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# BVS 543.19300 - Kraftförsörjningsanläggningar. Elektriska krav på fordon med avseende på kompatibilitet med infrastrukturen och andra fordon

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## 1 Syfte

Denna standard, som var en ändrad utgåva av tidigare utgiven (2007-01-26) standard med samma beteckning, togs fram i samarbete med norska Jernbaneverket inom ramen för det nordiska NIM/ NESsamarbetet.

Anledningen till att dokumentet har ändrats är att vissa krav har förändrats samt att nya krav har tillkommit.

Syftet med dokumentet är ställa krav på järnvägsföretag och fordonstillverkare som ansöker om tillstånd för ett fordon eller en fordonstyp att få trafikera den spåranläggning som Trafikverket förvaltar. Dokumentet är dessutom tänkt att vara ett stöd för projekt som tar fram fordon och fordonstyper som är avsedda att trafikera svenska och norska banor.

## 2 Omfattning

Denna standard innehåller de elektriska krav som Trafikverket ställer på fordon med avseende på kompatibilitet med infrastrukturen och andra fordon för att ett fordon eller en fordonstyp ska kunna anpassas till den svenska järnvägen och därmed erhålla tillstånd att få trafikera den spåranläggning som Trafikverket förvaltar. Jernbaneverkets krav i **bilaga 1** finns enbart med som information samt för att underlätta för järnvägsföretag och fordonstillverkare att erhålla tillstånd att få trafikera såväl den svenska som den norska spåranläggningen.

Befintliga europastandarder avseende kompatibilitet mellan fordon och infrastrukturen samt mellan andra fordon täcker inte alla aspekter; speciellt inte de som är specifika för svenska och norska förhållanden på grund av den höga markresistiviteten och de relativt svaga matningsnäten.

Dokumentet innehåller inga krav på strömavtagare och heller inga funktionskrav som rör ATC, ERTMS och ETCS. Vidare omfattar inte dokumentet störningar på tågradio och digitala system, exempelvis PCM och ISDN, annat än indirekt.

Dokumentet riktar sig till järnvägsföretag och fordonstillverkare som ansöker om tillstånd för ett fordon eller en fordonstyp att få trafikera den spåranläggning som Trafikverket förvaltar. Dokumentet är dessutom tänkt att vara ett stöd för projekt som tar fram fordon och fordonstyper som är avsedda att trafikera svenska och norska banor.

## 3 Definitioner och förkortningar

#### 3.1 Definitioner

Se NES TS 02.

## 3.2 Förkortningar

ATC Automatic Train Control ERTMS European Rail Traffic Management System ETCS European Train Control System



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#### ISDN

Integrated Services Digital Network PCM Pulse-code modulation

## 4 Ansvar

Ej relevant





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# 5 Elektriska krav på fordon med avseende på kompatibilitet med infrastrukturen och andra fordon

Samtliga elektriska krav på fordon med avseende på kompatibilitet med infrastrukturen och andra fordon beskrivs i **bilaga 1**, som framför allt är baserad på **EN 50121**, **EN 50163**, **EN 50238** och **EN 50388**. I **bilaga 1** beskrivs även de tester som ett fordon eller en fordonstyp måste genomgå för att få tillstånd att trafikera den svenska spåranläggningen. **Bilaga 1** innehåller dessutom omfattande bilagor, som beskriver den elektriska infrastrukturen, befintliga fordon samt andra förhållanden som är av intresse för att ett fordon eller en fordonstyp ska kunna uppfylla kraven.



