 50 388:2005, clause 10 shall be performed in its relevant parts. It is recommended that the simulation results (step 10 of the compatibility process) are presented before the tests in the real railway system begin.

See Appendix A4.1.2 and A4.1.3 of this document for further information on stability studies.

As the properties of stability are a result of the co-operation between several systems, Jernbaneverket and Banverket have chosen to state only the issues that are emphasised when considering whether rolling stock have sufficient properties of stability:

- How often and for which reasons oscillation occurs: Experience shows that some oscillation in phase position for rotary converters may be difficult to avoid, e.g. when wheel slip and slide protection or protective relays are activated. When no extraordinary causes exist, such as the ones described above, the rolling stock is expected not to cause oscillations.
- Any oscillation that is initiated by the vehicle, by other vehicles, or by any event in the power supply, will normally be damped by the converters as shown in appendix A5. Vehicles must not react to an oscillation in a way that maintains the oscillation or obstruct the damping of the oscillation.
- The relationship between oscillations in 3-phase power and single-phase power at converter units: A large amplification indicates that the converter is exposed to power variations that excite oscillations in an unfavourable way.
- Oscillation amplitude for contact line voltage and/or power: Increased amplitude deteriorates the conditions for both existing and future rolling stock. A definite limit will be such that new or modified vehicles shall not cause worse maximum values than values existing today.

NORWAY:

Numerical requirements for the vehicle-infrastructure interface are under investigation. Until this investigation has been finished, the requirements are as described above, **and the verification has to include measurements in the converter station.**

4.3.8.3 Verification

NORWAY AND SWEDEN:

The verification shall be done by testing for typical operational as well as one or several worst case situations. These situations shall be as similar as possible to those investigated in the simulation study. A test plan according to EN 50 388:2005, clause 10, step 12, is required before starting the tests. The tests are specified in chapter 4.4 *Validation and tests*.

NORWAY:

At present, additional measurements in the converter station are required to ensure proper low frequency behaviour. Details are given in chapter 4.4 *Validation and tests*.

4.3.8.4 Documentation

NORWAY AND SWEDEN:

The documentation consists of the conformity statement, the simulation report, and the test report. The simulation report shall point out the stability limit in terms of line impedance, number of vehicles and substation power rating, and show which oscillation frequency would be created if this stability limit is exceeded.

Note that the simulation report must be ready at the time of writing the test plan (see chapter 4.4.4 *Requirements prior to testing*).

The test results shall also be presented in a report. The report shall include diagrams with the relevant variables (voltage, current, active and reactive power, etc.) both full-scale and zoomed during oscillations as in figure 9, i.e., in a way such that it is possible to read how the different variables change relative each other.

4.3.9 P9: Electrical resonance stability

4.3.9.1 Information

See Appendix A4.2.1 for the background of electrical resonance stability.

Both networks have similar and demanding conditions in view of resonance stability, since they include vehicles and static converters with partially large filters, a dedicated 132-kV transmission system (Sweden only, Norway has a small 55-kV system), long feeding distances between substations, and in the future an increasing amount of cables in the 15 kV network. Autotransformer systems also have a lower resonance frequency than other supply systems.

For values regarding line resonances see Appendix 1 section A1.5.9 and A1.510, which gives numerical values for booster transformer and autotransformer systems.

4.3.9.2 Requirements

The relevant characteristic for resonance stability is the frequency response (or small signal behaviour) of the input admittance Y(f) seen from the pantograph into the vehicle. If the real part Re(Y(f)) is negative at any frequency f, then the vehicle is capable of causing instabilities when combined with critical resonance points in the power supply system or other vehicles. These instabilities will appear as self-excited oscillations at the corresponding frequency f. In such a case, the vehicle is said to be “active”, otherwise it is “passive”.

Vehicles must be passive for all frequencies above the frequency f_g as defined below. This is the acceptance criterion as required by EN 50 388:2005, clause 10, step 7.

The criteria for electrical resonance stability are applicable for inverter vehicles only.

f_g is 90 Hz.

For all types of vehicles special attention must be taken if passive filters are used. For frequencies where the filters are capacitive the filters must be well damped and the filters must not produce overvoltages.

4.3.9.3 Verification

The frequency response Y(f) is preferably obtained by measurements, but for the time being, real-time simulations with hardware-in-the-loop are also accepted. The test specification for frequency response measurements used by Swiss State Railways (SBB) and Austrian State Railways (ÖBB) describes a reasonable measurement set-up and scale. The upper frequency limit for evaluation of Y(f) depends on the applied inverter and controller technology and has to be selected at least so high that no active behaviour can be expected beyond it.

Hardware-in-the-loop simulations must include different operation points (typically zero power, maximum traction power, and maximum braking power).

No stability study for the full power supply system has to be performed, provided that the vehicle meets the requirements as defined above for inverter vehicles. For vehicles which do not meet these requirements, a full study according to EN 50 388:2005, clause 10 has to be performed by the vehicle manufacturer or by the infrastructure owner on the applicants costs.

For vehicles equipped with passive filter, the applicant must show simulations or calculations which confirm that the filters are well damped at frequencies where the filters are capacitive, and that there is no risk for resonances or overvoltages, according to EN 50 388:2005, clause 10.

Tests are to be performed in connection with other tests. The voltage shall be recorded and analyzed with respect to harmonics, see chapter 4.4 *Validation and tests*. In particular, this is valid for the mixed traffic tests with test runs in areas with heavy other traffic.

4.3.9.4 Documentation

Simulation report, conformity statement, and validation/test report.

Numerical data giving the frequency response Y(f) has to be delivered in a commonly used electronic format (ASCII files, Excel, Matlab), with a maximum resolution of 1/3 Hz from the line frequency up to 1 kHz or up to the sample frequency of the converter control, whatever is the higher frequency. The choice of using the sampling frequency comes from the experience that some vehicles have had problems above the Nyquist frequency.

The circuit diagram and component parameters of the line-side circuits of the vehicle must be included in the report for comparison purposes.

Note that the simulation report must be ready at the time of writing the test plan (see chapter 4.4.4 *Requirements prior to testing*).

Evaluation of the voltage and the harmonics measured during the tests shall be presented.

4.3.10 P10: Current harmonics

4.3.10.1 Information

These requirements are not a part of EN 50 388: 2005, but due to the high harmonic content in the Norwegian and the Swedish network, which in turn causes high peak value in the line voltage (see section 4.3.3 *P3: Line voltage distortion*), these requirements are needed in order not to worsen the situation.

4.3.10.2 Requirements

GENERATED CURRENT HARMONICS

The current harmonics generated by the vehicle are not allowed to exceed the levels in the following table. The individual harmonics are related to the rated current of the vehicle.

Harmonics	3	5	7	9
Current level, % of I_N	5%	3%	3%	3%

Table 5. Limits for individual current harmonics.

THD_I shall not exceed 8% (0.08), where

$$THD_I = \frac{\sqrt{I_2^{\,2} + I_3^{\,2} + \ldots + I_n^{\,2}}}{I_N}$$

I_N = rated current for the vehicle (fundamental, 16 2/3 Hz).
n = Varying harmonics, n = 2, 3, 4 …

Even harmonics are implicitly limited by the THD_I –value.

Individual inter-harmonics in the current shall not exceed more than 3% of the fundamental rated current.

The limits presented above for current harmonics are under investigation and shall be considered as target values. The limits represent the 95%-percentile of the measured line current harmonics.

CONDUCTED CURRENT HARMONICS

The vehicle design must consider the high levels of the line voltage harmonics, meaning that the vehicle must have sufficiently high input impedance not to act as an “interference vacuum-cleaner” or amplifier. This applies to both the passive input impedance (determined mainly by the main transformer and line filters, if any), and the active input impedance below 90 Hz in case harmonic anti-control is used, e.g., in order to stabilize the DC link voltage.

The harmonic current limits of table 5 above apply for harmonic voltage distortion levels up to the 90% percentile of table 4 in section 4.3.3 *P3: Line voltage distortion.*

4.3.10.3 Verification

Verification of the requirement shall be made by test measurements. Tests are specified in chapter 4.4.

4.3.10.4 Documentation

The conformity statement and the results of the tests shall be presented in a technical report.

4.3.11 P11: Relay protection and coordination

4.3.11.1 Information

NORWAY AND SWEDEN:
All current values in this clause refer to the sub-transient short circuit currents.

The highest short circuit current in the railway power supply system is 25 kA.

NORWAY:
Feeding stations and switching posts are normally equipped with the following relay protection:

- Distance protection as normal primary protection at branches:
    - Zone 1 covers normally 60-85% of line and has a disconnect time less than 0.15 s
    - Zone 2 covers the whole line and 20 % or more of adjacent lines with disconnect time usually less than 0.3 s. Zone 2 is triggered by a current step of 200 A or a voltage step of 2 kV during 0.2 s.
- Time delayed over current protection covering approx. 50% of the line. Used as primary protection covering the whole line at branches without distance protection (often short, single fed switching yards). Approximate setting: 0.8-1.6 kA, delay time 0.2-3 s (inverse or constant).
- High speed over current protection at some branches.
- Under voltage protection of busbar, usually trigged by voltages less than 9 kV in 0.5 s. On a few branches additional under voltage protection usually triggered by voltages less than 10 kV in 2.0 s
- Thermal protection of the overhead contact wire at some high loaded branches/lines.
- Testing resistor (640 Ohm) at most branches
    - Before a line/branch is activated, the voltage is applied via the testing resistor in order to detect faults or short circuits. If the line impedance is sufficiently high, the branch circuit breaker will be switched on. In a few stations the line is tested with an electronic test circuit
- Automatic circuit breaker re-closing at most branches, if the circuit breaker has tripped due to distance, over current, 100 Hz and under voltage protection. Re-closing is executed 5 s after the breaker has tripped first time, and then 30 s and 180 s, respectively, after the

previous re-closing attempt has ended. If the last attempt fails, the breaker is blocked and must manually be closed from the dispatch centre.
- In general, the 100 Hz protection in the static converter stations orders disconnection if the current harmonics around 100 Hz exceed given levels.

Coupling posts are equipped with the following relay protection:
- Under voltage protection disconnecting if the voltage is below approx. 6 kV for more than 20 s.
- Combined under voltage and over current protection disconnecting if the voltage is below approx. 10 kV and the current is above 300 A for 0.4 s.

SWEDEN:
The relay protection for the lines and the busbar at converter stations and switching posts is normally of the following types:

Protection of the 15 kV lines:
- High speed over current protection (< 50 ms for static and < 10 ms for numerical relays): Normal setting for the current is 1.5-2.0 kA.
- Two-step distance protections in combination with a current/voltage jump relay. The second step is activated by the current/voltage jump relay, set at 175 - 450 A and 2 kV. The first step covers 65 - 85% of the line, step two covers 100 % of the first line and from 30 % up to 50 % of the next line.
- Time over current protection with an approximate setting of: 0.8-1.2 kA, delay time 1-3 s (inverse or constant).
- Thermal protection against prolonged overloading of the contact line.
- Normally each line has a test resistor of 640 Ω. Before the circuit breaker for a line is closed, a voltage is applied to the line via this test resistor, and if the impedance is sufficiently high the circuit breaker closes.
- Automatic circuit breaker re-closing exists on most lines, operating if the circuit breaker has tripped due to distance or over current protection. Re-closing is executed 5 s after the breaker has tripped the first time, and then again 60 s after the previous re-closing attempt has failed and is terminated. If the last attempt fails, the breaker is blocked and must manually be closed from the dispatch centre.

Protection of the 15 kV busbar:
- Under voltage protection with a normal setting of 9 kV, 0.5 s.

The disconnection time for a fault with a high current (> 1.5 kA) is less than 150 ms.

4.3.11.2 Requirements

NORWAY AND SWEDEN:
Requirements are in accordance with EN 50 388:2005, clause 11.

Note that in case the breaker capacity is higher than the highest short circuit current in the power supply system, the breaker shall open immediately for all faults in the vehicle. When applying this rule, it must be considered if the vehicle is also operating in other countries where higher short circuit currents may occur. In that case the breaker shall be staged for faults on the primary side of the transformer.

4.3.11.3 Verification

NORWAY AND SWEDEN:

Functional description.

4.3.11.4 Documentation

NORWAY AND SWEDEN:

Technical report and conformity statement.

4.3.12 P12: AC inrush currents

4.3.12.1 Information

NOTE: This is not the same requirement and test that is specified for DC inrush current for Sweden in section 3.2.1 *S1: DC track circuits*. The DC inrush current requirement is only of interest in Sweden due to the DC track signalling circuits, whereas the AC inrush current requirements and tests are of interest in both countries due to the relay protection.

One of the relay protection systems commonly used in both Norway and Sweden is over current relays with different tripping time (see chapter 4.3.11 *P11: Relay protection and coordination*). These over current protections disconnect the line if the inrush currents exceed the trip levels and/or trip times.

4.3.12.2 Requirements

Maximum magnitude of the inrush current from the transformer or any other equipment in the vehicle shall not exceed 2.0 kA (peak value) during the two first periods, 120 ms, after breaker closure. This value is valid when connecting the vehicle to a stiff 16.5 kV, 16.7 Hz voltage source. The requirements are valid for a complete traction unit which can be more than one vehicle.

When several vehicles are connected (multiple unit operation) to the 15 kV system, it is desired that breaker operations on the vehicles are unsynchronized, i.e. that there are different delays imposed on each vehicle.

4.3.12.3 Verification

Verification shall be made by calculations and tests. The tests are specified in chapter 4.4.

4.3.12.4 Documentation

Technical report with conformity statement and test results.

4.3.13 P13: Regenerative braking

4.3.13.1 Information

NORWAY AND SWEDEN:

Normally, most of the regenerative power from rolling stock will be consumed by other trains. Temporary sectioning of the network may to a large extent reduce, or completely disable, the single-phase network's ability to absorb regenerative power feedback.

Regenerative power feedback may in some sections be limited even further as mentioned below, due to special reasons.

All rotary converters and some static converters can feed power back to the 3-phase network. Some static converter stations cannot receive power feedback from the single-phase network at all. In these stations the energy may be "pushed" forward by shifting the phase angle of the output voltage.

NORWAY:

Due to the contact line's thermal capacity, and in order to enable the protection for outgoing lines to detect a short circuit while at the same time rolling stock feeds back regenerative power, the power supply is divided into classes of allowable regenerative current. These classes and where they apply is given in register of infrastructure (*Network Statement*).

Norwegian infrastructure is not equipped for automatic power selection. An on board installed technical current or power selector which limit the current or power demand of the train to the given electrical capacity of the line is not required. In case such a selector is not installed, the maximum current limiting must be carried out manually by the driver.

4.3.13.2 Requirements

NORWAY AND SWEDEN:

Requirements for regenerative braking in EN 50 388:2005, clause 12 must be fulfilled. Furthermore, it is not allowed to regenerate power to a neutral section. Feedback of regenerative braking power should be brought to zero when entering such a section.

Vehicles must not continue to feed back power if the requirements for maximum voltage limit given in section 4.3.1 in this document are exceeded, but there is no requirement for the durations of unspecified period described in EN 50 163:2004, table 1, subsection f) given for regenerative power feedback.

NORWAY:

A train must not feed back more regenerative power than the limit for the section on which the train is currently operating.

If a system, which automatically stops feeding back power from the train when a short-circuit occurs in the actual section, can be documented to have adequate performance, then the restrictions due to the protection's ability to detect short circuits can be lifted.

SWEDEN:

New rolling stock must not cause the line voltage locally at any existing vehicle to increase above 17.5 kV to any greater extent (amplitude and time duration limited to approximately 5 seconds) than what is already seen in the existing system. A compatibility study according to EN 50 388 must be made, showing that this requirement is met.
A train may continuously generate up to 17.5 kV during regenerative braking.

NOTE: There are several possible technical solutions in order to meet this requirement. One possible solution is to limit the line voltage at the new rolling stock to 17.5 kV. Another solution is a control of cos(φ) during regeneration (please also refer to section 4.3.5 *P5: Power Factor*), as suggested by the figures 11 (red crossed area) and 12 below.

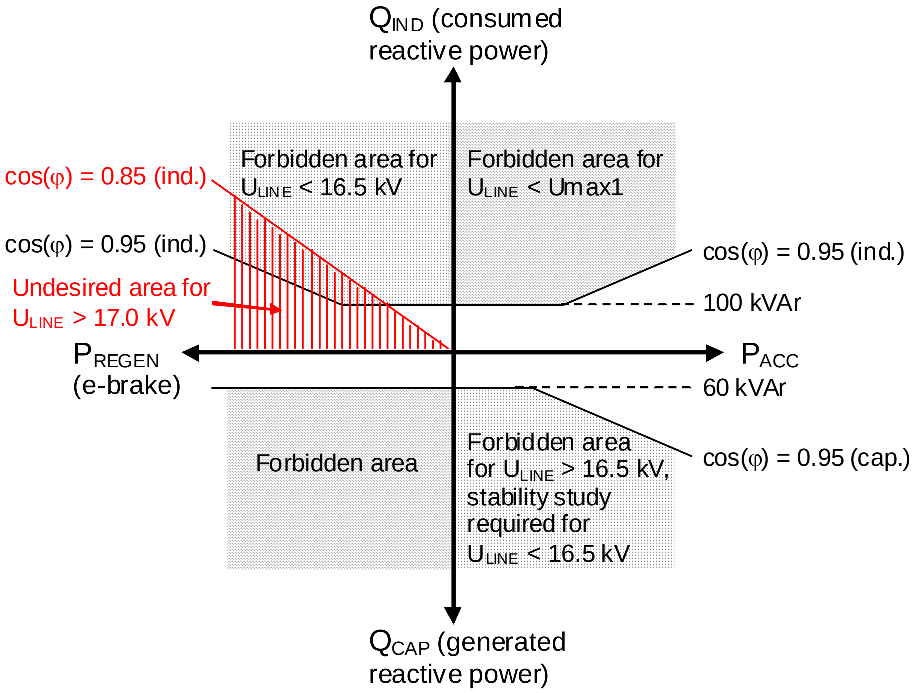


Figure 11. Suggested cos(φ)-control in regenerative braking.

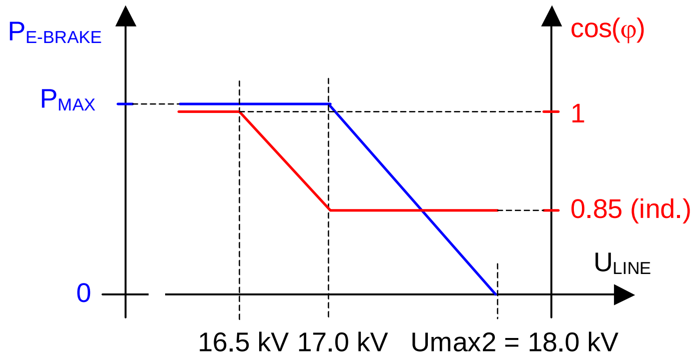


Figure 12. Suggested power limitation and cos(φ)-control in regenerative braking.

4.3.13.3 Verification

NORWAY AND SWEDEN:

Testing of regenerative braking must be carried out in accordance with EN 50 388:2005, section 13 and 14.

Verification that the vehicle does not regenerate power to a neutral section or to a contact line that is disconnected from the power supply system, or to a short circuit, shall be based on conformity statements and functional descriptions. No practical tests on sites in Norway and Sweden are required.

Verification of the voltage limiting function shall be made by test measurements. The tests are specified in chapter 4.4.

SWEDEN:

Verification that the vehicle does not cause the line voltage locally at any existing vehicle to increase above 17.5 kV to any greater extent than what is already seen in the existing system, may be by means of calculations presented in a separate report.

4.3.13.4 Documentation

NORWAY AND SWEDEN:

Conformity statement. Tests shall be documented in test reports with diagrams presenting the results.

Functional descriptions must be presented, showing how the vehicle/s act when entering a neutral section or when a short circuit occurs, both close to the vehicle and at a far distance.

4.3.14 P14: Train pre-heating systems

4.3.14.1 Information

NORWAY:

Jernbaneverket offers three different systems for connecting rolling stock to stationary pre-heating facilities. For more information about the systems and geographic location of connection points see Network Statement, item 5.3.3.1.