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## 6 Hjälpmedel och referenser

## 6.1 Hjälpmedel

Ej relevant

#### 6.2 Referenser

I denna standard refereras till följande dokument:

**NES TS 02** Technical specification: Requirements on rolling stock in Norway and Sweden regarding EMC with the electrical infrastructure and coordination with the power supply and other vehicles. NIM NES 2009-07-01



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Bilaga 1: NES TS 02 - Technical specification: Requirements on rolling stock in Norway and Sweden regarding EMC with the electrical infrastructure and coordination with the power supply and other vehicles. NIM NES 2009-07-01

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

1 (138)



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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 3<sup>rd</sup> and 5<sup>th</sup> 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	3.2.1
		transformer inrush.	
S2	95 Hz and 105 Hz (N only)	1.00 A. Monitoring required.	3.2.2
S <sub>3</sub>	TI21 track circuits (N only)		3.2.3
	16 bands 1532 Hz to 2610 Hz	TBD A	
S4	FTGS track circuits (N only)		3.2.4
	4 bands 4.75 kHz to 6.25 kHz	1.00 A	
	8 bands 9.5 kHz to 16.5 kHz	0.50 A	
S5	Psophometric currents	1.50 A	3.2.5
S6	Broad-band (N only)		3.2.6
	TBD-7 kHz	1.00 A	
	7-9 kHz	0.50 A	
	> 9 kHz	0.33 A	
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



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## 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	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
Р3	Line voltage distortion	The line voltage may be heavily distorted, with up to 5 kV 3 <sup>rd</sup> and 5 <sup>th</sup> 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 $\cos(\varphi)$ 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 $(\cos(\varphi))$ 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 3 <sup>rd</sup> , 5 <sup>th</sup> , 7 <sup>th</sup> , and 9 <sup>th</sup> 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





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## **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,	Alvesta-Emmaboda (S)	S1-S6 (LOOP)	< 130
	rotating converters	Hønefoss-Nesbyen (N)	P1, P2, P5-P10, P13 (ABAB,	km/h
			ARO)	
T2	Closed track,	Eskilstuna-Södertälje (S)	S1-S6 (LOOP)	200 km/h
	static converters	Gardermoen line (N)	P1, P2, P5-P10, P13 (ABAB,	
			ARO, voltage jump)	
T3	Mixed traffic	Borlänge area (S)	S1-S6, P1-P3, P5-P10, P13	
		Oslo area (N)	(Normal operation)	
T4	Transformer inrush	Ockelbo (S)	P12	
	(peak AC)	Oslo S (N)		
T5	Transformer inrush	Ockelbo (S)	S1	
	(DC, S only)			
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 ( $\approx$  1-2 t per kN max. tractive effort, or  $\approx$  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



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- 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,  $\cos(\phi)$ -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 Trafikverket 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 Trafikverkets document TDOK 2014:0774 (former 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.



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#### 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 Trafikverket, 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



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BT	Booster trar	Booster transformer	
BW	Butterworth	1	
bw	Bandwidth		
DAT	Digital audio tape		
DC	Direct current		
EMC	Electromag	netic compatibility	
EMI	Electromag	netic interference	
$f_{C}$	Centre frequ	lency	
FFT	Fast fourier	transform	
FTGS	Type of trac	k circuit	
GPS	Global posit	ioning system	
ID	(Data record	ding) idendity	
IIR	Infinite imp	ulse response	
$I_N$	Rated curre	nt	
LOOP	Operation s	equence (see 3.3.4)	
Ν	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	Compatibili	ty requirements, signalling and telecommunication systems	
T1-T7	Test categor	ries	
TBD	To be define	ed	
THD	Total harmo	onic distortion	
TI 21	Type of trac	k circuit	
2.3.2	DEFINITIONS		
Bandwidt	h	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 o Hz (DC), 1 Hz, 2 Hz,	
Closed tra	ack	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.	



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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 $\rm kV$
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.





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- 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	Age of the rolling stock		
rolling stock	Vehicle design started after	Vehicles designed before	
	2007-01-01	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.	
		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).





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#### 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.



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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<br/>title as this document, from 27.11.2006.07-01-2009:Second version



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#### Signalling systems and telecommunication 3

#### 3.1 References

#### 3.1.1 NORMATIVE REFERENCES

No.	Standard	Applica	ble to
		Signalling	Power
1.1	EN 50 110-1: Operation of electrical installations. CENELEC, European Standard.		Х
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.		Х
1.4	EN 50 128: Railway applications – Communications, signalling and processing systems – Sofware for control and protection systems. CENELEC, European Standard.	Х	
1.5	EN 50 153: Railway applications – Protective provisions relating to electrical harzards. CENELEC, European Standard.		Х
1.6	EN 50 155: Railway applications Electronic equipment used on rolling stock. CENELEC, European Standard.	Х	
1.7	EN 50 163: Railway applications – Supply voltages of traction systems. CENELEC, European Standard.		Х
1.8	EN 50 207: Railway applications – Electronic power converters for rolling stock. CENELEC, European Standard.		Х
1.9	EN 50 215: Railway applications – Test of rolling stock after completion of construction and before entry into service. CENELEC, European Standard.	Х	Х
1.10	EN 50 238: Railway applications – Compatibility between rolling stock and train detection systems. CENELEC, European Standard.	Х	
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.		Х
1.13	UIC 552: Electrical power supply for trains – Standard technical		Х



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	characteristics of the train line.		
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.	Х	
1.15	UIC 512: Conditions to be fulfilled in order to avoid difficulties in the operation of track circuits and treadles.	Х	
1.16	TDOK 2014:0777 (former BVS 545.43501): Requirements on external antennas for railway vehicles (only published in Swedish: "Krav på yttre antenner för järnvägsfordon") . Trafikverket. Only normative for Sweden.	Х	
1.17	ITU-T Recommendation O.41: Psophometer for use on telephone- type circuits.	Х	

#### 3.1.2 OTHER REFERENCES

No.	o. Standard		ble 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.	Х	Х
2.2	Characteristics of infrastructure. Document JD 590. Jernbaneverket, 01.02.2005.	Х	Х
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. Trafikverket, July 2004.	Х	Х
2.4	Rotating converters TRV/JBV: Description of simulation model. emkamatik document 06-0132, ver. 1. Stefan Menth, emkamatik, 18.9.2006.		Х
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.		Х

## 3.2 Compatibility Requirements

#### NOTE:

The limits and requirements in this chapter are under investigation and shall be treated accordingly. Please notice that operating experience indicates that lower limits may be required in some frequency ranges on certain line sections in Norway. These requirements are under consideration. Jernbaneverket may on some route sections permit slightly excessive interference currents for some frequencies. Based on documentation for the noise current spectrum of the vehicle, Jernbaneverket will decide whether or not it is compatible with the route sections in question.



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#### 3.2.1 S1: DC TRACK CIRCUITS

#### 3.2.1.1 Information

#### NORWAY:

DC track signalling circuits are used only at non-electrified railway stations, plus one single electrified railway station.

#### SWEDEN:

DC track circuits are the only train detection system in use on electrified lines in Sweden.

Only two credible mechanisms have been identified by which an electric vehicle is capable of generating excessive DC interference currents:

1. Transformer inrush. Low levels can be achieved by a proper design of the main transformer.

2. Ice on the overhead contact wire. It is recognised that it may not be feasible to design a rail vehicle in such a way that compliance can be guaranteed at all ice conditions.

A third cause can be faults in the vehicle.

#### 3.2.1.2 Requirements

General requirements for the vehicle and the signalling equipment are in accordance with EN 50 121-3-1 and EN 50 121-4.

NORWAY:

No requirements.

SWEDEN:

#### Interference limits, normal operation.

The following interference limits apply, with the exception of the inrush current of the main transformer:

Frequency band	Bandwidth (low-pass)	RMS time	Limit value
0.0 - 2.0 Hz	-3.0 dB: 2.0 Hz	N/A	25.0 A

These limits are applicable for one vehicle, and for the maximum configuration of vehicles (i.e. multiple units) for which the approval must be valid.

#### Interference limits, transformer inrush.

The DC-component of the inrush current of the main transformer/s, must not exceed 45.0 A for more than 1.50 seconds, and also not exceed 25.0 A for more than 2.50 seconds. The DC-component is here defined as the mean value over one period of the fundamental, moving average calculation.