The following systems exist in Norway (but with different and limited extension):
1000 V, 50 Hz
1000 V, 16.7 Hz (most common)
3 x 400 V, 50 Hz (up till now only on non-electrified lines)

Maximum power output per pre-heat post:
For 1000 V post: 100 - 630 A (large variations, local limits are described in the Network statement).
For 400 V post: 63 A.

The 50 Hz facilities are from local distribution grid. Variation in output voltage must be expected to be according to the allowed medium-voltage supply characteristics in EN 50160.

The 16.7 Hz facilities are supplied from the overhead contact line via a step-down transformer with ratios from 15:1 kV to 16.5:1 kV and without automatic tap-changing. Variation in output voltage must be expected according to the transformer ratios and the given line voltage variation in 4.3.1 *P1: Line voltage levels.*

SWEDEN:

The following system exists in Sweden:
1000 V, 16.7 Hz

These facilities are supplied from the overhead contact line via a step-down transformer with ratios from 15:1 kV to 16.5:1 kV and without automatic tap-changing. Variation in output voltage must be expected according to the transformer ratios and the given line voltage variation in 4.3.1 *P1: Line voltage levels.*

4.3.14.2 Requirements

The train pre-heating systems must meet all of the following requirements.

For all systems the following apply: Automatic or technical interlocking devises in the train, or manual operating routines are required in order to prevent interconnecting the power supply from stationary pre-heat posts, other potential external power supplies, or supply through the train pantograph.

NORWAY:

For 1000 V systems the connection plug must be designed in accordance with UIC 552.
For 400 V systems the contact type must be a circular pin plug 436-6 with pilot contact (L1-L2-L3-N-PE-pilot). Connections in accordance with UIC 554-1, plate IV.

SWEDEN:
The design of the connection to the pre-heating installation must be in accordance with UIC 550 and UIC 552.

NORWAY AND SWEDEN:
To ensure selectivity, the first peak of the inrush current, when connecting the vehicle to a pre-heating installation, must not exceed 2.0 kA (peak) at 1000V, 16.7 Hz.

4.3.14.3 Verification

NORWAY AND SWEDEN:
Verifications shall be made by technical and functional descriptions.

Verifications shall also be made by tests. The tests are specified in chapter 4.4.

4.3.14.4 Documentation

NORWAY AND SWEDEN:
Conformity statement, and a technical report which shall include the test results.

4.3.15 P15: Energy measurements

4.3.15.1 Information

NORWAY AND SWEDEN:
Both Jernbaneverket and Banverket are members of European Railway Energy Settlement System (ERESS). This system allows automatic transfer of data such as time and date, energy demand and GPS-position from the train energy measurement system.

4.3.15.2 Requirements

NORWAY AND SWEDEN:
Energy measurement system onboard in train shall have a total uncertainty of max. 1.5 %. For older rolling stock that had the current and/or voltage transformer installed since before 2007-01-01, a total uncertainty of max. 5 % may be accepted.

The energy meter shall be accepted by either Jernbaneverket or Banverket.

NORWAY:

Rolling stock operating in Norway may be equipped with energy meters as described in this section. Otherwise energy invoicing will be based on key figures and reported/estimated gross ton kilometre driven.

SWEDEN:

New and old rolling stock, not operating in Sweden before, shall be equipped with energy meters as described in this section.

4.3.15.3 Verification

NORWAY AND SWEDEN:

Total system uncertainty shall be calculated in accordance with calculation method given in Guide to Expression of Uncertainty in Measurement (GUM) by International Bureau of Weights and Measures (BIPM). The calculations shall be based on square distribution and a coverage factor of 2.

4.3.15.4 Documentation

NORWAY AND SWEDEN:

A conformity statement. The total system uncertainty shall be documented.

4.3.16 P16: Other electrical equipment

4.3.16.1 Information

NORWAY:

No specific information.

SWEDEN:

This can refer to heating of driver cabins in some cases, but not whole trains.

4.3.16.2 Requirements

NORWAY:

No specific requirements.

SWEDEN:

If vehicles have equipment that demands 400/230 V, 50 or 16,7 Hz power supply from local main supply or auxiliary systems the installation must be in accordance with UIC 554 in applicable parts. Note that these types of connections are very rare in Sweden and exist foremost on non-electrified lines.

4.3.16.3 Verification

NORWAY:
No specific verification.

SWEDEN:
Technical description.

4.3.16.4 Documentation

NORWAY:
No specific documentation.

SWEDEN:
Technical report.

4.3.17 P17: Ice on the overhead line

4.3.17.1 Information

At conditions with ice or frost on the overhead line, arcs between contact wire and pantograph can result in DC components in the traction current. Measurements on existing vehicles have shown that DC currents can flow through the primary of the main transformer of the locomotive or traction unit, with levels exceeding 40 A continuously for up to 60 seconds, and with short-time (a few seconds) levels up to 70 A.

4.3.17.2 Requirements

No specific requirements.

4.3.17.3 Verification

No specific verification.

4.3.17.4 Documentation

No specific documentation.

4.4 Validation and tests

4.4.1 Requirements prior to tests

NORWAY AND SWEDEN:

Before test runs and/or demonstrations are allowed on the railway lines in Norway or Sweden, some documentation is required. In addition to the documentation mentioned later in this chapter, which refers to electrical requirements and how to perform tests, there are some other pre-requirements to be met. These pre-requirements and documentation concern topics like:

- train control (ATC)
- profile
- running dynamics
- axle loads
- current collector
- etc.

These pre-requirements are not covered in this document and it is the responsibility of the applicant for the acceptance to contact Jernbaneverket and/or Banverket to get the complete information regarding these requirements.

(Note: it is possible to test or demonstrate a vehicle without ATC by connecting the vehicle under test to an accepted vehicle. Special provisions must however be made so that correct test conditions are met, i.e. the accepted extra vehicle must not influence the test results.)

NORWAY:

The requirements regarding other topics than electric compatibility captured in this document is to be clarified as a part of the overall compatibility process which is described in JD 590 chapter 1.

4.4.1.1 Interference currents

Documentation which contains estimations, calculations, or previous measurements of interference currents according to the requirements S1-S6 is required. If such documentation cannot be made available, a preliminary test must be performed on a closed track before any other tests are performed. See also the requirements in section 3.2.1 to 3.2.6.

4.4.1.2 Radiated EMI (S7, part of T6)

EMC test regarding radiated emission shall be performed by the manufacturer (or applicant) at the factory before any tests on railway lines in Norway or Sweden. See section **Feil! Fant ikke referansekilden.**, **Feil! Fant ikke referansekilden.**.

4.4.1.3 Simulations of dynamic vehicle behaviour

Testing of new vehicles on the railway infrastructure is very costly and shall be kept to a minimum for the benefit of all involved parties in long term. In order to reduce the risk of a failure of some tests as well as to document vehicle characteristics which can not be tested directly, simulations shall be performed by the vehicle manufacturer.

It is recommended that the simulation results are presented to and discussed with Jernbaneverket and/or Banverket prior to the first tests with the new vehicle.

This concerns low frequency power oscillations (see 4.3.8) and electrical resonance stability (see 4.3.9) and is based on EN 50388:2005, clause 10, steps 1 to 11 of the compatibility study.

4.4.1.4 Current or power control at low voltage

Documentation of current limitation as function of voltage is required.

4.4.1.5 Regenerative braking

Documentation of the voltage limitation function when using regenerative brake is required.

4.4.1.6 Test plan

A test plan shall be presented to Jernbaneverket and/or Banverket before any measurements or tests are carried out. The test plan shall contain a description on how the tests are performed (i.e. what lines shall be used, closed track or mixed traffic and so on) and on the vehicle constellation (load, weight and so on). Furthermore, the test plan shall include a description of the instrumentation and measurement methods that will be used and how the instrumentation is calibrated. This information shall also be included in the test reports.

4.4.2 Coordination with tests regarding signalling systems and telecommunication

The tests specified below can to a wide extent be coordinated with the tests regarding signalling systems and telecommunication (S-requirements).

4.4.3 General test plan

Table 6 below defines the test categories T1-T7, and outlines the minimum number of successful tests specifically addressing the requirements P1-P13.

Cat.	**Condition**	**Scope and train operation**
T1	Closed track, rotating converters	4 ABAB sequences and 2 ARO-sequences in each end of the line, all in each train configuration. (Plus additional tests for S-requirements; the data from these tests must be analyzed also for all relevant P-requirements).
T2	Closed track, static converters	4 ABAB sequences and 2 ARO-sequences in each end of the line, all in each train configuration. 6 voltage jump tests. (Plus additional tests for S-requirements; the data from these tests must be analyzed also for all relevant P-requirements).
T3	Mixed traffic	8 hours of effective operation on the specified lines. All data must be analyzed for all relevant P- and S-requirements.
T4	Transformer inrush (peak AC)	Minimum 25 successful inrush events
T5	Transformer inrush (DC, S only)	N/A (S-requirement only)
T6	Other tests (train heating system)	Minimum 25 successful inrush events
T7	Non-test approval	N/A

Table 6. Test categories and general test plan.

The Tests T1, T2, T4, and T6 can be performed in either country. The tests T3 must be performed in the country/countries where the vehicle is going to operate.

4.4.4 Test details

4.4.4.1 Test sites

The following test sites are suggested:

Cat.	Norway	Sweden
T1	Hønefoss-Nesbyen on the Bergen line.	Gemla-Lessebo on the Alvesta-Kalmar line.
T2	Lillestrøm-Gardermoen, Gardermoen Airport line.	Eskilstuna-Nykvarn on the Eskilstuna-Södertälje line.
T3	Oslo area.	Borlänge area (Borlänge-Krylbo, Borlänge-Ludvika).
T4	Oslo S	Ockelbo.
T5	N/A (S-requirement)	
T6	Any location with posts for train heating supply.	
T7	N/A	

Table 7. Suggested test sites.

4.4.4.2 Power supply configurations

CATEGORY T1: CLOSED TRACK, ROTATING CONVERTERS

The test line must be single-end supplied from one rotating converter in island operation. There must be no other trains activated or in operation on the test line. It is recommended that the test permissions allow for operation without ATC.

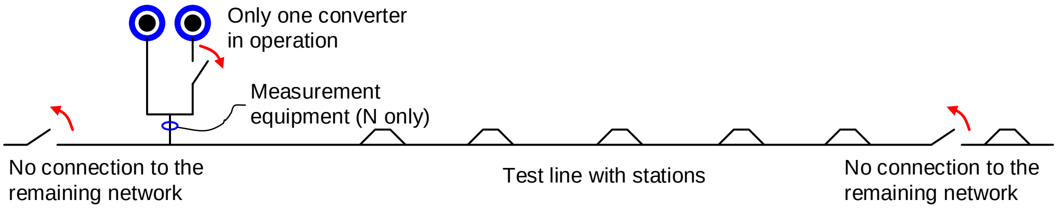


Figure 13. Supply conditions for T1 tests, P-requirements.

For an approval in Norway, measurements in the feeding converter station are required in addition to the measurements on vehicle. The activities in the converter station must be carried out according to Jernbaneverkets instructions.

CATEGORY T2: CLOSED TRACK, STATIC CONVERTERS

The test line must be single-end supplied from one or two static converters. Since these converters are not designed for island operation, the remaining network must be connected in the supply end. There must be no other trains activated or in operation on the test line. It is recommended that the test permissions allow for operation without ATC.

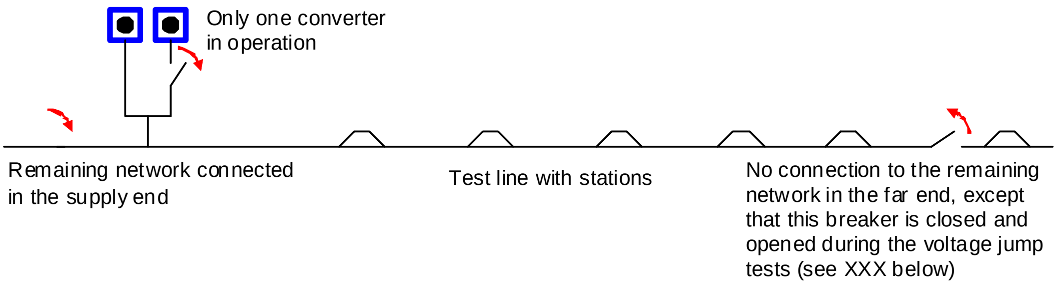


Figure 14. Supply conditions for T2 tests, P-requirements.

CATEGORY T3: MIXED TRAFFIC

The mixed traffic tests must be performed by running in timetable-like operation in areas with heavy traffic as well as low traffic, and lines which are fed from rotary as well as static converters. For Sweden, these trips shall also include driving on lines fed by the 132 kV system.

CATEGORY T4: TRANSFORMER INRUSH

The supply must be the strongest possible. Please refer to the detailed description of these tests in section 4.4.4.9 below.

4.4.4.3 Adhesion conditions

The tests must be performed at adhesion conditions that are good enough to allow the vehicle to reach full power, but also poor enough to cause frequent wheel-slip. Track-watering equipment must be used if the tests are performed at so good natural adhesion conditions that wheel-slip is not seen, and sand must be used in case the natural adhesion is very low such that full power is not reached.

4.4.4.4 Train configuration

All tests shall be performed with one vehicle alone, and with the maximum configuration of vehicles (i.e. multiple units) for which the approval must be valid.

4.4.4.5 Train load, tests T1-T3

Locomotives must be loaded by a reasonably heavy train (≈ 2 t per kN max. tractive effort, or ≈ 100 t per MW max. power, whichever is the greater) during all tests T1 and T3. During tests T2, a somewhat lighter load may be used (some 25% of the values above).

4.4.4.6 Train operation – ABAB and ARO sequences

The train must be operated according to the ABAB and ARO speed profiles shown in figure 15 and 16 below, during the tests specifically addressing the P-requirements.

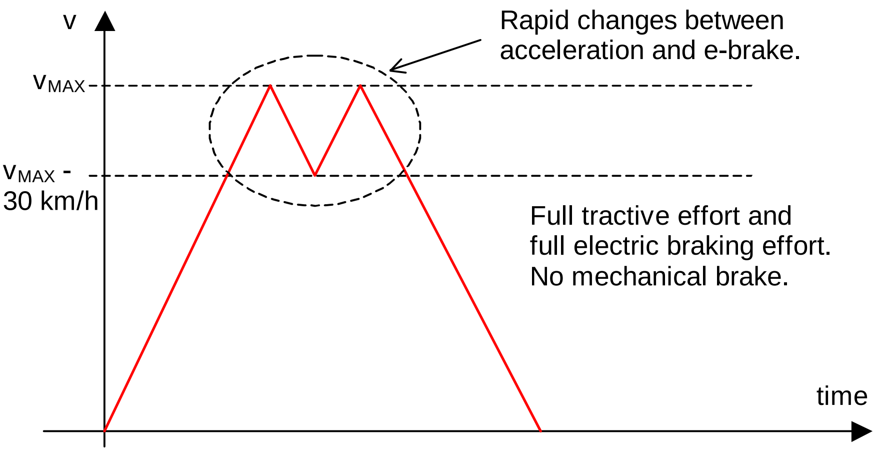


Figure 15. ABAB (Acceleration-Brake-Acceleration-Brake) operation sequence.

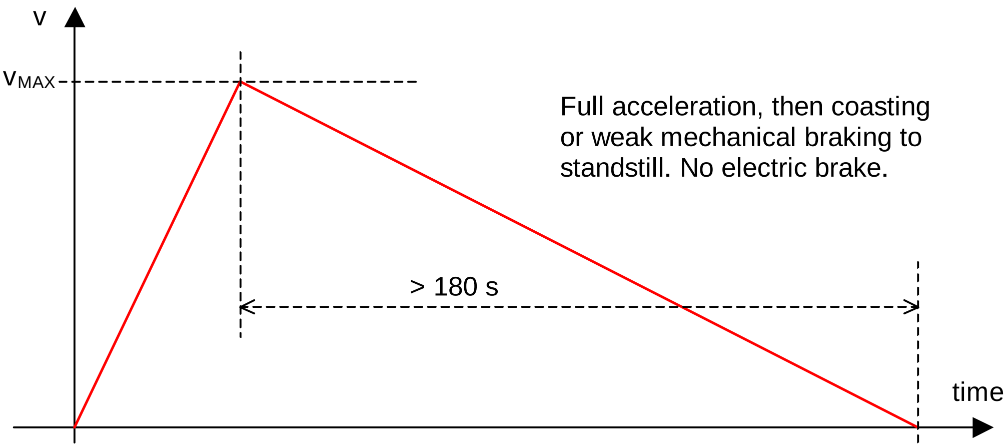


Figure 16. ARO (Acceleration-RollOut) operation sequence.

All vehicles must perform tests up to their speed limit during test category T2. During the test categories T1 and T3, the maximum speed is typically given by the speed limit of the line (or, in the case of locomotives, by the load wagons), meaning that the sequences must be terminated at a lower speed.

4.4.4.7 Voltage jump tests (part of T2)

Tests of voltage jumps shall be performed on a weak double end fed line where one of the feedings shall be switched on and off when the vehicle is fairly close to that station.

The train is accelerated with maximum tractive effort. When the maximum power is reached, the feeding condition is switched. A minimum of 3 successful tests with positive voltage jump (double feeding switched on) and 3 tests with negative voltage jump (double feeding switched off) must be performed.

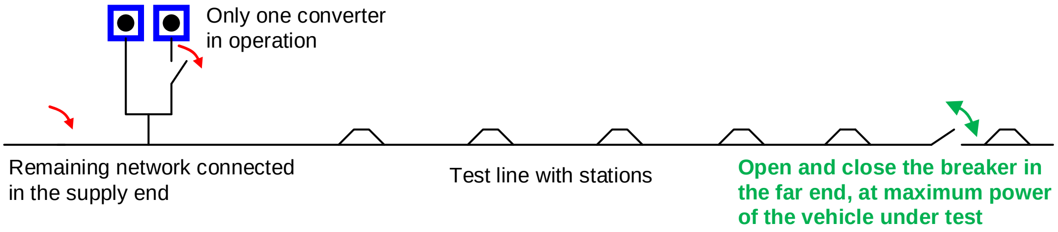


Figure 17. Voltage jump test.

4.4.4.8 Transformer inrush (AC) test (T4)

NOTE: This is not the same test that is specified for DC inrush current for Sweden in chapter 3.2.1 *S1: DC track circuits.*

The tests shall be performed at a location where the short-circuit current is greater than 20 kA, i.e. Ik > 20 kA. In Sweden this means tests directly outside Ockelbo converter station with connection to the 132 kV system, and the maximum number of converters running in Ockelbo, Borlänge, Häggvik and Ånge. In Norway this means tests at Oslo S with all converter unites in the surrounding stations running (Asker, Alnabru, Lillestrøm, Jessheim, Holmlia and Smørbekk).

The tests shall be performed with the maximum configuration of the vehicle (i.e. maximal number of units in multiple operation for which the approval must be valid). At least 10 trials of breaker closures must be performed if the breaker closure is synchronized to a voltage zero crossing. If the breaker closure is not synchronized to the voltage zero crossing, at least 25 trials of breaker closures shall be performed. All trials must be within limits for acceptance.

The current shall be recorded, and the whole course of the inrush current (instantaneous values) for each trial shall be presented after the tests.

4.4.4.9 Train heating systems tests (T6)

These tests refer to the requirement regarding inrush currents in chapter 0, *P14: Train pre-heating* systems.

Verifications shall be made by tests of at least 25 trials of inrush current tests, apart from the description mentioned in clause 0, when the vehicle is connected to a heating post. No specific test site is specified.

The current shall be recorded and the whole course of the inrush current (instantaneous values) for each trial shall be presented after the tests.

4.4.5 Measurement instrumentation and methods

The verification of the requirements shall primarily be made by measurements, if not stated otherwise.

4.4.5.1 Measurement instrumentation – P-requirements

All measurements shall be performed with adequate voltage and current transducers (transformers and/or active transducers such as Rogowski coils and Hall transducers.

Sampling instruments as shown in figure 18 are recommended. For measurements of high frequency phenomena, such as the Norwegian signalling circuit interference, a sampling frequency of approximately 50 kHz is recommended together with an anti-aliasing filter with a cut of frequency of approximately 20 kHz.

It is required that adequate anti-aliasing filters are used. The cut-off frequency of the anti-alias filter for the current measurement must be higher than the highest frequency of interest, i.e., higher than 17 kHz for Norway (FTGS track circuits) and higher than 6 kHz for Sweden (psophometric currents). The sampling frequency must be well above two times these values.