This is applicable for one vehicle, and for the maximum configuration of vehicles (i.e. multiple units) for which the approval must be valid. In a multiple formation, it is suggested that the cut-in of the main circuit breakers is staggered, e.g., with a 5 s delay between each cut-in event.

#### 3.2.1.3 Verification

NORWAY:

N/A.

SWEDEN:



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#### Normal operation test

Verification shall be done by test runs with measurement and data recording equipment being installed in the vehicle, at normal weather conditions (no frosty lines), and in accordance with the test specification section 3.3. The current transducer must handle the frequencies from DC and upwards.

The following signal processing of the recorded line current signal is suggested:

Signal processing	Limit value
(Downsampling to 1 kHz, followed by)	25.0 A
2.0 Hz 4 <sup>th</sup> order Butterworth low-pass filter,	
followed by an ideal rectifier to give the absolute	
value.	

#### Inrush current test

The tests shall be performed at a location where the short circuit current is greater than or equal to 20 kA, i.e. Ik  $\geq$  20 kA on a single-track line. The train shall be placed beyond the first booster transformer, counting from a converter station, as described in section 3.3.4. (NOTE: this is not the same situation as for the AC inrush current tests, see chapter 4.4.4. The test specified here implies the test location to be at Ockelbo converter station with all converters in operation and all other converter stations connected to the 132 kV system. Other tests sites with scaling of the limit are under investigation.)

The following signal processing of the recorded line current signal is suggested:

Signal processing	Limit value
(Downsampling to 1 kHz, followed by)	
60 ms moving average, followed by an ideal rectifier to	
give the absolute value, followed by an assessment of the	
time duration for the level exceeding the following values:	
45.0 A:	
25.0 A:	1.50 s
	2.50 s

#### 3.2.1.4 **Documentation**

NORWAY:

N/A

SWEDEN:

Documentation shall be a conformity statement and documentation of performed tests.

3.2.2 S2: 95 HZ AND 105 HZ TRACK CIRCUITS (NORWAY ONLY)

#### 3.2.2.1 Information

Track circuits operating at 95 Hz and 105 Hz are the most commonly used in Norway. Impedance bonds for 95/105 Hz may be used to allow return current to pass by insulated joints used for separating track circuits.

#### Requirements 3.2.2.2

General requirements for the vehicle and the signalling equipment are in accordance with EN 50 121-3-1 and EN 50 121-4.



#### Interference limits.

The following interference limits apply:

Centre frequencies f <sub>C</sub>	Bandwidth	Time limit	Limit value
95.0 Hz	- 3.0 dB: $f_C \pm 3.0 \text{ Hz}$	1.00 s	1.00 A
105.0 Hz			

The 1.00 A current limit may be exceeded for shorter time periods than 1.00 s. These limits are applicable for one vehicle, and for the maximum configuration of vehicles (i.e. multiple units) for which the approval must be valid.

#### Requirements for monitoring.

The vehicles must be equipped with interference monitoring systems for the 95 Hz and 105 Hz line current components. The monitoring system must automatically open the main circuit breaker within 2.0 s if the 2.00 A trip level is exceeded.

The suggested signal processing for the monitor is FFT with 1.00 Hz resolution (1.00 s window length).The trip level is 2.00 A RMS for any bin in the bands 92-98 Hz and 102-108 Hz.

#### 3.2.2.3 Verification

Verification shall be done by test runs with measurement and data recording equipment being installed in the vehicle, in accordance with the test specification section 3.3.

The following signal processing of the recorded data is suggested:

Centre frequencies f <sub>C</sub>	Signal processing	Limit value
95 Hz and 105 Hz	(Downsampling to 1 kHz, followed by) $2 \cdot 3^{rd}$ order Butterworth band-pass filters with – 3.0 dB points at each $f_C \pm 3.0$ Hz, followed by moving RMS, time window < 1.00 s	1.00 A

#### 3.2.2.4 Documentation

Documentation shall be a conformity statement and documentation of performed tests.

3.2.3 S3: TI 21 TRACK CIRCUITS (NORWAY ONLY)

#### 3.2.3.1 Information

TI 21 track circuits are used on some new lines in Norway, e.g., the Vestfold line.

TI 21 track circuits are designed with 8 channels A-H. The frequency of the carrier signal for the track circuit shifts between two values in each channel. The modulation rate of the frequency shift must lie within certain limits for a correct operation of the track circuit.

#### 3.2.3.2 Requirements

General requirements for the vehicle and the signalling equipment are in accordance with EN 50 121-3-1 and EN 50 121-4.





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The following interference limits apply:

Centre frequencies f <sub>C</sub>	Bandwidth See note 1	Time limit	Limit value
Channel A: 1682 Hz and 1716 Hz	-3.0 dB: $f_C \pm 6.0 \text{ Hz}$	1.50 s	TBD
Channel B: 2279 Hz and 2313 Hz	-20 dB: $f_C \pm$ 30 Hz		
Channel C: 1979 Hz and 2013 Hz			
Channel D: 2576 Hz and 2610 Hz			
Channel E: 1532 Hz and 1566 Hz			
Channel F: 2129 Hz and 2163 Hz			
Channel G: 1831 Hz and 1865 Hz	]		
Channel H: 2428 Hz and 2462 Hz			

Note 1: The bandwidth definitions are from the former British Rail Group Standard GS/ES 1914. This standard specifies a limit value of 100 mA, but this is probably not true for TI21s installed in a 16 2/3 Hz environment. The limit value is still under investigation.

The current limit may be exceeded for shorter time periods than 1.50 s. These limits are applicable for one vehicle, and for the maximum configuration of vehicles (i.e. multiple units) for which the approval must be valid.

#### 3.2.3.3 Verification

Verification shall be done by test runs with measurement and data recording equipment being installed in the vehicle, in accordance with the test specification section 3.3. The following signal processing of the recorded data is suggested:

Centre frequencies f <sub>C</sub>	Signal processing	Limit value
1682 Hz and 1716 Hz 2279 Hz and 2313 Hz 1979 Hz and 2013 Hz 2576 Hz and 2610 Hz 1532 Hz and 1566 Hz 2129 Hz and 2163 Hz 1831 Hz and 1865 Hz 2428 Hz and 2462 Hz	Band pass filters with a rejection of $\leq$ 3.0 dB at $\pm$ 6.0 Hz from each f <sub>C</sub> , and $\leq$ 20 dB at $\pm$ 30 Hz from each f <sub>C</sub> , followed by moving RMS, time window < 1.50 s. <i>See note 2</i> .	TBD

Note 2: Much work has been spent in the UK in order to design digital filters with the best possible match to these limits, and many proposals exist. It is suggested that the design of filters is left to the applicants. It is likely however that the -20 dB figure could actually be somewhat more - final value is under investigation. (TDB = To Be Determined).

#### 3.2.3.4 Documentation

Documentation shall be a conformity statement and documentation of performed tests.



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#### S4: FTGS TRACK CIRCUITS (NORWAY ONLY) 3.2.4

#### 3.2.4.1 Information

The jointless FTGS track circuits operate at 4 frequencies in the 4.5 to 6.5 kHz frequency band (FTGS46), and at 8 frequencies in the 9 to 17 kHz band (FTGS917). They are used on some newer lines in Norway, e.g., the Gardermoen line.

#### 3.2.4.2 Requirements

General requirements for the vehicle and the signalling equipment are in accordance with EN 50 121-3-1 and EN 50 121-4.

The following interference limits apply:

#### FTGS46

Centre frequencies f <sub>c</sub>	Bandwidth (see note 3)	Time limit	Limit value
4.75 kHz	-3.0 dB: $f_C \pm 200/2$ Hz	40 ms	1.00 A
5.25 kHz	-3.0 dB: $f_C \pm 206/2$ Hz		
5.75 kHz	-3.0 dB: $f_{C} \pm 214/2$ Hz		
6.25 kHz	-3.0 dB: $f_C \pm 220/2 \text{ Hz}$		

Note 3: Attenuation at adjacent channels: max. 30 dB.