It is recommended that all raw data be streamed directly to a storage device (DAT recorder, hard-disk, or similar) for later post-processing and analysis, in addition to the on-line supervision. For the signal processing see chapter 4.4.5.2 below.

Figure 18 below shows an example of the recommended principle of data recording and analysis, and how to install Hall transducers to measure the DC-current. It is recommended that the speed signal be taken from the vehicle control rather than via GPS, since the test lines comprise numerous tunnels without GPS coverage.

The tolerance of the overall signal chain including transducers, signal conditioners, A/D converters, and data analysis, must be determined before the tests. A measurement error of less than ± 1% at the fundamental, and less than ± 5% of any of the stated interference requirements, is expected.

Also the tolerance of the phase angle of the voltage and current fundamentals must be determined.

The principles of the data analysis, as well as the tolerances, must be described and presented before the tests, as a part of the test plan for the accepting authority.

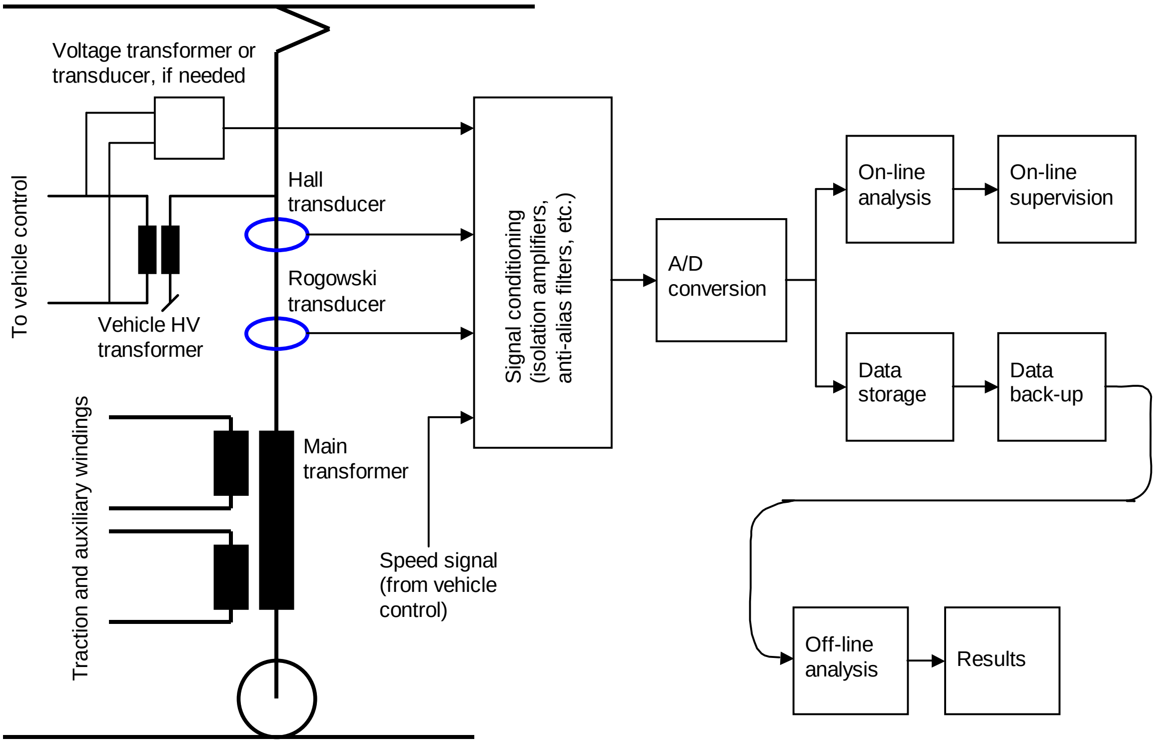


Figure 18. Transducer position and recommended measuring equipment.

4.4.5.2 Data analysis – general P-requirements

The recorded data must be processed and analysed in accordance with the interference requirements P1, P3, P5-P10, and P13. The result plots from the analysis (one or more plots per individual LOOP, ABAB, or ARO sequence) must present the following quantities, all versus time:

- RMS line current (60 ms RMS)
- RMS line voltage (60 ms RMS)
- Crest line voltage
- Train speed
- Active and reactive power (120 ms and 1.2 s), and cos(φ) and tan(φ) (1.2 s)
- 3rd, 5th, 7th, and 9th line voltage harmonics
- 3rd, 5th, 7th, and 9th current harmonics, and the current THD

In addition, the following information must be given in each plot:

- Test date
- Line section
- Test ID (reference to the test log)
- Status of the vehicle (software revision etc.)
- Distance covered during the test sequence
- 95%-percentiles of the 3^{rd}, 5^{th}, 7^{th}, and 9^{th} current harmonic, as well as the current THD

The summary report must present the following plots:

- Active power versus RMS line voltage (1.2 s), including the limit curves according to EN 50 388 section 7.2, figure 1.
- Tan(φ) versus RMS line voltage (1.2 s)
- Reactive versus active power, including the limit curves according to figure 8 in section 4.3.5 *P5: Power factor*.

Figure 19 below shows the suggested analysis method, based on a sampling frequency of the raw data of 50 kHz.

The comparably short RMS times of 60 ms are required in order not to mask out any low-frequency oscillations.

For FFT analysis, Hanning windows are recommended.

Other types of measurement and evaluation methods, than the recommendations above, can be discussed, but the applicant must then show how these measurements will be carried out and what accuracy will be achieved.

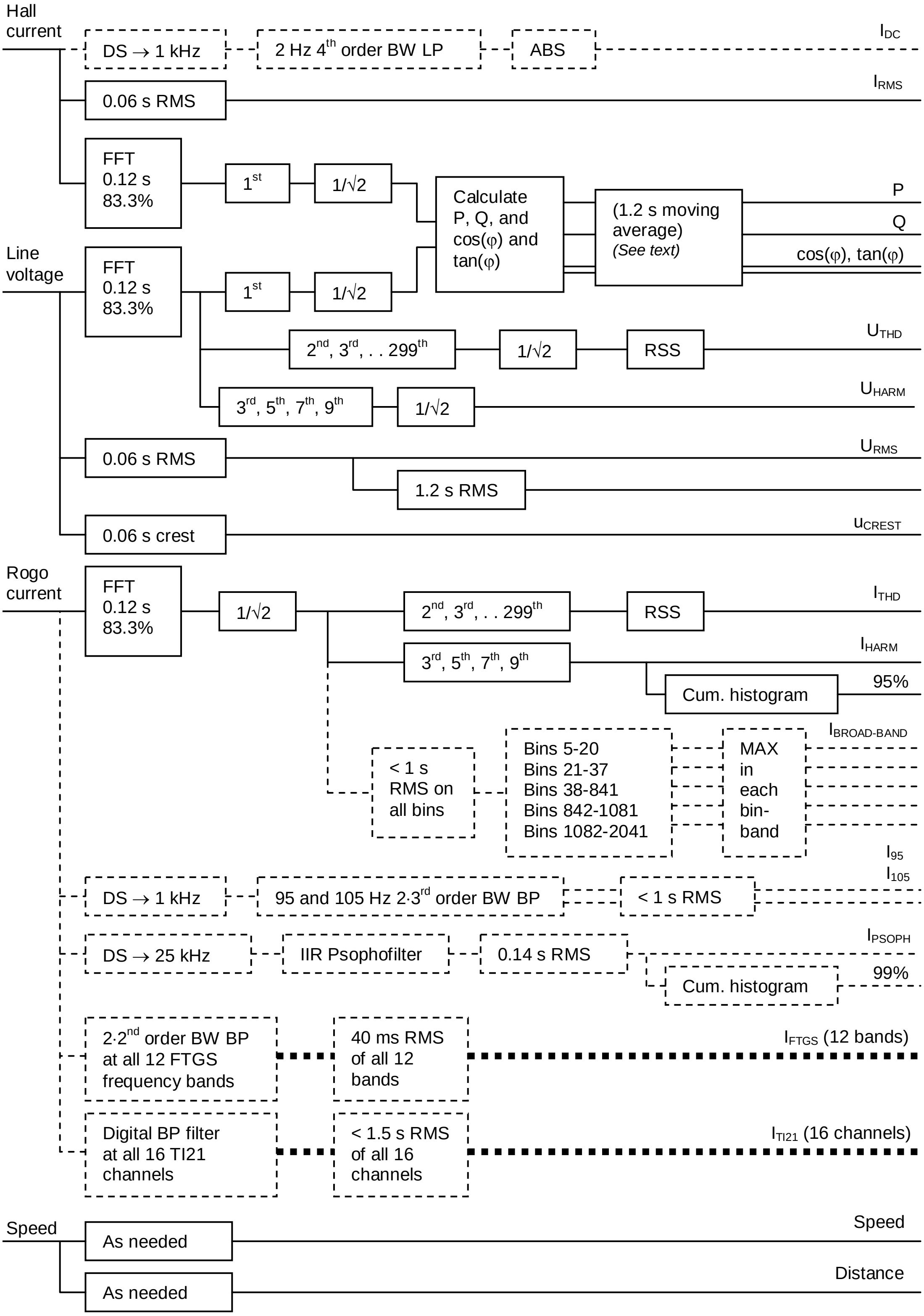


Figure 19. Suggested post-processing of the recorded data.

4.4.5.3 Data analysis – substation measurements (Norway only)

The recorded data from both the train and the substation must be processed and analysed in accordance with the requirement P8. The result plots from the analysis (one per individual LOOP, ABAB, or ARO sequence) must present time-aligned train and substation data in the same plots, all versus time:

- RMS line current, train and substation (60 ms RMS)
- RMS line voltage, train and substation (60 ms RMS)
- Train speed
- 3-phase and 1-phase active substation power (120 ms)
- Active and reactive train power (120 ms)

In addition, the following information must be given in each plot:

- Test date
- Line section
- Test ID (reference to the test log)
- Status of the vehicle (software revision etc.)
- Distance covered during the test sequence

4.4.5.4 Data analysis – P12- and P14-requirements

The current and voltage waveforms around each inrush event must be plotted, and the peak current value must be noted. Each plot must have information about the test date, the exact location of the test, and the data recording ID(s).

4.5 Documentation

4.5.1 General

All documentation shall be in English language. The documentation shall contain:

- Technical functional descriptions, when required
- Measuring equipment
- Accuracy
- Calibration
- Test set up (trains other locos and so on)
- Software version on vehicle
- Time and date for the tests
- Track/line sections and distance from start of line for the presented registrations
- Information about number of repetitions and approximate location for the various tests. Based on this, the applicant must evaluate whether the results can be considered

as typical and representative for the later use of the rolling stock, or if special conditions not included in the tests may potentially lead to future problems.

- Discussion of the results and evaluation and a conclusion whether each requirement is fulfilled or not, i.e. a confirmative statement for each requirement.
- A summary report (or a summary as a part of the whole report) where the test results are summarized with remarks and observations, especially incompatibilities and exceedances of limits.

Furthermore, a general technical description containing a principle block diagram of the traction circuits of the vehicle is required.

4.5.2 Input data for simulations

In order to develop traction power system for future, investigate power systems problems and do energy demand and loss calculations some key information about vehicles are needed.

The following information must be prepared and submitted to Jernbaneverket and/or Banverket as input to the traction power supply computer program:

4.5.2.1 Motor type (asynchronous motor or direct-current motor)
4.5.2.2 Dynamic mass [metric tons] of vehicle including load
4.5.2.3 Mass [metric tons] of vehicle including load
4.5.2.4 Adhesion mass [metric tons] of vehicle
4.5.2.5 Maximum speed [km/h] for vehicle
4.5.2.6 Length [m] of vehicle
4.5.2.7 Curve resistance CR0 [kNm/tons] and CR1 [m] as function of curve radius [m] as in formula *(curve resistance)=CR0/((curve radius)-CR1)·MASS*
4.5.2.8 Minimum allowed curve radius [m] for the vehicle
4.5.2.9 Running resistance RRA [kN], RRB [kN/(km/h)] and RRC [kN/(km/h)^2] on straight track as function of speed [km/h] in the formula $(running\ resistance)=RRA+RRB\cdot v+RRC\cdot v^2$
4.5.2.10 Adhesion coefficients ADH1 [km/h] and ADH2 [km/h] in adhesion formula *(adhesion)=ADHCOEFF+ADH1/(speed+ADH2)*. ADHCOEFF is track dependent and in this simulations presumed to be 0.161
4.5.2.11 Nominal voltage [kV] at current collector
4.5.2.12 Active power consumption [MW] for auxiliary power, train heating and air condition which is taken directly from the main transformer (no load losses not included)
4.5.2.13 Power factor at zero speed for auxiliary power, train heating and air condition which is taken directly from the main transformer
4.5.2.14 Losses [MW] for the tractive equipment from current collector to wheel at no load, for instance the no load losses of the main transformer
4.5.2.15 Maximum and continuous curve for tractive and electric braking effort [kN] as function of speed [km/h]
4.5.2.16 Desired acceleration and retardation [m/s^2] as function of speed [km/h]
4.5.2.17 Maximum tractive effort [kN] at wheels at motoring and maximum electrical braking effort [kN] at wheels as function of speed [km/h]

4.5.2.18 Maximum active power consumption and feedback [MW] at current collector as function of speed [km/h].
4.5.2.19 Efficiency [%] for maximum tractive effort from current collector to wheel at maximum tractive effort as function of speed [km/h]. Auxiliary power not included
4.5.2.20 Maximum power consumption and regeneration [MW] as function of contact line voltage [kV]. Power consumption for passenger coaches if the vehicle is a locomotive are to be added.
4.5.2.21 Maximum tractive effort [kN] as function of contact line voltage [kV]
4.5.2.22 Main circuit schematics
4.5.2.23 Filter configuration and component values/data including main transformer
4.5.2.24 Admittance frequency response including control system

Additional data required for phase angle controlled (thyristor) vehicles:

4.5.2.30 Number of converter bridges in series with one motor
4.5.2.31 Maximum allowed voltage between the motor’s terminals under the worst conditions in [%]
4.5.2.32 First limitation for the motors; current or flux
4.5.2.33 Power factor of the vehicle (thyristor brigdes) when the control is with fully advanced angle

Additional data required for inverter vehicles:

4.5.2.40 Power angle alternative power factor for power consumption and regeneration as function of contact line voltage [kV]
4.5.2.41 Active power consumption [MW] for auxiliary power, train heating and air condition which is taken from the converter bridge
4.5.2.42 Power factor at zero speed for auxiliary power, train heating and air condition which is taken from the converter bridge

All data that describe curves, such as the tractive effort versus speed, must be given as Excel tables.

Power system simulation software SIMPOW® and the additional module TRACFEED® Simulation are used.

NES NORDIC ELECTRIC POWER CO-OPERATION	TECHNICAL SPECIFICATION FROM THE NES GROUP	TS 02 APPENDICES PAGES: A58 DATE: 01.07.2009

Requirements on rolling stock in Norway and Sweden regarding EMC with the electrical infrastructure and coordination with the power supply and other vehicles

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A1 APPENDIX 1: INFRASTRUCTURE DATA AND RELATED INFORMATION

This appendix contains more detailed infrastructure data for Norway and Sweden based on requests from the ESC Infobank. The appendices also include a list of existing vehicles.

The data and values shall be regarded as information which can be changed without notice, hence the values shall not be considered as exact stipulated data. More specific information can be given by the authority in each country respectively.

Another source for information about the infrastructure and traffic may be the Network Statements.

A1.1 Main data

Data	Norway	Sweden
Owner	Norwegian National Rail Administration	Swedish National Rail Administration
Power supply system	15 kV, 16 2/3 Hz	15 kV, 16 2/3 Hz
Length of railway network	4000 km, of which 220 km double track	9882 km, of which 1734 km are double track or more (11 697 km track length)
Length of electrified railway network	2500 km, of which 220 km double track	7638 km, of which 1734 km are double track or more (9543 km track length)
Map	See appendix 2	See appendix 3
Modifications planned in future	Rebuilding of weak main lines and construction of some new lines (double track) that will increase capacity and cut travel time between existing railway destinations around Oslo	New single track lines on the east coast in the north of Sweden (Botniabanan and Haparandabanan) New city lines double track in Stockholm and Malmö Strengthening of some weak lines. Further away: High speed lines Stockholm-Mjölby and Gothenburg-Norway. Upgraded lines Stockholm-Sundsvall, Stockholm- Gothenburg, Stockholm-Malmö, Gothenburg-Malmö.
Other	The traction power supply is generally weak.	-

A1.2 Power generation

Data	**Norway**	**Sweden**
Direct supply from public network	No	No
Supply from public utility via rotary frequency converters	Yes	Yes
Supply from public utility via static frequency converters	Yes	Yes
Railway owned power stations / generators	Yes, but one hydro power station owned by other company (Statkraft SF)	No
Supply network structure	Decentralized, but a small centralized 55 kV network exists in the region south west of Oslo	Decentralized, including a 132 kV-feeding system which connects 8 converter stations
Frequency and phase stiffness	Synchronous to public utility. See section 6.1.2 in the report. Transient deviation in frequency may occur due to changing load. Phase: For both rotary and static converters phase angle depends on load demand. For a load at cos(φ) = 1.0 the phase normally lags 36° at converters at rated load.	Synchronous to public utility. See section 6.1.2 in the report. Transient deviation in frequency may occur due to changing load. Phase: For both rotary and static converters phase angle depends on load demand. For a load at cos(φ) = 1.0 the phase normally lags 36° at converters at rated load.

A1.2.1 Connection to public utility

Data	**Norway**	**Sweden**
Voltage level at connection point (PCC= point of common coupling)	min: 11 kV typ: 66 kV max: 130 kV	min: 70 kV typ: 130 kV max: 220 kV
Short circuit power at connection point (PCC= point of common coupling)	min: 70 MVA typ: 250 MVA max: 2500 MVA	min: 594 MVA typ: 2-3000 MVA max: 9260 MVA
Short circuit power at substation input	Not calculated	Without any contribution from rotary converters: min: 45 MVA

		typ: 150-200 MVA max: 480 MVA
Modifications planned in future	No information available.	Increased feeding capacity when new converters are commissioned.

A1.2.2 Power stations

Data	**Norway**	**Sweden**
Number of power stations	1	None
Number of generators per station	min: 2 typ: 2 max: 2	N.A. (= not applicable)
Rate generator power	min: 600 kW typ: 600 kW max: 600 kW	N.A.
Typical short circuit impedance of generator [%]	Unknown	N.A.
Typical short circuit impedance of transformator [%]	3.09+j0.978	N.A.
Modifications planned in future	Increasing generator capacity to 2500 kW	N.A.

A1.2.3 Rotary frequency converters

Data	**Norway**	**Sweden**
Converter name	ASEA Q24, Q38, Q48 and NEBB 7 MVA and 10 MVA	ASEA Q24/Q25 ASEA Q38/Q39 ASEA Q48/Q49
Number of converter stations	29	25 and 3 which have both rotary and static converters
Number of converters units per station	min: 1 typ: 2 max: 3	min: 2 typ: 3 max: 5
Type of converter	Synchronous to synchronous	Synchronous to synchronous
Type of excitation and control	Electro-mechanical	Electro-mechanical
Damping	Damping windings in generator-machine, none in motor-machine	Damping windings in generator-machine, none in motor-machine
Railway side connected to	Contact line for all, but also to 55 kV distribution network in two stations	Contact line
Regeneration capability	Yes	Yes

Rated converter power per unit [MVA]	min (Q24): 2.4 typ (Q38): 4 max (Q48): 10	min (Q24): 2.4 typ (Q38): 4 max (Q48): 10
Continuous power per unit (respectively) [MVA]	min (Q24): 3.1 typ (Q38): 5.8 max (Q48): 10	min (Q24): 3.1 typ (Q38): 5.8 max (Q48): 10
Typical short circuit impedance of generator+ Transformer [Ohm]	min (Q48): j7.0 typ (Q38): j14.35 max (Q24): j33.1	min (Q48): j7.0 typ (Q38): j14.35 max (Q24): j33.1
Voltage regulation	Stiff or slightly declining with increasing reactive power demand.	Stiff or slightly declining with increasing reactive power demand.
Capacity	The number of active units in each station is adapted to hourly variation in power demand	The number of active units in each station is depending on the actual load and adaptive load statistics.
Overloading capacity	Up to +40 % of continuous power for 6 minutes and +100 % of rated power for 2 seconds	Up to +40 % of continuous power for 6 minutes and +100 % of rated power for 2 seconds
If overloaded	Converter is instantaneously disconnected	Converter is instantaneously disconnected
Modifications planned in future	Static and brushless excitation may be implemented. Maybe increasing the number of converters in each station.	Brushless exciters may be introduced in the future.

A1.2.4Static frequency converters

Data	**Norway**	**Sweden**
Converter name	ABB PWM converter ABB/Adtranz PWM converter: MegaMacs Siemens	ASEA Cyclo-converter: YOQC ASEA/ABB PWM-converter: TGTO ABB/ADtranz PWM-converter: MegaMacs ALSTOM PWM-converter
Number of converter stations	6	18
Number of converters units per station	min: 2 typ: 2 max: 3	min: 2 typ: 3 max: 4 6 in future
Type of converter	PWM converter: Line voltage converter (rectifier) and pulse width modulated	15 cyclo converters and 37 PWM conveters

	inverter connected together with DC-link	
Filters on railway side	Yes, broad band and psofometric filter	Normal filter configuration for cylco converters and MEGAMACS is a wideband filter. Normal filter configuration for other PWM converters is 6th and 8th and wideband
Other filters	DC-link: 2nd, 4th, 6th and 8th/9th. Utility grid: Yes	DC-link: 2nd, 4th, 6th and 8th and wideband in MEGAMACS converters Utility grid: Yes
Regeneration capability	Only one station, in others the phase angle is shifted to push regenerated energy forward to other trains or stations. Some stations have a resistor for taking care of short term feedback power.	All cyclo converters can regenerate to the 50 Hz-grid. 2 converter stations with PWM-converters can regenerate to the 50 Hz grid. (Alingsås and Järna). All other PWM converters have resistors to take care of short term feedback power.
Rated converter power per unit [MVA]	min: 6 typ: max: 15	min: 6 typ: 15 max: 15
Typical short circuit impedance of output transformer [%]	0.013+j0.0677 pu	0.83+j13.0 but can vary a lot: 0.83% > ur >1.49% 7.94% > ur >13.0%
Voltage regulation	Stiff or slightly declining with increasing reactive power demand. Static converters imitate the dynamical response of a rotary converter (ASEA Q48) due to software parameterisation. The 1~ phase voltage angle depends therefore of the 3~ phase angle.	Stiff or slightly declining with increasing reactive power demand. Static converters imitate the dynamical response of a rotary converter (ASEA Q48) due to software parameterisation. The 1~ phase voltage angle depends therefore of the 3~ phase angle.
Frequency regulation	Synchronization with the 50 Hz grid is kept by means for phase-locked loops	Synchronization with the 50 Hz grid is kept by means for phase-locked loops
Capacity	The number of active units in each station are automatically adapted to	The number of active units in each station is depending on the actual load and

	variation in power demand	adaptive load statistics.
Overloading capacity	No short time exceeding of rated power	Normally no overload capacity but MEGAMACS have a short time capacity of 17 MVA
If overloaded	If current limit is reached, voltage will be reduced. The voltage will then not be sine adapted.	If current limit is reached, voltage will be reduced. The voltage will then not be sine adapted.
Extensions planned in future		7 new static converters are under commissioning, in operation 2007-2008

A1.3 Power distribution

A1.3.1 General data

Data	**Norway**	**Sweden**
Railway owned power distribution network exists	Yes at 16.7 Hz, in one limited area	Yes at 16.7 Hz
Nominal voltage [kV]	55 (2 x 27.5 kV)	132 kV (2x66 kV)
Number of phases	2	2
Purpose	Connecting one hydro power station, 2 rotary converters and 3 substations	To reduce number of converter stations and have a more even usage of the remaining converter stations
Network length [km]	Approx. 157	1925
Total cable length	No information available.	Cables north of Uppsala of length 6 km and south of Uppsala 3 km. (these are the longest existing cable sections)
Lowest network resonance frequency [Hz]	No information available.	Normally 100 -130 Hz. Resonance frequencies lower resonance frequencies can occur (combinations of lines and connected installed power).
Modifications planned in future	No significant modifications	No significant modifications planned

A1.3.2 Transformer stations

Data	Norway	Sweden
Number of transformer stations	3 plain transformers, 2 located together with converter stations	31 plain transformers substations, 8 transformer substations located together with converter stations
Nominal power rating [MVA]	min: 2x2.5 typ: max: 1x8	All plan transformer substations have one 16 MVA transformer Most transformer substations at converter stations have two 25 MVA transformers but normally only one operating.
Short circuit impedance [%]	min: typ: 6.3-6.5 max:	min: typ: 5 max:
Efficiency in nominal point [%]	typ: 98-99	> 99 at cos(φ) =1.0
Voltage regulation	Typically none, but one station has automatic tap changer	Only tap changers, no on load tap changers.
Modifications planned in future	None	No

A1.3.3 Transmission lines

Data	Norway	Sweden
Typical transversal section (cross section)	55 kV (2x27.5 kV) normally made up with concrete poles and with the phase height of 9.2 m and phase spacing of 3.5 m.	132 kV lines (2x66 kV) are normally built with wooden poles with a phase height of 10.8 m (sags included) and a phase spacing of 4m. Earthed top wires only close to substations and on some lines where old 3-pase 220 kV lines have been reused.
Conductor material(s)	Cu and FeAl	DOVE: 329 mm^2 FeAl
Conductor cross section (s) [mm2]	4x35, 4x50, 2x50 and 2x70	See above.
Specific impedance [Ohm/km]	0.34+j0.24 or 0.73+j0.28	Positive sequence: 0.1025+j0.126 Ω/km Zero sequence: 0.1349+j0.456 Ω/km

		Pos.seq. capacitance: 9.5862 nF/km Zero seq. capacitance: 6.4444 nF/km
Modifications planned in future	No significant modifications	No significant modifications planned.

A1.3.4 Cables

Data	**Norway**	**Sweden**
Specific impedance [Ohm/km]	0.1+j0.03 or 0.12+j0.28	Per phase: 0.1009 + j 0.026
Specific capacitance [nF/km]	Per phase: 0.16 μF/km	Per phase: 0.16 μF/km
Modifications planned in future	No significant modifications	None known.

A1.4 Substations

A1.4.1 General data

Data	**Norway**	**Sweden**
Map	Se appendix 2	Se appendix 3
Number of substations	38	See section A1.2.4 and A1.3.2.
Type of substations	Transformers only: 3 Converters feeding contact line: 35 Hydro power station: 1	See references above
Nominal power rating of complete substation [MVA]	min: 2x0.625 typ: 2x5.8 max: 3x15	See references above
Feeding of railway lines	Single side Double side Multiple side (2 T-connections)	Single and double sided feeding.
Distance between substations [km]	min: 12 typ: 80 max: 92	See section A1.5.1.
Distance of single fed line [km]	min: typ: max: 63	See section A1.5.1.
Normal operation of network	Interconnected	Interconnected
Separation of feeding areas (neutral sections)	Seldom sectioned, but depending on operation of utility grid	Normally no separation of feeding areas.

Voltage at railway side	Controlled during operation	16.5 kV controlled during operation, stiff or slightly declining, proportional to the inductive load (slightly increasing at capacitive load
Modifications planned in future	No information available.	More stations will have slightly declining voltage, proportional to the inductive load (slightly increasing at capacitive load

A1.4.2 Autotransformers

Data	**Norway**	**Sweden**
Autotransformers exist	No, but planned in future	Yes, but only on single track lines
Voltages [kV]	2x15	2x15
Transformer rating [MVA]	min: typ: 5 max: 2x5	5 Normally two AT's in parallel are used as feeding transformer feeding an AT-line.
Short circuit impedance [%]	min: typ: 0.4 max:	uk = 0,4 %, 57.53° (or 0.184+j0.117 Ω)
Distance between trafos [km]	min: 8 typ: 10 max: 12	min: 8 typ: 10 max: 12
Present on … fed lines	…both single and double side…	…both single and double …
Connection of AT to lines	Negative feeder (-15 kV), rail (0 kV) and positive feeder (+15 kV). Positive feeder interconnected to contact line (sectioned) typical each 5 km.	Normal connection, i.e. negative feeder (-15 kV), rail (0 kV) and contact line as positive feeder (+15 kV).
Combination with other systems	Not planned	At some lines with booster transformers, i.e. some lines may in the future be converted into ATBT-system.
Modifications planned in future	Planned to be used for today's weak lines	More AT-system lines are planned. AT-system may occur on double track lines in the future.

A1.4.3 Passive filters and compensators

Data	**Norway**	**Sweden**
Passive filters exist	Yes	No, only at converter stations with static converters, see A1.2.4
Type of filter	Series capacitor and shunt capacitor	N.A.
Schematics etc.	No information available.	N.A.
Resonance frequencies	Series: No significant effects on resonance frequencies. Shunt: No information available.	N.A.
Where in service	Series capacitor between converter stations on weak lines, shunt capacitor in heavy load area (Oslo S)	N.A.
Purpose	Series capacitor for voltage increase and shunt capacitor for reactive power feeding	N.A.
Rating	Series cap -j7.35 [Ohm] Shunt cap 4 [MVAr]	N.A.
Modifications planned in future	Series capacitors will probably be removed when line is reinforced/rebuilt with AT-system	More filters built when new converters are built

A1.4.4 Controlled filters, compensators and balancers

Data	**Norway**	**Sweden**
Controlled filters/ comp. exist	No	No
Type of installation	N.A.	N.A.
Schematics	N.A.	N.A.
Where in service	N.A.	N.A.
Purpose	N.A.	N.A.
Modifications planned in future	N.A.	N.A.

A1.4.5 Auxiliaries

Data	**Norway**	**Sweden**
Substation and station supply	Yes	Yes
Switch heating	Yes	Yes
Train heating	Yes	Yes

Any other equipment	No	See section 6.9.4 in the report.
Modifications planned in future	No information available.	None

A1.4.6 Other equipment

Data	**Norway**	**Sweden**
Other equipment exist	No	No
Description	N.A.	N.A.
Modifications planned in future	No information available.	None

A1.5 Railway lines

A1.5.1 Longitudinal characteristics

Data	**Norway**	**Sweden**
Map	See appendix 2	See appendix 3
Max length between feeding points [km]	92	156 (one weak line), normally 60-120 km but shorter in areas with heavy traffic, the longer distance reflects that 132 kV lines are present
Max length between feeding points and open line end [km]	63	63
Modifications planned in future	Introducing AT-systems, the max length between feeding points probably will be increased to 120 km	No specific modifications planned.

A1.5.2 Cross connections on double-track lines

Data	**Norway**	**Sweden**
Cross connection is done	Never in normal operation but one shorter line where the two tracks are operated n parallel (connected in the ends)	Exists on some lines (Tranås-Malmö) as normal operation. On other lines only during fault conditions or maintenance.
Cross-connections (if existing) are	Switchable, but just in use in fault situations	Switchable.
Distance between connections (if existing)	min: typ: very variable max:	Normally 7-10 km.

Modifications planned in future	No information available.	More lines using cross connections are under investigations

A1.5.3Cross sections of lines

Data	**Norway**	**Sweden**
Number of tracks on open line (i.e. outside stations/yards)	Mostly single track, but double and multiple track exist	Normally single track but double track between the cities Stockholm, Gothenburg and Malmö and north and west of Stockhom, see Appendix 3, Network map of Sweden. In the Stockholm area 4 track lines exists.
Earth wire	On some lines, both sectioned and interconnected exist	Exits on some lines.
Feeder (electrically parallel to contact line)	Normally not, but exist on some lines	Only on a few lines.
Feeder (connection in switch posts only)	On some lines	Only at a few locations, e.g . in the Stockholm area.
Return conductor	On some lines, normally two 240 mm^2 Al	Yes, normally two 212 mm^2 Al
Auto-/booster wires	No information available.	BT-systems: Booster wire is normally (212 mm^2 Al) used in the north of Sweden and some lines in the south, see Appendix 3, Network map of Sweden. AT-systems: Booster wire is normally used.
Public utility (no direct connection to railway system)	Not at all	None
Auxiliary supply (no direct to railway system)	Not at all	Auxiliary power of 3-phase 22 kV or 11 kV (also 2-phase exists) are normally placed on top of the contact line poles. This auxiliary power is normally fed from converter stations. Loads along the lines can also be fed from the public network. Transformers at loads along

		the line. The voltage is very weak
Open communication lines	On some lines	On most of the lines, placed in the embankment.
Typical cross section(s) layout(s)	No information available.	See appendix 6 for a typical BT-line and appendix 7 and 8 for AT-lines.
Any other important info	Isolation standard (target/planing level) for the contact overhead line system is 170/70 kV.	Isolation standard (target/planning level) for the contact overhead line system is 170/70 kV. There exists lines with isolation levels between 150/55 kV and 225/75 kV.
Modifications planned in future	No information available.	Earth wire are planned to be standard on all future AT-lines, probably also on BT-lines. Exits already on some lines.

A1.5.4Cable sections

Data	**Norway**	**Sweden**
Length of cable connection substation to contact line [km]	typ: 0.1 max: 5	0.1 – 4 km, typical value 300 m.
Length of feeder cable parallel to railway line (e.g. tunnels, urban areas) [km]	typ: max: short	Exist only in the Stockholm area (4 cable feedings). Typical length : 13 km.
Specific impedance [Ohm/km]	min: 0.10+j0.03 typ: 0.12+j0.06 max:	For cables in the Stockholm area: 0.12 + j 0.054 and 0.15 + j 0.036
Specific capacitance [µF/km]	min: typ: 0.26 max:	For cables in the Stockholm area: 0.16 and 0.26 µF/km.
Modifications planned in future	Introducing AT-system may cables for negative and positive feeder in tunnels may be necessary	Under investigation (Citybanan in Stockholm).

A1.5.5Return current arrangement

Data	**Norway**	**Sweden**
Rail types	S49: 2700 km S54: 750 km	Normally UIC 50 and UIC 60 or corresponding.

	UIC60: ca. 200 km	
Rail info	Normally welded, isolated gaps/joints exists	One rail welded (S-rail) and one rail with isolated joints (I-rail) which is used by the DC-track signalling circuit.
Isolated rails	No isolation at all	Yes, see item above.
Return conductor	See section A1.5.3.	See section A1.5.3.
Earth wire	On some lines, both sectioned and interconnected (typical distance between connections to rail is 3 km) exist	See section A1.5.3.
Track transformers	No	No
Other characteristics	No	No
Earth resistivity [Ωm] Wet soil: 20-200 Humus/clay: 50-200 Wet sand: 100-300 Dry sand: 1000-50000 Mountains: 1000-10000	Railway lines are very often build on bedrock ground or rocky ground. A usable value is 2500 Ωm.	Earth resistivity is high. A usable value is 2500 Ωm.
Future modifications plans	No information available.	None

A1.5.6 Booster transformers

Data	**Norway**	**Sweden**
Booster transformers exist	Yes	Yes, on all lines except AT-system lines.
Transformer power rating [kVA]	min: 33 (380 A, 87 V) typ: 55 (680 A, 92 V) max: 95 (800 A, 118 V)	500 A Booster transformer: 158 kVA (500 A, 316 V, 800 A for 1 hour). Older booster transformers of 300 A exists.
Short circuit impedance [%]	min: 2.7 + j 2.5 typ: 8.4 + j 22.3	500 A Booster transformer: typ: 3.86 + j 10.3 typ: 11 (absolute value)
Distance between booster transformers [km]	min: 2 typ: 3 max: 20	typ: 5.6
Specific contact line system impedance [Ohm/km]	typ: 0.013	See section A1.5.9.
Modifications planned in future	No information available.	3-windings boosters may be introduced if ATBT-systems are introduced.

A1.5.7 Neutral sections/Phase gaps

Data	**Norway**	**Sweden**
Neutral sections exist	Yes	Yes
Neutral part is	See clause 6.2 in the report.	Normally floating
Location	See clause 6.2 in the report.	At substations and switching posts.
May be shunted	See clause 6.2 in the report.	Yes, normally to earth, but to contact line voltage exists.
Length [m]	min: 40 typ: 90 max: 350	min: 2 at stations min: 60 typ: 180 max: 180
Concept for emergency supply (e.g. one substation out of order)	No information available.	Converter stations are design for outage of one converter unit with out influencing the traffic.
Modifications planned in future	Neutral sections of 402 m are planned for future.	None

A1.5.8 Interaction AC/DC railways

Data	**Norway**	**Sweden**
Infrastructure segment lies adjacent to DC-railways/tramways	Yes	Yes
Special arrangements (such as DC train supply with current return through rails on AC lines)	No, not as we know	No
Description	Grefsen station (750 V DC parallel and 600 V DC crossing) Bryn station (750 V DC crossing) Trondheim station (600 V DC crossing)	Trams lines (750 V DC) parallel to railway lines in Gothenburg. Underground/subway lines (750 V DC) parallel to railway lines in Stockholm.
Modifications planned in future	Lysaker station – tramway face to face planned	No

A1.5.9 Numerical values BT system

Data	**Norway**	**Sweden**
Line impedance , single track lines [Ohm/km] including BT	min: 0.092+j0.106 typ: 0.190+j0.210 max: 0.233+j0.228	min: 0.13+j0.16 typ: 0.21+j0.20 max: 0.30+j0.23
Line impedance , double track lines [Ohm/km] including BT	min: 0.160+j0.180 typ: max: 0.218+j0.188	Not calculated.
Specific capacitance, single track [nF/km] (caternary–earth)	min: 9 typ: max: 17	typical for booster transformer lines: 8.8 – 11.1
Lowest resonance frequency (contact line network) double side feeding [Hz]	typ: 800 Hz global typ: 450 Hz local	typ: 800 Hz global typ: 450 Hz local
Lowest resonance frequency (contact line network) single side feeding [Hz]	typ: 450 Hz local	typ: 450 Hz local
Other interesting values	Earth resistivity is high.	Earth resistivity is high. A usable value is 2500 Ωm.
Modifications planned in future	No information available.	No

A1.5.10 Numerical values AT system

Data	**Norway**	**Sweden**
Fixed impedance at feeding or starting points [Ohm]	Not yet decided or calculated.	min: 0.189+j0.343 typ: max: 0.468+j0.755 (see note below the table)
Line impedance on single line track [Ohm/km]	Not yet decided or calculated.	min: 0.0335+j0.031 typ: max: 0.0715+j0.066 (linear approximations including AT's)
Line impedance on double line track [Ohm/km]	Not yet decided or calculated.	Not calculated.
Specific capacitance, single track [nF/km] (caternary–earth)	Not yet decided or calculated.	typ: 11.9 – 13.5
Specific capacitance, double track [nF/km] (caternary–earth)	Not yet decided or calculated.	Not calculated.
Lowest resonance frequency (contact line network) double	typ: 450 Hz global typ: 350 Hz local	typ: 400 Hz global typ: 250 Hz local

side feeding [Hz]		
Lowest resonance frequency (contact line network) single side feeding [Hz]	typ: 200 Hz local	typ: <200 Hz local
Modifications planned in future	Exact system design not decided yet	No

NOTE that the values for AT-systems in Sweden regards single track systems. Furthermore note that the AT-system impedances are linear approximations of the AT-system impedances with the intension to get values which can easily be used in simulation programs and for calculations of settings of relay protections. The fixed impedance corresponds approximately to the level of the zero sequence impedance of the system. This impedance shall be placed as a fixed impedance at both ends of the system in case of a AT-system fed from both ends and at the feeding end in case of a single end fed system. The impedance per km corresponds approximately to the positive sequence impedance.

A1.6 Signalling equipment

A1.6.1Track circuits

Data	**Norway**	**Sweden**
DC track circuits	Only on non-electrified lines and at one electrified railway station (Filipstad)	DC track signalling circuits exists on nearly the whole network. None existing only on none electrified lines.
High voltage impulse	Do not exist	Do not exist
Low frequency (25-275 Hz)	Exist on most of the electrified lines. 95 and 105 Hz only, uncoded.	Do not exist
Reed frequency (275-1000Hz)	Do not exist	Do not exist
Lower audio frequency (1-4 kHz)	Exist on a small part of the network. Bombardier TI 21 (1.5 - 2.6 kHz), digital processor based and not transmitter signal coded.	Do not exist
Upper audio frequency (4-20 kHz)	Exist on a part (110 km) of network. Siemens FTGS (4.7-16.5 kHz), digital and transmitter signal coded.	Do not exist
Other	Do not exist	Train radio or radio blocking of trains on some none electrified low traffic lines
Modifications planned in future	No information available.	More radio block systems are planned for low traffic

		lines.