FTGS917			
Centre frequencies f <sub>C</sub>	Bandwidth (see note 4)	<b>Time limit</b>	Limit value
9.5 kHz	-3.0 dB: $f_C \pm 360/2$ Hz	40 ms	0.50 A
10.5 kHz	-3.0 dB: $f_C \pm 380/2$ Hz		
11.5 kHz	-3.0 dB: $f_C \pm 400/2$ Hz		
12.5 kHz	-3.0 dB: $f_{C} \pm 425/2$ Hz		
13.5 kHz	-3.0 dB: $f_{C} \pm 445/2$ Hz		
14.5 kHz	-3.0 dB: $f_{C} \pm 470/2 \text{ Hz}$		
15.5 kHz	-3.0 dB: $f_C \pm 490/2$ Hz		
16.5 kHz	-3.0 dB: $f_{C} \pm 510/2$ Hz		

Note 4: Attenuation at adjacent channels: max. 30 dB.

The current limits may be exceeded for shorter time periods than 40 ms.

#### 3.2.4.3 Verification

Verification shall be done by test runs with measurement and data recording equipment being installed in the vehicle, in accordance with the test specification section 3.3.

The following signal processing of the recorded data is suggested:

FTGS46				
Centre frequencies f <sub>C</sub>	Bandwidth bw	Signal processing	Limit value	
4.75 kHz	200 Hz	$2 \cdot 2^{nd}$ order Butterworth band pass filters, -	1.00 A	
5.25 kHz	206 Hz	3 dB at each $f_C \pm bw/2$ Hz, followed by		
5.75 kHz	214 Hz	moving RMS, time window < 40 ms		
6.25 kHz	220 Hz			



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#### FTGS917

Centre frequencies f <sub>C</sub>	Bandwidth bw	Signal processing	Limit value
9.5 kHz	360 Hz	$2 \cdot 2^{nd}$ order Butterworth band pass filters, -	0.50 A
10.5 kHz	380 Hz	3 dB at each $f_C \pm bw/2$ Hz, followed by	
11.5 kHz	400 Hz	moving RMS, time window < 40 ms	
12.5 kHz	425 Hz		
13.5 kHz	445 Hz		
14.5 kHz	470 Hz		
15.5 kHz	490 Hz		
16.5 kHz	510 Hz		

#### 3.2.4.4 Documentation

Documentation shall be a conformity statement and documentation of performed tests.

#### 3.2.5 S5: TELECOMMUNICATION DISTURBANCES AND PSOPHOMETRIC CURRENTS

#### 3.2.5.1 Information

Interference with digital systems such as PCM, ISDN, etc is not yet covered in this document. This is a field for which more work will be done. Information regarding GSM-R can be found in EIRENE standards from UIC.

The harmonics in the traction current of a railway system may induce noise in conventional analogue telecommunication system. The acceptable level of noise on conventional analogue telephone lines is specified by ITU-T. The limits in this document refer to the psophometric weighted traction current defined as:

$$I_{pe} = \frac{1}{P_{800}} \sqrt{\sum_{n=1}^{\infty} \left( h_f \times P_{fn} \times I_n \right)^{*}}$$

where  $h_f = 1$ , which is the equivalent psophometric current measured or calculated for interaction with a telephone line as a cable.  $P_{fn}$  is in accordance with ITU-T. For values of  $P_{fn}$  see Appendix 9.

#### 3.2.5.2 Requirements

The psophometric weighted traction current must not exceed 1.50 A. The value refers to the 99%-percentile of the measured psophometric current, i.e., the level must be below 1.50 A for 99% of the operation time.

The requirement is applicable for one vehicle and for the maximum configuration of vehicles (i.e. multiple units) for which the approval must be valid.





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In case of a fault on the vehicle, for instance when one or more of the traction modules or filters is/are disconnected and the increase of the psophometric current is less than 6.0 dB, the vehicle is allowed to be in working condition until it reaches a workshop, for up to 24 hours. For such a case the limit is doubled. If this demand can not be fulfilled, the vehicle shall be transported in a non-working condition.