A1.6.2 Axle counters

Data	**Norway**	**Sweden**
Mechanical	Do not exist	No
Electro-magnetic	Do not exist	Yes, but not used as signalling equipment They are placed together with axle box heating locked braking detectors
Electronic	Do not exist, but are being tested	No
Others	Do not exist	No
Modifications planned in future	Are planned for future use	None

A1.6.3 Automatic train protection (ATP) and automatic train control (ATC)

Data	**Norway**	**Sweden**
ETCS/ERTMS level 1	Does not exist	Does not exist.
ETCS/ERTMS level 2	Does not exist	Introduced on the Botniabanan
ETCS/ERTMS level 3	Does not exist	Does not exist.
National system(s)	“ATC” used in nearly the whole network. EBICAB700 manufactured by ATSS and Bombardier	“ATC” used in nearly the whole network, manufactured by ATSS and Bombardier. Radio blocking of trains or manual train blocking used on some none electrified low traffic lines.
Modifications planned in future	Long term strategy is ERTMS level 2	Ongoing project for introducing ERTMS level 2 (the lines Malmö-Stockholm-Sundsvall are planed for 2010-2015)

A1.6.4 Interference monitors

Data	**Norway**	**Sweden**
Philosophy of application	Monitors recommended. Monitors needed if safety case can not be fulfilled otherwise	DC-current monitor on new electrical traction vehicles is required.

Purpose	Monitored frequencies: 95 and 105 Hz. Trip level 2 A rms. Filter characteristics ±3 Hz. Response time 1 sec.	To monitor the DC-component, a component which can have an influence on the track signalling circuits.
Type(s) in service	95 and 105 Hz monitor for warning and disconnection of main circuit breaker.	DC-monitors are in operation on some new vehicles.
Modifications planned in future	No information available.	None

A1.6.5 Interference limits

Data	**Norway**	**Sweden**
Frequency band (name)	See section 5.2 and 5.4 in the report.	Limits on DC-components and psophometric currents, see section 5.2 and 5.4 in the report.

A1.6.6 Data transmission and remote control systems

Data	**Norway**	**Sweden**
System(s)	Various communication systems exists, such as PCM (puls code modulation, BF (frequency carrier), etc, on Cu-cable. Also ordinary telephone lines on Cu-cables excists. Opto-communication is the dominating transmission for long distances communication. GSM-R is being introduced in the whole country.	Various communication systems exists, such as PCM (puls code modulation, BF (frequency carrier), ADSL, etc, on Cu-cable. Also ordinary telephone lines on Cu-cables exists. Opto-communication is the dominating transmission for long distances communication. Transmission used for SCADA-systems are ELCOM, X25, RP570 and more. At the moment IEC 870-5-104 (on TCP/IP) is introduced. GSM-R is being introduced in the whole country.

A1.7 Operational conditions

A1.7.1 Line frequency

See section 6.1.2.1 in the report.

A1.7.2 Line voltage RMS value

See section 6.1.1.1 in the report.

Based on simulation in SIMPOW® TRACFEED® the figures below show a typical statistical distribution of the fundamental voltage at the pantograph of a vehicle in Norway. The values can be used as a fairly good approximation also for Sweden.

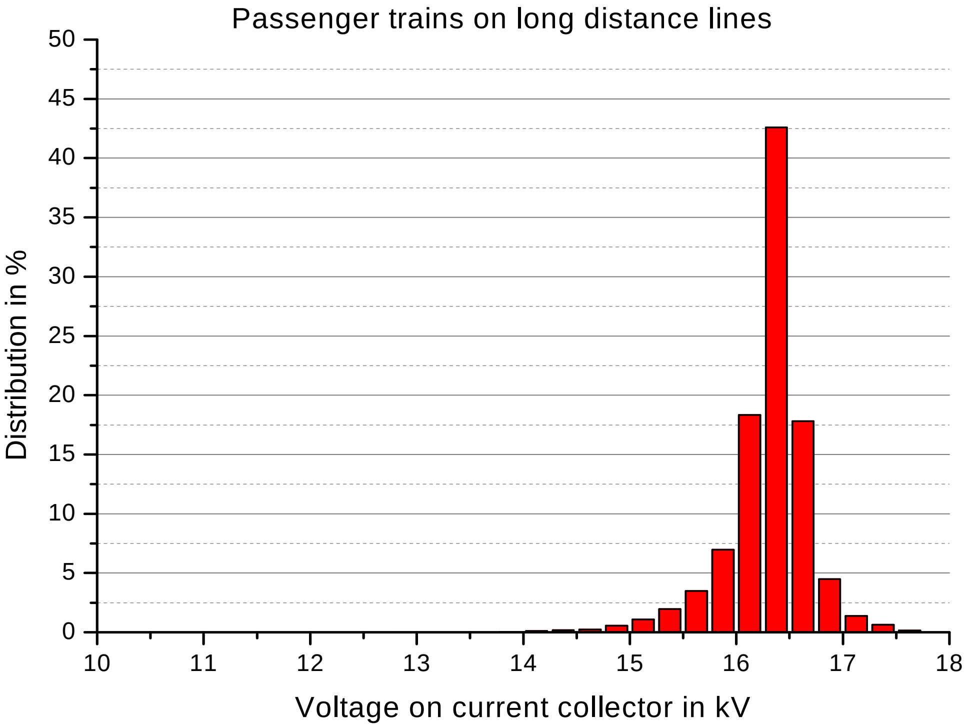
The information is based on 1-second values (mean values during one second) for a 35 different trains considered as representative of the operation to day. Vehicle and line vary and the trains are divided and aggregated into the following groups:

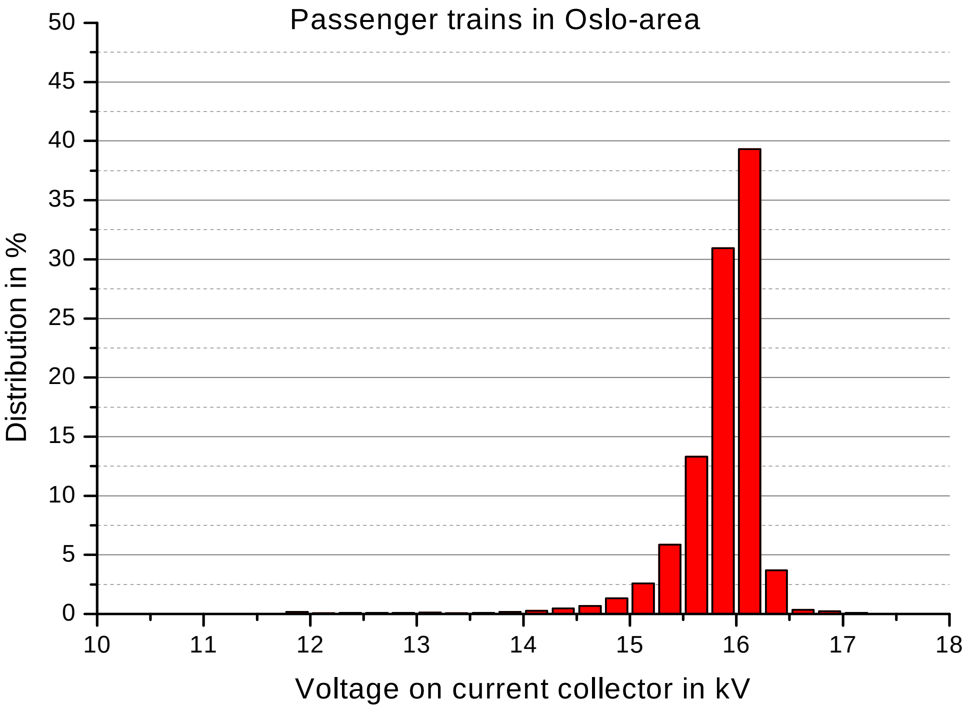
- Freight trains on long distance lines, normally considered as weak lines (Bergen line, Dovre line, Sørland line and Ofoten line).
- Passenger trains on long distance lines, normally considered as weak lines (Bergen line, Dovre line, Sørland line and Ofoten line).
- Passenger trains in Oslo area, also including the Gjøvik line, Østfold line and the Vestfold line. The Olso area is normally considered as relatively stiff compared to long distance lines.

The voltages shown below are simulated for traction, coasting and braking mode, and includes stops at stations between start and stop.

Note that this figures show an overall distribution. For shorter time intervals the voltage distribution for a single train deviates from the figures shown due to sections of lines with lower voltage quality.


Freight trains on long distance lines
Distribution in %
50
45
40
35
30
25
20
15
10
5
0
10
11
12
13
14
15
16
17
18
Voltage on current collector in kV


Passenger trains on long distance lines
Distribution in %
50
45
40
35
30
25
20
15
10
5
0
10
11
12
13
14
15
16
17
18
Voltage on current collector in kV



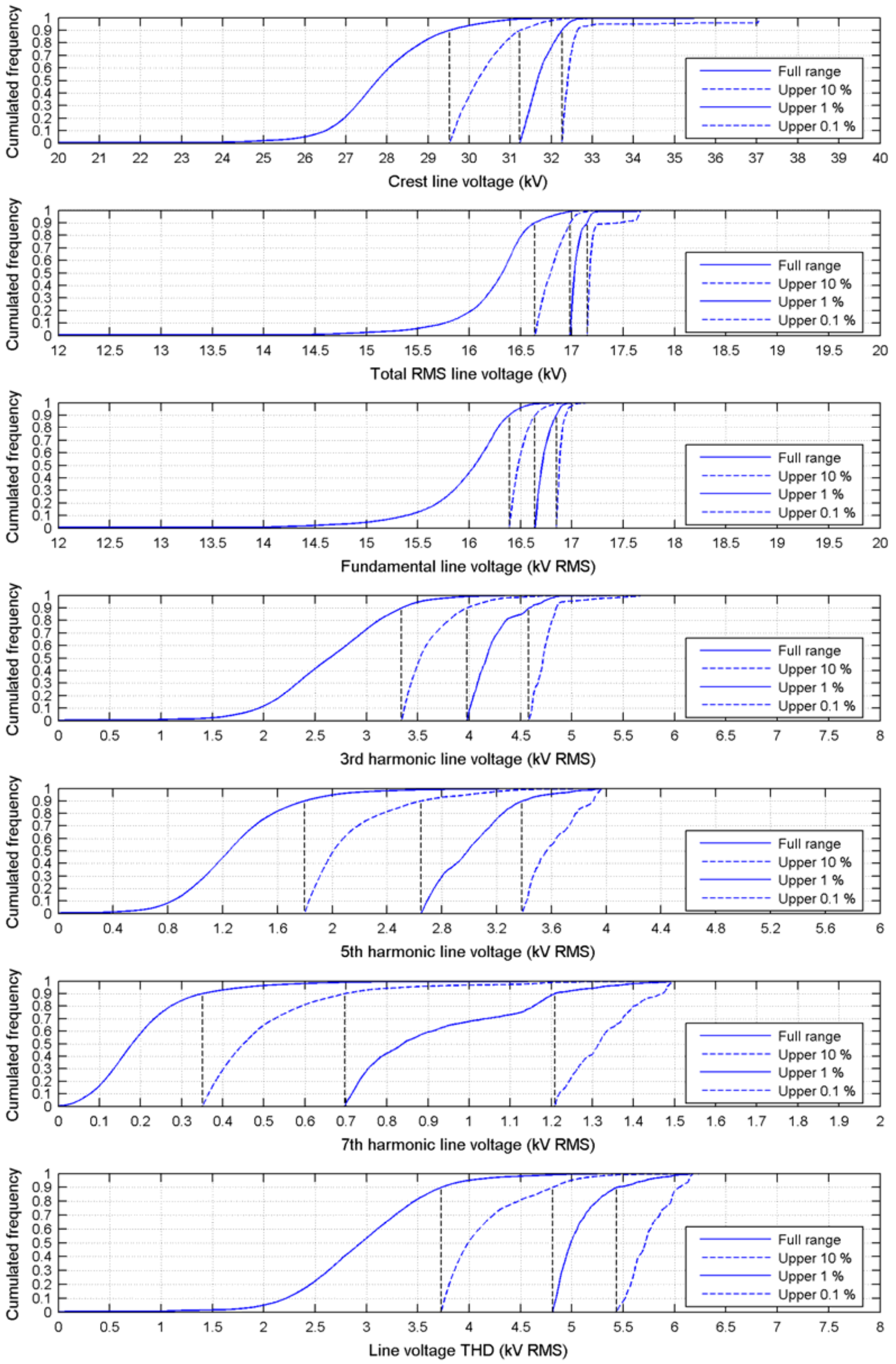
A1.7.3 Line voltage spectrum

Data	**Norway**	**Sweden**
Sub-harmonics or regular frequency variations occur	Yes, see clause 6.5.1 in the report.	Yes, see clause 6.5.1 in the report.
Line voltage content with harmonics up to 1000 Hz	Significant to very large, higher harmonic orders do occur but are not significant, see section 6.1.3.1 in the report.	Significant to very large, higher harmonic orders do occur but are not significant, see section 6.1.3.1 in the report.
Line voltage content with harmonics 1000-3000 Hz	Very low, no influence on vehicle known from earlier tests	Very low, no influence on vehicle known from earlier tests, so far.
Typical spectra	See section 6.1.3.1 in the report.	See section 6.1.3.1 in the report.

The figure below can be regarded as a typical statistical distribution of the line voltage harmonics for Norway and Sweden. (The values of the figure below are based on recordings made during tests with a locomotive on the Borlänge-Ludvika/Krylbo-Frövi-Eskilstuna line sections in Central Sweden, October 2005. Recordings and analysis by L. Buhrkall.)

Typical distribution of line voltage interference components, measured in Central Sweden.

PLEASE NOTICE: The curves showing the distribution of the fundamental 16 2/3 Hz voltage components are not typical for low voltages at weak supply.



A1.7.4 Regenerative brake

See clause 6.8 in the report.

A1.7.5 Power factor

See clause 6.3 in the report.

A1.7.6 Earthing

Data	Norway	Sweden
Earthing principles	The midpoint of the 2x27.5 kV high transmission line is directly earthed.	The 132 kV system has directly earthed midpoints in the 2-phase system (2x66 kV). AT-systems (2x15 kV) have directly earthed midpoints.

A1.7.7 Traffic information/characterisation

Data	Norway	Sweden
City area	Train density equal to line capacity	Train density equal to line capacity
Suburban area	Train density equal to line capacity	Train density equal to line capacity
Long distance lines	0-6 trains per feeding distance depending on traffic. In high load periods up to or even higher than line capacity.	Some lines (south from Storvik and south from Hallsberg to Mjölby has train density equal to line capacity. Otherwise 0-6 trains per feeding distance.

See respective Network Statement.

A1.7.8 Network operation

Data	Norway	Sweden
Case	The network is normally interconnected with adapted feeding capacity. Sectioning of contact line due to maintenance or failure often occur. Maintenance of converter stations may result in reduced feeding capacity. Sectioning and reduced feeding capacity results in lower resonance frequencies	Single feeding of lines during maintenance or fault conditions may occur resulting in very high impedances at the far end from feeding point and lower resonance frequencies. Other cases not applicable for vehicle compatibility

A1.7.9 Infrastructure classes

Expressions used in table below correspond to the definitions in EN50 163 and EN 50388. For more details see corresponding chapters in the report. Classification of infrastructure is to be given in respective Network Statement, but classes written in *italic* are most used.

Data	**Norway**	**Sweden**
Line voltage levels	*V1: according to EN 50163:2004* V2: U_{min2}=10000 V and U_{min1}=11000 V	*V1:* $U_{max2} = 17500$ *V*
Maximum current limitation	C1: $I_{max} = 900$ A C2: $I_{max} = 700$ A C3: $I_{max} = 450$ A	Max current per train is 900 A in tractive mode. Higher values in braking mode can be accepted.
Regenerative braking	B1: I_{max} B2: 10 MW / 600 A B3: 8 MW / 500 A *B4: 5 MW / 300 A*	No classes defined.
Low frequency power oscillations	Under investigation.	Under investigation.

A1.8 Existing electrical vehicles

Passive filters refers to HV-filters or filters on a separate winding of the transformer, not filters on the DC-link in case of an inverter vehicle.

Active behaviour refers to if the control system compensate for harmonics in the traction current in order to draw a sinusoidal current

A1.8.1Electrical locomotives in Norway and Sweden

Operator	**Vehicle (no of vehicles in op. in brackets.)**	**Type**	**Passive filter**	**Active behaviour**
Hector Rail AB (pre-liminary accepted)	BR 441 (2) (DB BR 189)	Inverter	Yes	up to 83 1/3 Hz
Hector Rail AB	BR141 (3) (ÖBB Class 1012)	Inverter	No	up to 250 Hz
Hector Rail AB	BR142 (6) (ÖBB Class 1142)	Tap changer	No	No
CargoNet AS, Hector Rail AB, GreenCargoAB	CE119/BR241/BR 185.2 (20-30) (DB BR185.2)	Inverter	Yes	up to 83 1/3 Hz
MTAB	Dm 3 (19)	Tap changer	No	No
MTAB, TKAB	Da (5)	Tap changer	No	No
Raillion AS	EG 3100 (13)	Inverter	Yes	Yes, up to unknown freq.
NSB AS, Ofotbanen AS	El 13 (5)	Tap changer	No	No
CargoNet AS	El 14 (31)	Tap changer	No	No
Hector Rail AB	El 15 / BR 161 (6)	Tap changer, diode rectifier	No	No
CargoNet AS, TKAB, TGOJ	El 16 (17)	Phase angle control	Yes	No
NSB AS	El 17 (10)	Inverter	Yes	Unknown
NSB AS	El 18 (22)	Inverter	No	up to 83 1/3 Hz
MTAB	IORE (2x9=18)	Inverter	Yes	up to 83 1/3 Hz
TGOJ	MA (32)	Tap changer	No	No
SJ AB, Green Cargo AB, TÅGAB, TGOJ	Rc 1 to Rc 7 (356)	Phase angle control	Yes	No
Green Cargo AB	Rm (6)	Phase angle control	Yes	No

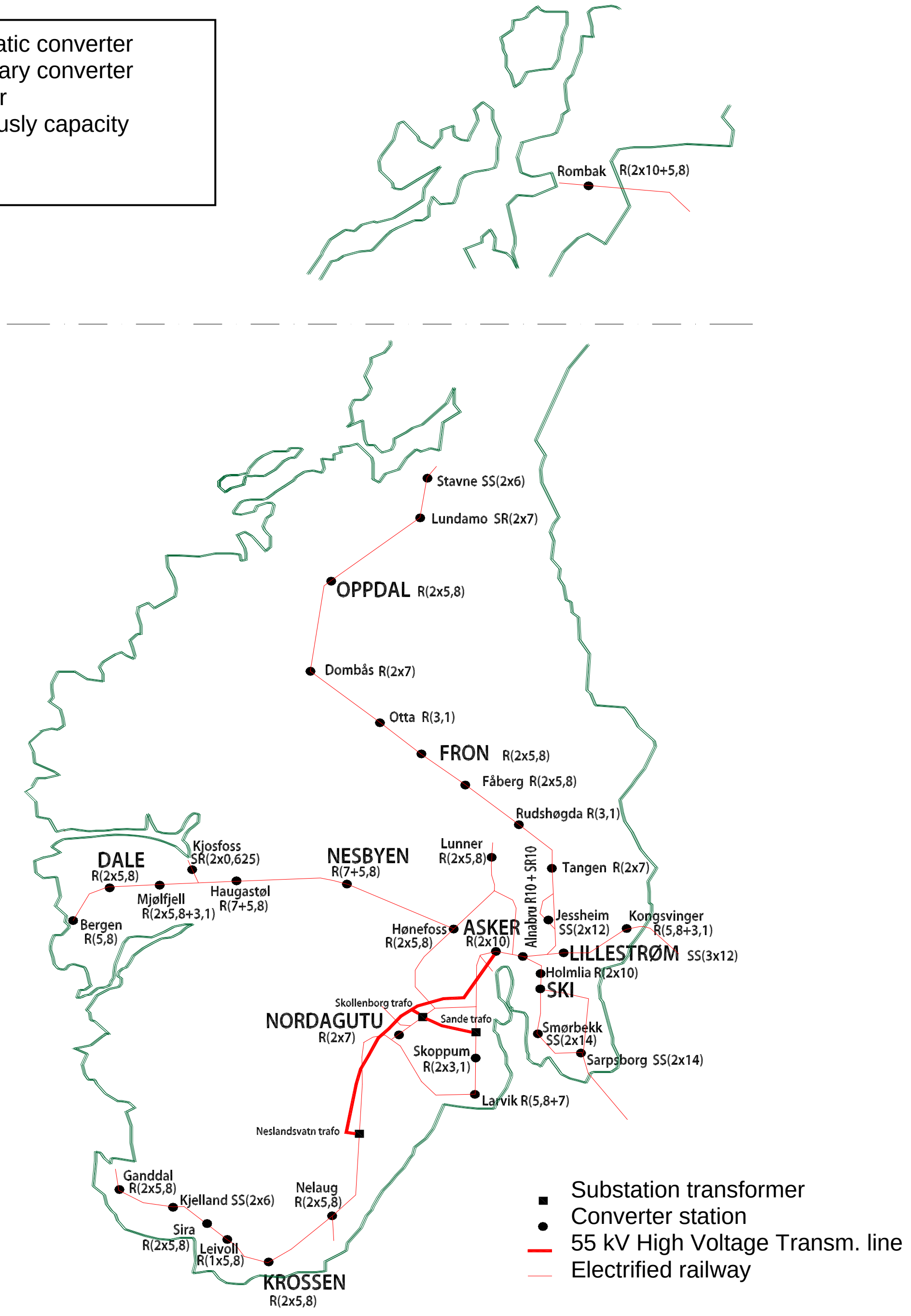
A1.8.2 Electrical multiple units in Norway and Sweden

Ofotbanen AS	Class 68 (3)	Tap changer	No	No
NSB AS	Class 69 a-g (77)	Phase angle control	a-c: yes d-g: no	No
NSB AS	Class 70 (16) ("IC 70")	Inverter	No	up to about 300 Hz
Flytoget AS	Class 71 (16) ("FPT")	Inverter	No	up to about 850 Hz
NSB AS	Class 72 (36)	Inverter	No	Unknown
NSB AS	Class 73 (22) Identical to class 71	Inverter	No	up to about 850 Hz
SL	X1 (94)	Phase angle control	Yes	No
SJ	X2 (43) ("X 2000")	Inverter	Yes	up to 216 2/3 Hz
Arlanda Banan AB	X3 (7) ("Arlanda Express")	Inverter	No	unknown
SJ and SL and other regional operators	X10 to X14 (137)	Phase angle control	yes	No
SJ, TKAB	X20 to X23 (3)	Tap changer, diode rectifier	unknown	No
SJ / DSB	X31-32 (3x53) ("Öresund train")	Inverter	yes	unknown
SJ	X40 (2x16 and 3x27 ordered)	Inverter	no	up to 150 Hz
SJ and regional operators	X50-54 (50) ("Regina")	Inverter	yes	up to 83 1/3 Hz
SL	X60 (71 ordered)	Inverter	no	up to 150 Hz

(for a good general overview of vehicles in NO and SE see also www.jarnvag.net)

A2 APPENDIX 2: NETWORK MAP NORWAY

SS = Stationary static converter
SR = Stationary rotary converter
R = rotary converter
Maximum continuously capacity
given in parentes



A3 APPENDIX 3: NETWORK MAP SWEDEN

(Applies to Sweden only)

A4 APPENDIX 4: ADDITIONAL INFORMATION FOR STABILITY STUDIES

A4.1 Low frequency power oscillations

A4.1.1 Background

- Inverter vehicles typically control the line current and the dc link voltage depending on the train's operation point and the line voltage. The involved control loop includes the substation (rotary or static), the ohmic-inductive line and the vehicle's dc link capacitors. All these elements store and exchange energy. The number of vehicles, the impedance of the line and the tuning of the controllers have a large influence on the stability margin of the control loop.
- Responsible for the oscillations are the time delays and the tuning of the vehicle controllers. With increasing line impedance and number of vehicles instabilities can occur. The resulting oscillations have an eigen-frequency up to half the line frequency (e.g. 8 Hz) and lead to low frequent variations in the line voltage (phase and amplitude), pole angle of rotary converters, dc link voltage and motor torque. An unstable situation can also lead to protective shutdown of vehicles and / or infrastructure.
- This means that if a vehicle is controlled to consume constant active power by increasing its current when the voltage at pantograph decreases it can cause pole angle oscillations in a rotary converter. The variation in current is enough to give active overhead contact line losses which may obstruct damping of the oscillation or excite pole angle oscillation in the converter (pole angle oscillations in rotary converters are mostly excited by variations in active power load which consists of both train load and transmission losses).
- There are also vehicle controllers which act in a discontinuous way, e.g. adhesion control (sudden reduction of motor torque to prevent wheel slip) or line voltage limitation (to prevent breakdown of voltage at pantograph). Such interventions provoke the power supply system to answer with a step response, which is not critical by itself. However, if the action is continued repetitively and with frequencies close to eigen-frequencies of the supply system, low frequency oscillations may occur. This effect could occur both with inverter and phase angle controlled vehicles.

A4.1.2 Definition of a simulation model

- According to earlier projects the described effects can be reproduced in time domain simulations with a good accuracy.
- The simulation model must contain all relevant subsystems. It can either be off line or based on a hardware-in-the-loop simulation including a real-time simulator and the original control units. The modelling depth must be chosen such that the critical effects can be reproduced in simulation. The model should contain the following subsystems:
    - A vehicle model with a transformer, line converter including controller with accurate timing (time discrete implementation with sampling and delay

effects), DC link and the motor side with motor inverter including controller and motors to simulate the load.
- Line with adjustable impedance. An R-L-impedance is sufficient. The parameters are provided by the infrastructure manager (see chapter A1.5.9 and A1.5.10 of this document).
- Substation (rotary converters). The dynamic behaviour is provided by the infrastructure manager, see chapter A5 of this document. No models of static converters can be given, since they include proprietary knowledge of the respective manufacturer, but some time constants should however be possible to retrieve. Experience so far has shown that the vehicles are compatible with static converters if they are compatible with the rotary ones for all required operational conditions.

A4.1.3 Stability study

- Based on the simulation model as described above, a stability analysis of the new vehicle together with the existing power supply system has to be performed.
- It has to be shown that neither self excited oscillations due to feedback effects nor repetitive excitation of power system resonances due to discontinuous controllers occurs.
- Typical parameters for this sensitivity analysis can be taken from Appendix 1: Infrastructure data and related Information of this document. Minimum / maximum values have to be taken into account as well, but it is not necessary to combine all values to a “worst worst” case.
- The parameters (power supply, operation) on which the stability margin (and therefore the acceptance criterion) is based may be quite different for various types of operation (long distance freight traffic, or rapid mass transit) and can not be given with concrete values in this document. They have to be defined and agreed between vehicle manufacturer, operator and infrastructure manager right at the beginning of the study (EN 50 388:2005, clause 10, steps 1 and 7 of the compatibility process). They must be realistic for the planned operation, including a sufficient margin to guarantee stable operation.
- It has to be shown that the stability of the system is robust. The goal is to show that the foreseen operation is stable with sufficient margins. (Example: “It is possible to run up to 10 vehicles at the end of a 50 km long line. Only 4 are required. There is enough stability margin.”).
- Testing of the vehicle (EN 50388:2005, clause 14) will be based on the same conditions as for the simulation studies.

A4.2 Electrical resonance stability

A4.2.1 Background

- The control of the line inverter (four-quadrant power converter) of a vehicle reacts on the line voltage with short time constants, since the control e.g. has to shape the line current regardless of the line voltage waveform, or has to suppress specific frequency contents in the line current (compatibility with signalling installations). Delay times in this reaction are inevitable, due to both microprocessor control cycles and pulse width modulation (PWM).

- Seen from the power supply system, the vehicle has a frequency response of its input admittance Y(f), i.e. the ratio between line current and line voltage. If the admittance has a phase angle above / below +/– 90° (i.e. Re(Y) <0) the vehicle is „active“ on the corresponding frequency, and may excite power system or filter resonances. This leads to corresponding instabilities and overvoltages. Such resonance and instability effects occur on frequencies higher than the line frequency. Linear or linearised methods can be applied for a stability analysis.
- Note that anti-control of a frequency component in the primary current of a vehicle (e.g. a 100-Hz anti-control) can result in the fact that the vehicle is active around this frequency.
- Most critical with respect to electrical resonance stability is the lowest system resonance frequency. This is valid for all type of networks. In contact line network, this frequency is typically between 800 and 1500 Hz in central Europe, but lower in Finland, Norway and Sweden due to the system build-up in these countries, i.e. booster transformer systems. It but may be even lower if a lot of cables are installed or if the lines are very long. The lower the frequency, the worse the damping is. Natural damping is mainly caused by eddy current losses in synchronous machines and substation transformers. Excessive cabling may lower the resonance frequency to critical values.
- Typical resonance frequencies in a 132-kV network are between 100 and 200 Hz, strongly depending on the geographical extension of the network as well as on the installed generator power. High voltage networks (including autotransformer systems) are, therefore, critical with respect to electrical resonance stability. Compared to filter resonances in converter stations or vehicles, transmission network resonances are much more critical due to their lower damping.
- Both static frequency converters and vehicles can include passive filter components, in order to reduce harmonic currents produced by the converter. These filters have resonances, which can also be excited to oscillations by the line converter control of vehicles. The situation is less critical compared to resonances in contact line and high voltage lines since the filters include damping resistors.

A4.2.2 Definition of a simulation model

- For electrical resonance stability investigations with respect to vehicle requirements as defined in this document, only a vehicle simulation model is required.
- The model must have a similar form as described above for low frequency oscillations.
- It is very important that all sampling and time delay effects (controllers, pulse width modulation) are correctly included.
- The motor side of the vehicle can be omitted if no fast feedback from the motor side to the line-side inverter and current circuits exists.

A4.2.3 Stability study

- The frequency response of the input admittance of the vehicle has to be simulated with the model as defined above.
- The frequency response has to be simulated for different operation points (typically zero power, maximum traction power, maximum braking power).
- As long as the vehicle holds the requirements as defined in the main part of this document (section 6.5.2) no simulation of the power supply network and other vehicles is necessary. If a vehicle can not hold this requirement, a full stability study according to EN 50388:2005, clause 10, has to be performed in order to demonstrate that the vehicle is stable together with the railway system.

A5 APPENDIX 5: DYNAMIC BEHAVIOUR OF ROTARY CONVERTERS

A5.1 Summary

The following general characteristics apply to rotary converter units:

- Even small steps in contact line power excite noticeable oscillation in the converter rotor.
- The direction of the power step (increase or decrease) has no significance for the magnitude of the rotor oscillation.
- The oscillation magnitude decreases greatly when power consumption occurs as a ramp of limited steepness instead of as a step.
- Even small repetitive power changes of limited steepness cause considerable oscillation when occurring at an unfavourable frequency (1.0 – 2.0 Hz). If a relative steep reduction of power under certain conditions is necessary, e.g. due to the function of wheel slip and slide protection, the amount of oscillation may to some extent be limited by imposing considerably stricter restrictions on following power increase.
- The time until an oscillation is damped increase with the oscillation magnitude, and is for large oscillations of the size of 10 – 15 s when rolling stock does not contribute to maintaining the oscillation.
- The rotor oscillation results in oscillations in the contact line voltage amplitude and the voltage’s steepness and zero crossing every 16 2/3 Hz period is displaced relative to a ideal sine.
- Depending on the train current-voltage characteristic, the contact line impedance may result in deviation between the voltage oscillation amplitude at the pantograph and at the converter station. Trains having power output independent of voltage will increase the amplitude while the amplitude will decrease for constant impedance load characteristic trains.

A5.2 Examples of converter unit response to changes in load.

A5.2.1Introduction

The dynamic behaviour of rotary converter units is in the following text illustrated by computer simulations for a 5.8 MVA rotary converter unit (Q38) which on the single-phase side supplies the train without interconnection with other converter units. The train is simulated with voltage independent power consumption. Further description of the simulation model can be given by Norwegian National Rail Administration on request.

A5.2.2 Definitions

Definitions/Abbreviations used:

U 60km:	Pantograph voltage at 60 km from the converter station when contact line has a resistance of 0.18 ohm/km and an inductive reactance of 0.19 ohm/km (16 2/3 Hz)
PA 60km:	Angle of pantograph voltage at 60km from the converter station when overhead contact line has a resistance of 0.18 ohm/km and an inductive reactance of 0.19 ohm/km (16 2/3 Hz). Phase angle is relative to the 50 Hz power supply of the converter station.

A5.2.3 Frequency response

Figure 4b.1 shows the converter unit’s frequency response characteristics for active power between the single-phase and the 3-phase side in the 0 – 5 Hz frequency band, i.e. the dynamic, electromechanical connection between a single-phase power disturbance ΔP1 and the response in 3-phase power ΔP3 for the converter unit. It is assumed that the disturbance is sine shaped.

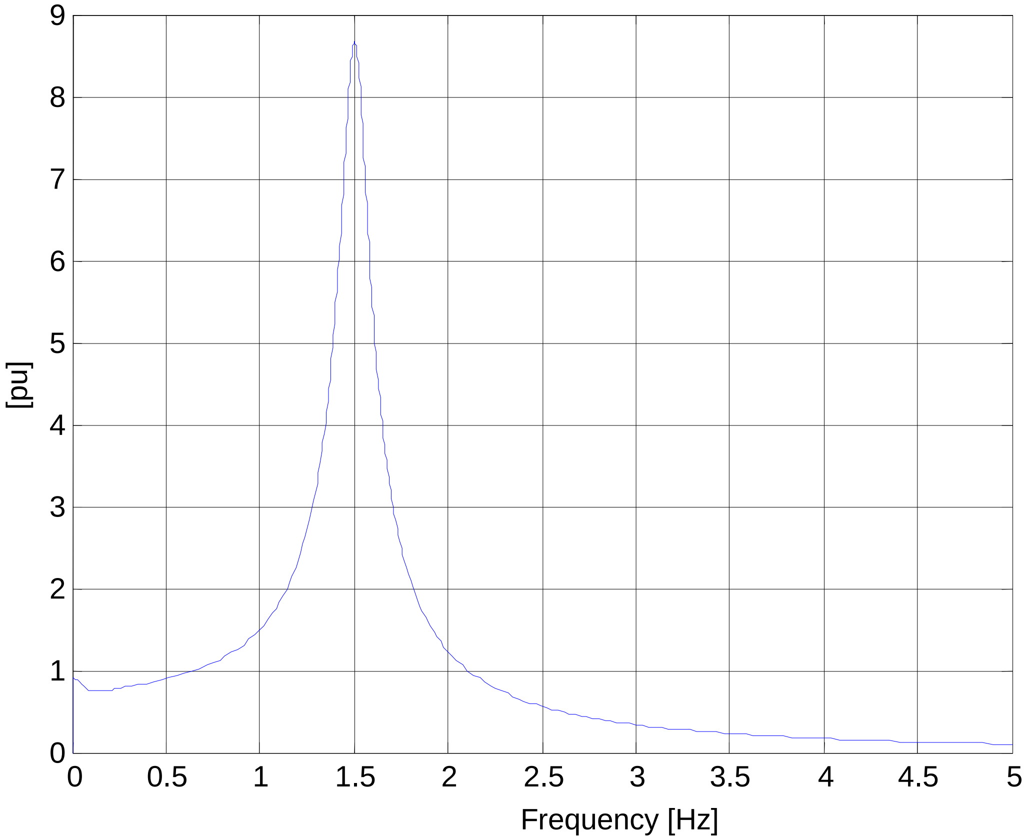


Figure A5-1 Example of the converter unit's frequency response characteristic, ΔP3/ΔP1, for sine shaped change in single-phase power ΔP1.

The frequency response characteristic for this converter unit has a distinctive resonance crest at approximately 1.5 Hz with an amplification of 9 pu.

A5.2.4 Active power step response

The voltage oscillations shown in the figures below arise due to changes in the converter rotor velocity when the converter's pole angle oscillates.

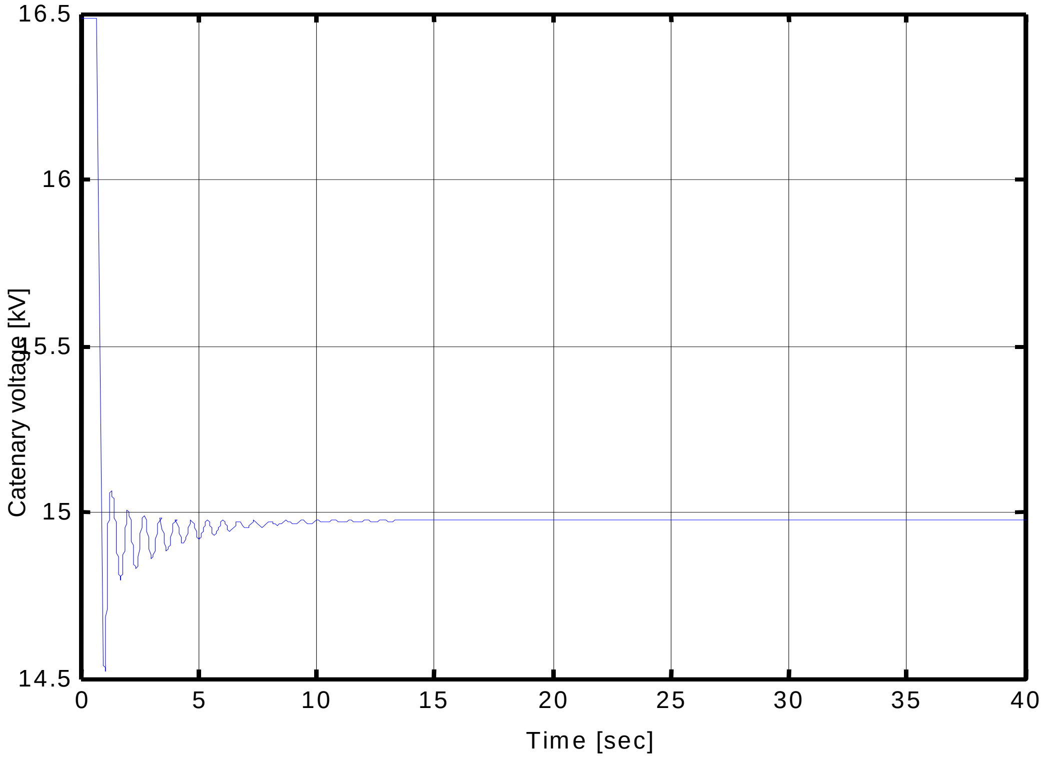


Figure A5-2 U 60km for active power step in the train of 0 – 2.0 MW

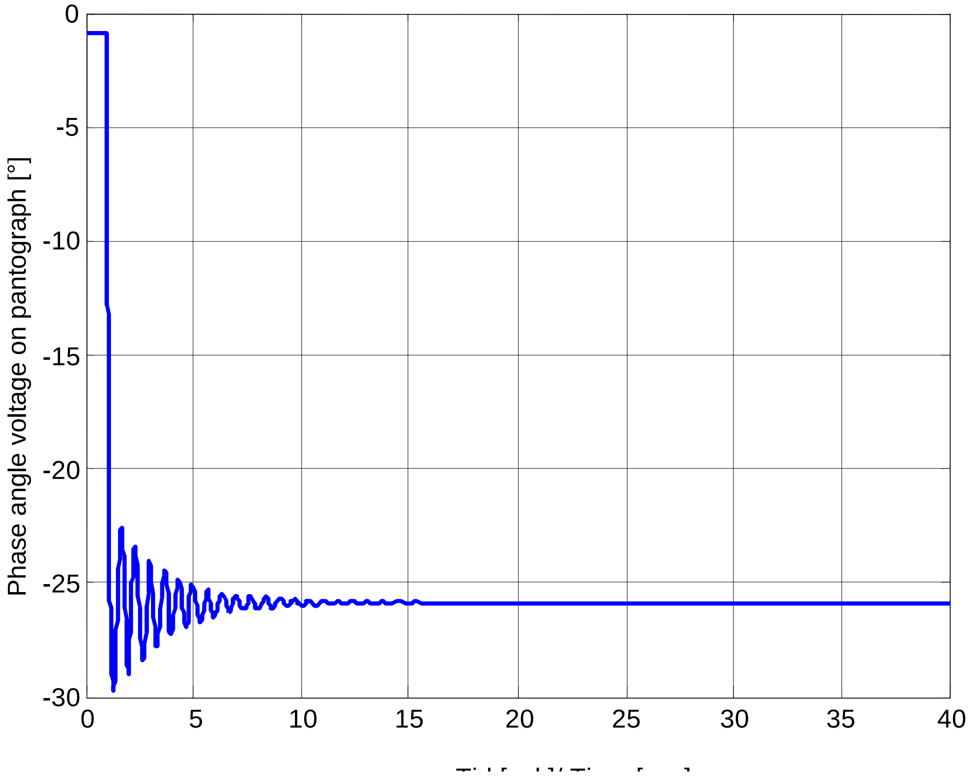


Figure A5-3 PA 60km for active power step in the train of 0 – 2.0 MW

Maximum oscillation (top – bottom) varies with the power step size as follows:

Power step in train	Max. oscillation U 60km	 PA 60 km
0 – 3.50 MW	≈ 690 V	≈ 13°
0 – 2.00 MW	≈ 270 V (Shown in Figure A5-2)	≈ 7° (Shown in Figure A5-3
0 – 0.25 MW	≈25 V	

Comments:

- Sudden step changes in active power cause heavy oscillation in the converter rotor position (pole angle).
- Even small power steps cause noticeable oscillation.
- Whether the power step is caused by load decrease or load increase has little significance for the oscillation's magnitude.

A5.2.5 Active power ramp response

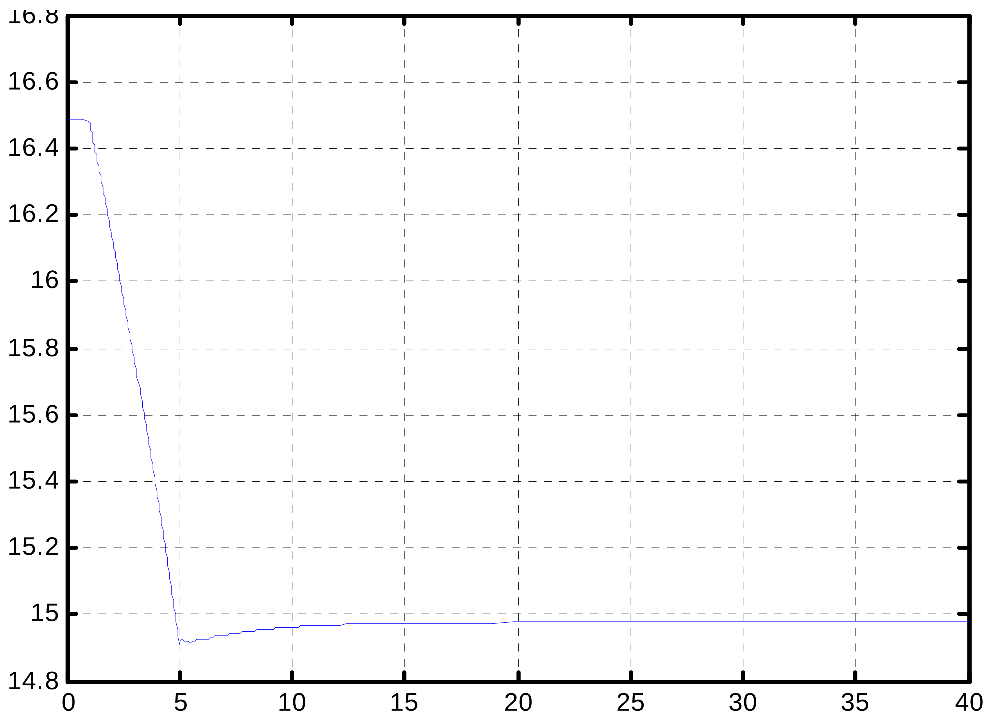


Figure A5-4 U 60km for increased power 0 -2.0 MW for linear steepness of 0.5 MW/s

Maximum oscillation (top – bottom) varies with the power step (ramp) steepness as follows:

Power change in the train 0 – 2.0MW	**Max. oscillation U 60km**
Step	270 V (Shown in Figure A5-2)
1,5 MW/s linear steepness	14 V
0,5 MW/s linear steepness	5 V (Shown in Figure A5-4)

Comment:

- The oscillation magnitude due to change in active power decreases significantly when the power change take place as a ramp of limited steepness. Whether the oscillation is caused by load decrease or load increase has little significance for the oscillation's magnitude.

A5.2.6 Repetitive changes in active power

Figure A5-5 shows U 60km for a train that in the beginning consume 4.0 MW and then an unsymmetrical saw-tooth shaped change in load with maximum unfavourable frequency (1.6 Hz) and flank steepness of -1.5 MW/s and + 0.5 MW/s respectively. Repeating power change in each saw-tooth period is 234.375 kW with 4.0 MW as maximum power.

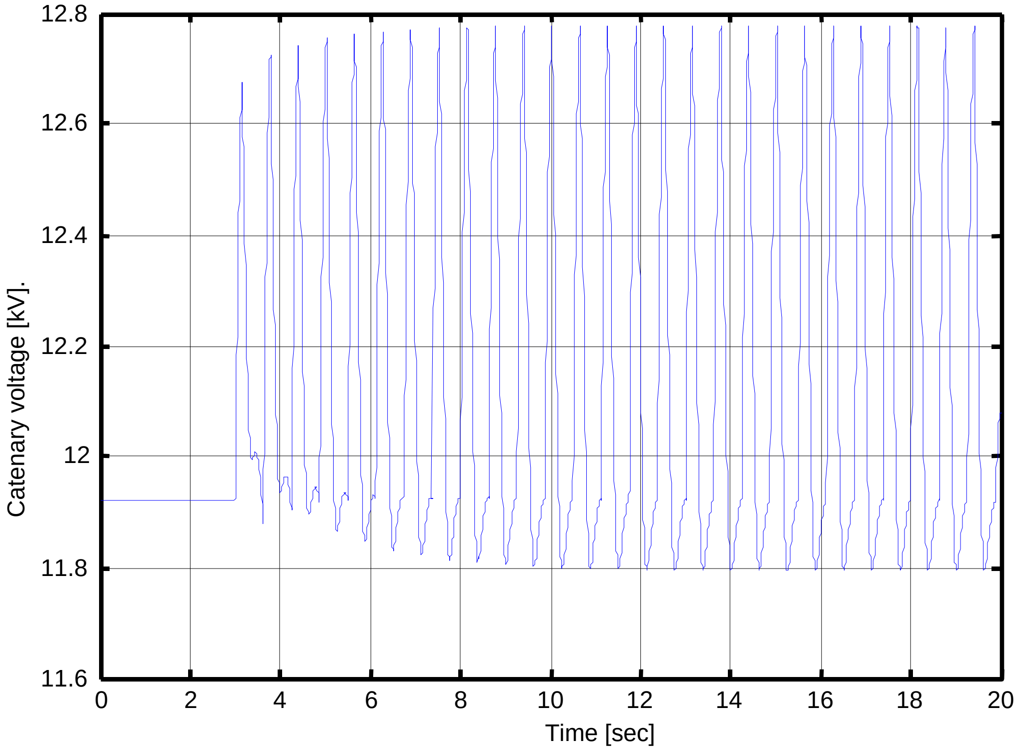


Figure A5-5

Maximum oscillation in contact line voltage (top – bottom) is as follows:

Periodic power change 1.6 Hz:	Max. oscillation U 60km
234.375 kW	990 V (Shown in Figure A5-5)

Comparatively, a repetitive symmetric load change having the same change in each saw-tooth will have flank steepness of +0.75 MW/s and -0.75 MW/s and cause about 5 % larger oscillation in the contact line voltage.

Comment:

- Even small power changes will after a few oscillation periods cause considerable oscillation if they are repeated at an unfavourable frequency. If being able to allow rapid repeating power changes in one power direction (e.g. power reduction when activating wheel skid or glide protection) is technically desirable, the converter rotor oscillation can to some extent be limited by implementing stricter restrictions for power changes in the opposite direction.

A5.2.7 Reactive power step response

Figure A5-6 shows U 60km for a converter having 2.0 MW preload and voltage independent load for steps of 0 – 1.0 MVAr inductive power.

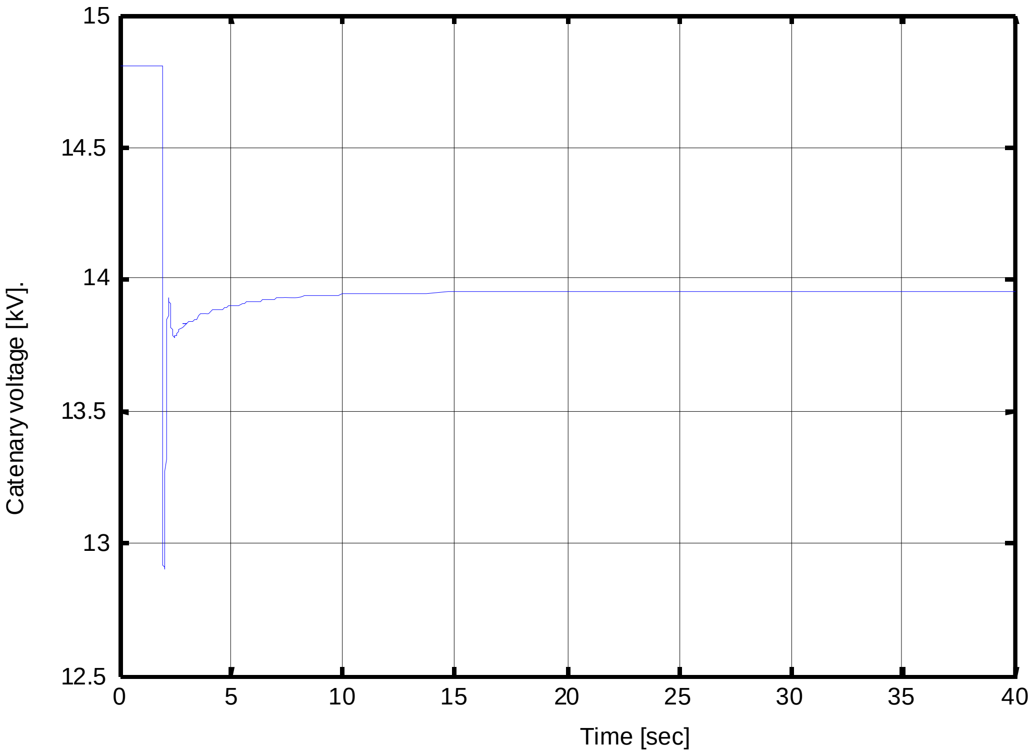


Figure A5-6

Maximum deviation in contact line voltage will be:

Reactive power step:	Trancient reduction U 60km
0 - 1,0 Mvar	ca. 1000 V (Shown in Figure A5-6)

Comment:

- Steps in reactive power in themselves cause only marginal oscillation in the converter unit’s pole angle. However, due to converter unit and contact line inductance, a big initial contact line voltage variation occurs. Indirectly, steps in reactive power may cause some oscillation due to the resulting changes to active losses in the system.

Step reductions of reactive power will also cause brief powerful variations in contact line voltage, but causing the voltage to rise rather than drop.

A5.3 Voltage phase angle variation with load

During increasing load the converter units' power angle and thus the phase angle for generated single-phase voltage decreases considerably relative the voltage in the 50 Hz grid. The 1-phase phase shift relative to the 50 Hz grid can be calculated as:

$$\Psi = \Psi_0 + \Psi_{conv} \quad \text{where}$$

$$\Psi_0 = \text{angle differnce between the } 50\text{ Hz and } 16.7\text{ Hz at no load on the converter and}$$

$$\Psi_{conv} = -\left[\frac{1}{3}\arctan(x_{qM} \cdot i_G \cdot \cos\varphi_G) + \arctan(\frac{x_{qG} \cdot i_G \cdot \cos\varphi_G}{1 + x_{qG} \cdot i_G \cdot \sin\varphi_G})\right]$$

where

x_{qM}	is the converter motor quadrature-axis synchronous reactance in p.u.
x_{qG}	is the converter generator quadrature-axis synchronous reactance in p.u., including the short circuit impedance of the transformer
i_G	is the current of the converter generator in p.u. of rated current

$i_G = I_G/I_{n\_G}$

I_G	is the current of the converter generator [A]
I_{n_G}	is the rated current of the converter generator [A]
φ_G	is the phase shift between the current and voltage of the generator

In the equation the following assumptions are made:

- Both the 3-phase synchronous motor and the 1-phase synchronous generator are modelled as synchronous machines with salient poles.
- The 3-phase motor is not magnetized, i.e. $Q_{50} = 0$.
- The axle between the synchronous motor and 1-phase synchronous generator is stiff and has no losses.
- All losses in the motor and generator are neglected.

Figure A5-7, below, shows 1-phase phase lag for 10 MVA converter units. 5.8 MVA converter units have approximately 10 % larger phase lag for the same relative load. The figure is plotted for and inductive load when cos(φ) < 1. In the figure Ψ_0 is set to zero.

As can be seen from the figure all lines goes through the origin. If the losses in the motor and generator were to be included there should be a death-band around the horizontal line $-\Psi=0$, i.e. positive active power would mean that the line would start from lag greater than zero and for negative active power the lines would start from a lag less than zero.

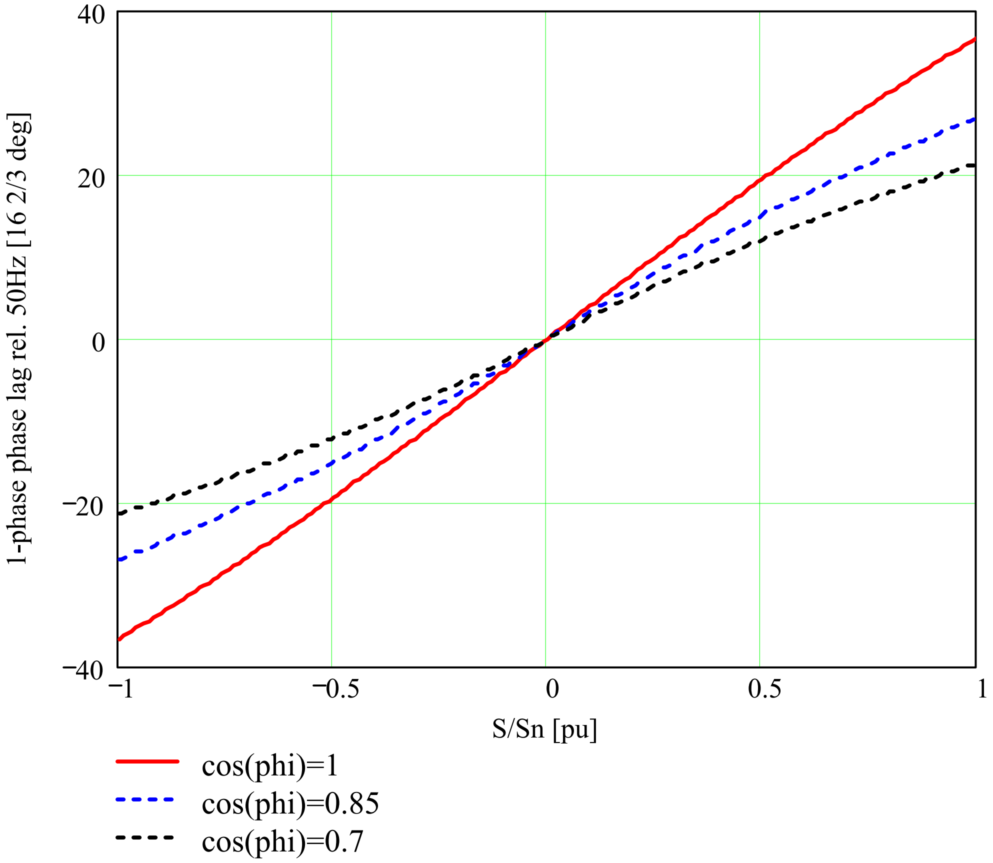


Figure A5-7 Phase angle lag single-phase voltage relative to 3-phase voltage for 10 MVA rotary converter units.

Note that the figure depicts the phase lag, not the phase shift. The angel lags more and more with increasing load. Note also that the figure is valid also for negative active power, i.e. when feeding from the 1-phase side to the 3-phase side, but only the active power is reversed. The reactive load is still the same, i.e. an inductive load at the 1-phase side which correspond to a electrical braking vehicle with cos(φ)-control.

While the converter unit change power angle, the voltage's steepness change and the voltage zero crossing will be displaced, increasingly with the speed of change. By increasing the distance to the converter station, the voltage's phase will vary even more with the load due to the contact lines inductive impedance.

A5.4 Time domain Model

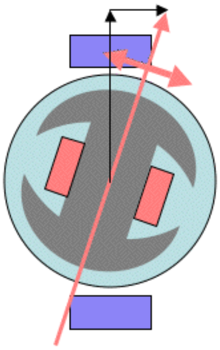
This chapter describes a simple time domain simulation model for rotating converters as they are in operation in the Norwegian and Swedish railway system. This model can be used by railway vehicle manufacturers for compatibility studies prior to first tests with new vehicles. The model is derived by emkamatik, document 06-0132. It is derived from more detailed models implemented by SINTEF Energy Research, Trondheim. The document includes some validation examples and an application guide on how to use the model.

The model is programmed in Matlab / Simulink and is available as a Simulink block on request.

A5.4.1 Physical background

The rotating frequency converters in Sweden and Norway consist of a 50-Hz synchronous motor directly coupled to a 16 2/3-Hz synchronous generator. They perform a frequency conversion by a factor of three and allow a power flow in both directions. The converters used in Sweden and Norway do not have damping windings on the rotor of the 50-Hz machine (3-phase side), therefore the corresponding eigenfrequency of the pole angle oscillation (between 1.6 and 1.8 Hz) is poorly damped (quality factors up to 10). Excessive oscillations of the rotor around its stationary pole angle can be produced by either strong or repetitive power variations of a train (e.g. adhesion control) or by feedback loop effects with the vehicle control in general. Negative effects of excessive converter oscillations include higher mechanical stress in the machines as well as significant periodic variations („flicker“) in weaker parts of the 50-Hz network.
Seen from a railway vehicle, the rotating converter shall be modelled as a „black box“ with the following main characteristics:

- Inner impedance of the generator. This also an RL impedance and is, therefore, not considered specially. In principal it has the same effect as a longer line.
- Voltage control, depending on the load. Normally, the output voltage is controlled to a nearly constant value, by means of variation of the excitation current of the machine.
- Pole angle variations. The angle of the induced voltage of a synchronous machine varies with the load current in the machine. The angle is lagging if load is drawn. For steady state operation, the relation between load current and angle follows a sine curve, but for small variations of the angle the behaviour can be linearised. Therefore, the generator reacts like a spring. Together with the rotating mass of the generator an oscillating system of 2nd order is formed. The following small figure shows a sketch of the spring – mass system formed by the rotating converter.



For all following considerations, the converter is always treated as a whole, not making any difference between 50-Hz and 16 2/3-Hz machine.

A5.4.2 Model structure

Chapter A5.2 contains the description of the behaviour of a rotating 5.8-MVA converter which is widely used in Norway and Sweden and a number of active and reactive load step and ramp responses. The task of the simulation model is to reproduce the shown behaviour in a “black box” manner, i.e. the reaction of the converter is just modelled as transfer functions while the motor and generator are not included as detailed electrical circuits and controllers. The figure below shows the simplified model of the rotating converter as a Matlab / Simulink model. It contains the following functional units:

- The model contains one output, the generator voltage U_{Gen}. It is calculated by the following expression:

  $$U_{Gen}(t) = A(t) \cdot \sin\left(2\pi f_N t + \varphi(t)\right)$$

  where
  - $f_N = 16\tfrac{2}{3}\,Hz$ is the nominal line frequency,
  - $A(t)$ the amplitude and
  - $\varphi(t)$ the pole angle.

  Both amplitude and pole angle depend on the active and reactive power. The corresponding functional simulation blocks are marked with yellow background colour.

- The electric power delivered by the generator is calculated as

  $p(t) = U_{Gen}(t) \cdot I_{Line}(t)$, where $I_{Line}(t)$ is the line current.

  The active power $P(t)$ is calculated as the mean value of p(t) over one fundamental line period

  $$P(t) = \frac{1}{T}\int_{t-T}^{t} U_{Gen}(\tau) \cdot I_{Line}(\tau)\,d\tau\,.$$

  The reactive power $Q(t)$ is calculated as

  $$Q(t) = \frac{1}{T}\int_{t-T}^{t} U_{Gen}^{*}(\tau) \cdot I_{Line}(\tau)\,d\tau\,,$$ where

$U^*_{Gen}(t) = A(t) \cdot \cos(2\pi f_N t + \varphi(t))$ is the 90° phase shifted generator output voltage. The simulation blocks which calculate $P(t)$ and $Q(t)$ are marked with light green background colour.

The functions for the generator voltage's ***phase*** $\varphi(t)$ and ***amplitude*** $A(t)$ describe the dynamics of the generator and are conveniently formulated in the s domain (see also structure figure below).

- **Phase angle function:**

In the simplified model, the phase angle $\varphi(t)$ depends only on the active power $P(t)$:

$\varphi(s) = [G_0(s) + k(P) \cdot G_1(s)] \cdot P(s)$ where $P(s)$ is the Laplace transformed time domain signal $P(t)$.

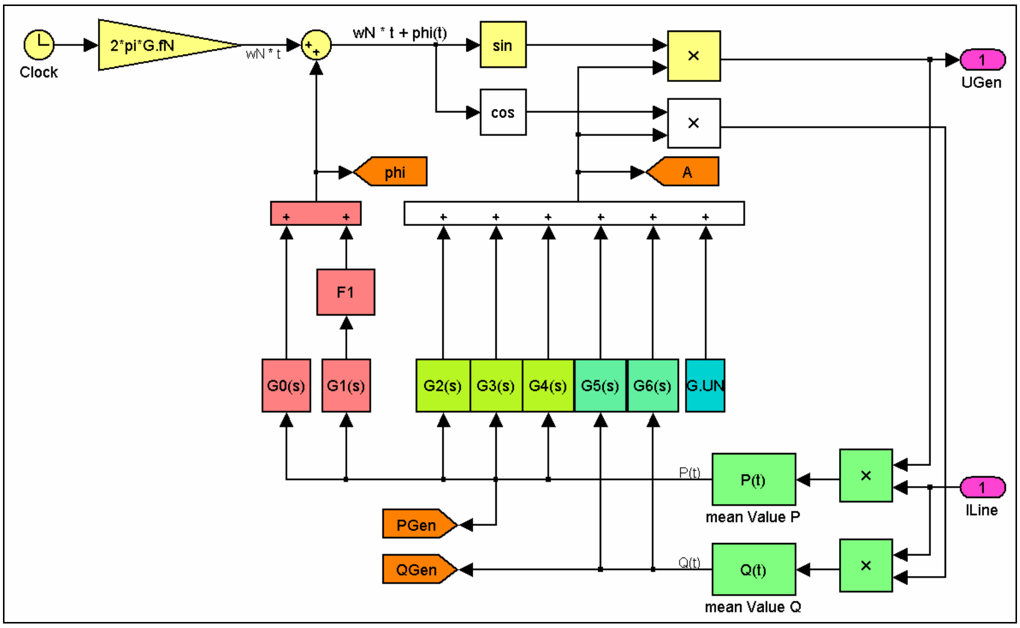
$G_0(s) = \dfrac{A_0}{T_0^2 s^2 + 2d_0 T_0 s + 1}$	is an "oscillation component".
$G_1(s) = \dfrac{A_1}{T_1 s + 1}$	is a "static component", which is combined with
$k(P) = \varphi_0 + k_\varphi \cdot abs(P)$	the load depending gain $k(P)$, which approximates the nonlinear load – pole angle characteristics of the generator (included in the block "F1" below).

- **Amplitude function:**

In the simplified model, the amplitude $A(t)$ depends on active and reactive power:

$$A(s) = U_N + [G_2(s) + G_3(s) + G_4(s)] \cdot P(s) + [G_5(s) + G_6(s)] \cdot Q(s)$$

$U_N = \sqrt{2} \cdot 16.5kV$	is the nominal line voltage amplitude,
$G_2(s) = \dfrac{A_2 s}{T_0^2 s^2 + 2d_0 T_0 s + 1}$	is an "oscillation component" (same denominator as $G_0(s)$)
$G_i(s) = \dfrac{\mathrm{A_i}}{T_i s + 1}$	with i = 3 … 6 represent transient effects.



A5.4.3Model parameters

The following parameter sets have been determined and allow the reproduction of the step responses shown in chapter A5.2 with good accuracy:

	Q 38 weak 3-phase network
A_0	$-12.25° / 5.8\,MW$ $= -3.6863\cdot 10^{-8}\,W$
T_0	$\dfrac{1}{2\pi \cdot 1.5Hz} = 0.1061\text{s}$
d_0^*	0.045
A_1	1
T_1	$0.05s$
φ_0	$-1.3541\cdot 10^{-7}$
k_φ	$6.0184\cdot 10^{-15}$
A_2	$1.5\cdot 10^{-5}\ V/W$
A_3	$-2.0\cdot 10^{-4}$
T_3	$0.05s$
A_4	$2.0\cdot 10^{-4}$
T_4	$1.5s$
A_5	$1.5\cdot 10^{-3}$
T_5	$0.25s$

A_6	$-1.5 \cdot 10^{-3}$
T_6	$0.001s$

*** Remark:**
Measurements done with different vehicles around Lunner and Oppdal (Norway) have shown that the damping ratio d_0 can be in the range from 0.025 to 0.07 and the oscillation frequency from 1.45 to 1.9 Hz.

A5.4.4 Line parameters

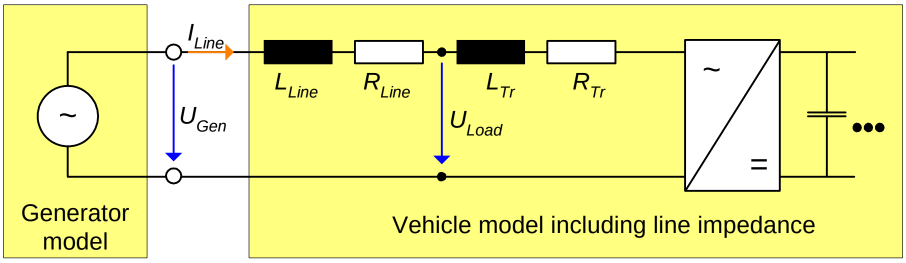
To create a complete power supply model a line impedance has to be added between the models of converter and train (see below). Typical values can be taken from section A1.5.9. For the investigation of realistic cases of low frequency behaviour the following values can be taken:

- $Z_{Line,km} = 0.18 + j\,0.19\,\Omega/km$
- The line of 60 km, which gives a line impedance of $Z_{Line} = 10.8 + j\,11.4\,\Omega$.

The resulting model is then comparable to the situation in Gjøvik, a single-side fed line in Norway, which has been taken already several times to test the behaviour of new trains.

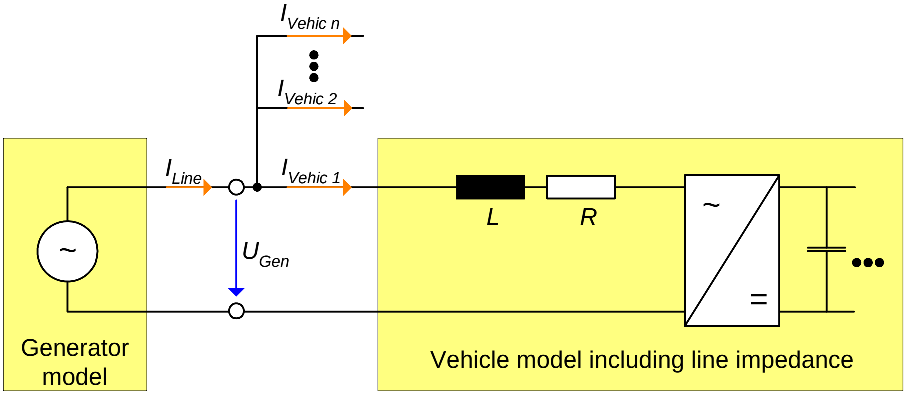
A5.4.5 Simulations with vehicles

The operation of railway vehicles in networks with high line impedance can lead to low frequent power oscillations. The risk of such oscillations is reduced significantly if the vehicle controllers are tuned and verified with time domain simulations.
The simulation model as described above contains a simplified, however appropriate model of the power supply infrastructure. This model can now be combined with a detailed model of the vehicle including its control systems. The motor circuits and control shall be included in the vehicle model.
For the integration of a single vehicle the line impedance must be combined with the vehicle transformer short circuit impedance as shown below. The reason is that the current through the line and transformer inductance are equal and must be treated as one state variable in the simulation model. The pantograph voltage U_{Panto} can be calculated easily (Z_{Line} and Z_{Tr} form a voltage divisor).



A5.4.6 Simulation of several vehicles

For the situation with more than one traction chain or several vehicles, it is normally still sufficient to simulate only one vehicle. This saves a lot of simulation time. It is assumed, that all vehicles are fed by the same catenary voltage and behave identically. This is a simplification, but yields good results as long as interactions between vehicles and the power supply system are investigated.



For this case the parameters of the converter and line model are scaled as follows:
As the voltage drop along the line depends on the number of simulated vehicles, the combined line and transformer impedance is now calculated with the following values:

$$R = R_{Tr} + n \cdot R_{Line}$$

$$L = L_{Tr} + n \cdot L_{Line}$$

n is the number of simulated vehicles, R_{Line}, L_{Line}, R_{Tr} and L_{Tr} are the same as above.
The generator current I_{Line} is equal to the sum of all vehicle line currents:

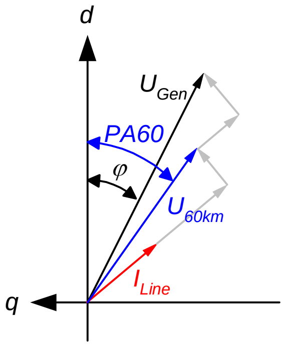
$$I_{Line} = n \cdot I_{Vehicle}$$

A5.4.7 Validation examples

The simulation model shown in this chapter, A5.4, has been tested and compared both for an RL load and with a detailed simulation model of an existing train. Each simulation is documented with the following signals:

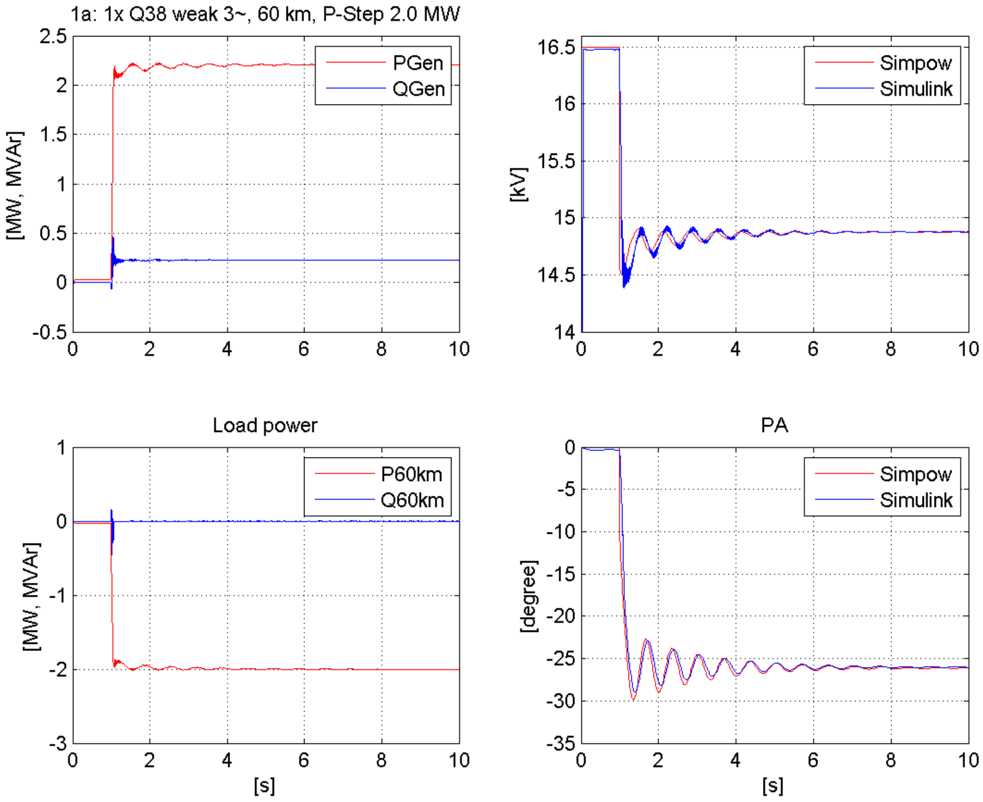
- Upper left plot: active and reactive power at generator (P_{Gen}, Q_{Gen})
- Lower left plot: active and reactive power at line end (P_{60km}, Q_{60km})
- Upper right plot: line voltage at line end (U_{60km})
- Lower right plot: phase angle of voltage at line end (PA_{60km}).

  PA60km is the sum of the generators load angle and the phase shift caused by the line impedance and is measured relative the d axis. The d axis represents the phase angle of the generator for the no load situation.



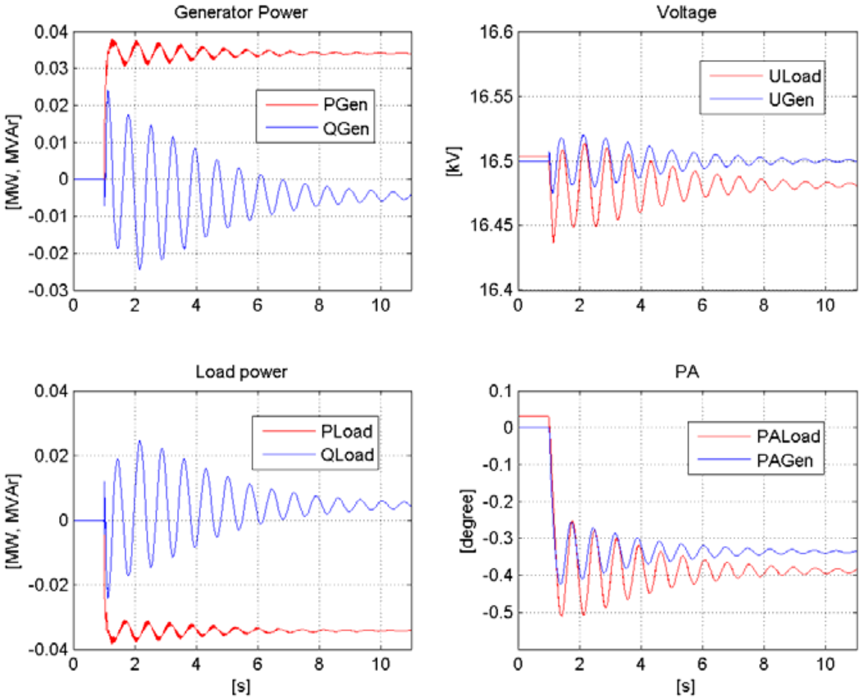
A5.4.7.1 Simulation with RL load

The following plots show the reaction of a 2.0-MW active power load step, and the comparison with the SIMPOW simulations shown in chapter A5.2.4.

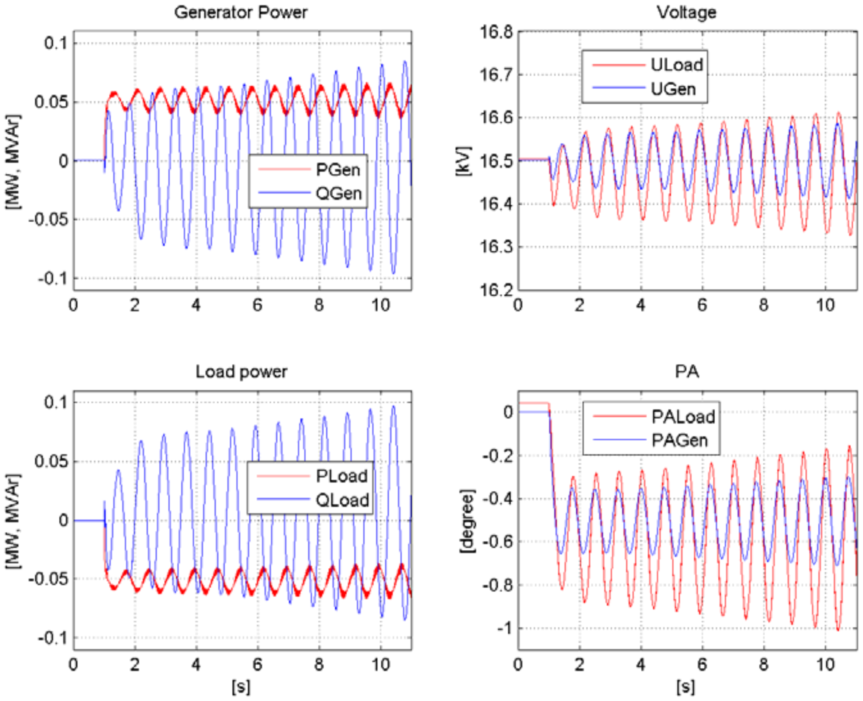


A5.4.7.2 Simulation with a vehicle

The simulation model contains one 5.8 MVA converter of type Q38 / Q39 and a 60 km long line. The structure and parameter of the vehicle model represents a modern EMU with two inverter traction units, being present in the system in a certain number.
At t = 1 second, the motor power of the vehicle is slightly increased in a stepwise manner to excite the system. The increase of active power is clearly visible at the generator. All signals show short transients with the quite well damped 1.5-Hz oscillation.



In the situation with twice the number of vehicles the 1.5-Hz oscillation is increasing and the situation unstable:



A5.4.8 Application of the model

When applying the converter model for compatibility studies, the following items shall be considered:

- The model shall help to evaluate and optimise the control structure and parameters of the inverter and traction control of electrical rail vehicles. Therefore, the simulations shall be done for various configurations of power supply and vehicle models. It must be the goal to reach a robust controller design rather than a sophisticated optimisation for one case derived from this simplified converter model.
- Typical numbers of converters are one to three, typical numbers of vehicles one to about five. A variation and combination of these numbers shall be performed until the stability limit can be derived. However, not all combinations will allow a realistic simulation for all operation points of the vehicle Example: one converter plus the maximum number of vehicles at full power and longest line length will not be a realistic case.
- Typical line lengths are between 10 and about 60 km. A line length of less than 5 to 10 km is not realistic, since in the model configuration the line impedance contains also the internal impedance of the synchronous generator.
- The parameters shall be varied also to change the eigenfrequency between 1.5 and 1.9 Hz.
- The damping ratio of the generator oscillation shall be varied between 0.03 and 0.07. The low values have been observed in situations with low load power.
- Various effects caused by different controller parts of the vehicle shall be checked, including:
    - Closed loop stability in steady state operation at zero power, half and full traction power, half and full braking power.
    - Operation under bad rail – wheel conditions with active adhesion control.
    - Line power limitation due to low or high pantograph voltage in traction and braking.

A5.5 Phasor domain model

Description and input data for a phasor model of a rotary converter including utility network can be handed over by Norwegian National Rail Administration on request.

A6 APPENDIX 6: TYPICAL CROSS SECTION OF A BOOSTER TRANSFORMER LINE IN SWEDEN

(Applies to Sweden only)

A7 APPENDIX 7: CROSS SECTION OF EXISTING AT-SYSTEM LINES IN SWEDEN

(Applies to Sweden only)

A8 APPENDIX 8: CROSS SECTION OF NEW STANDARD FOR AT-SYSTEMS LINES IN SWEDEN

(Applies to Sweden only)

A9 APPENDIX 9 : PSOPHOMETRIC WEIGHTING FACTORS ACCORDING TO ITU-T

(Applies to “Signal interference and telecommunication” only)