#### 3.2.5.3 Verification

Verification shall be done by test runs with measurement and data recording equipment being installed in the vehicle, in accordance with the test specification section 3.3.

For each LOOP operation cycle, the 99%-percentile of the psophometric current level shall be determined. See also EN 50 121-3-1, Annex A (informative). The tolerance of the psophometric weight characteristics, as well as the dynamic characteristics, shall comply with ITU-T O.41.

The following signal processing of the recorded data is suggested:

Signal processing	Limit value
IIR band-pass filter with a characteristic as defined in Appendix 9,	1.50 A
followed by a moving RMS with a time window of 140 ms, followed by	
an analysis of the levels over time (e.g., by determining the percentage	
cumulative distribution), followed by an assessment of the 99%-	
percentile level.	

#### 3.2.5.4 Documentation

Documentation shall be a conformity statement and documentation of performed tests in a technical report. The report shall for each test lap state the 99%-percentile, and the summary shall state the variation of the 99%-percentiles (minimum, typical, and maximum values) for each operation mode (normal operation, and all relevant fault modes).

If the psophometric current varies significantly with speed (e.g., in the case of a rectifier vehicle), the report must additionally present a plot of the psophometric current versus speed.

#### 3.2.6 S6: BROAD-BAND INTERFERENCE (NORWAY ONLY)

#### 3.2.6.1 Information

Historically, the Norwegian State Railways applied broad-band interference limits rather than limits specifically at the signalling frequencies. Jernbaneverket has now initiated an investigation whether or not these broad-band limits are still technically justified; however, until this investigation is finalized, the limits remain valid.

#### 3.2.6.2 Requirements

The following interference limits apply:

Frequency band	Time limit	Limit value
TBD – 7 kHz See note 5	1.00 s	1.00 A RMS
7 – 9 kHz		0.50 A RMS
> 9 kHz		0.33 A RMS

*Note 5: The lower frequency limit is currently under investigation and is to be decided (=TBD).* 

The current limits may be exceeded for shorter time periods than 1.00 s.



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#### 3.2.6.3 Verification

Verification shall be done by test runs with measurement and data recording equipment being installed in the vehicle, in accordance with the test specification section 3.3.

The following signal processing of the recorded data is suggested:

Frequency band	Signal processing	Time limit	Limit value
TDB – 7 kHz See note 6	FFT with 8 $1/3$ Hz resolution	1.00 S	1.00 A RMS
7 – 9 kHz	(120 ms time window) followed by		0.50 A RMS
> 9 kHz	< 1.00 s moving RMS along the time axis of each FFT bin.		0.33 A RMS
	The limit value applies per FFT bin.		

*Note6: The lower frequency limit is currently under investigation and is to be decided (=TBD).* 

#### 3.2.6.4 Documentation

Documentation shall be a conformity statement and documentation of performed tests.

#### 3.2.7 S7: RADIATED INTERFERENCE

#### 3.2.7.1 Information

Conformance with EN 50 121 is the basis for new constructions and upgrading of infrastructure systems.

#### 3.2.7.2 Requirements

Requirements are in accordance with EN 50 121-2 and EN 50 121-3-1. Deviations, based on further evaluation, may be acceptable on a case-to-case basis.

#### 3.2.7.3 Verification

Verification shall be performed by tests in accordance with EN 50 121-2 and EN 50 121-3-1.

#### 3.2.7.4 Documentation

Documentation shall be a conformity statement and documentation of performed tests.

#### 3.2.8 S8: OUTSIDE ANTENNAS ON VEHICLES

#### 3.2.8.1 Information

NORWAY AND SWEDEN:

Requirements in this document consider outside antennas for railway vehicles.

#### 3.2.8.2 Requirements

NORWAY AND SWEDEN:

Antennas for railway vehicles shall satisfy the requirements on touch voltage in accordance with EN 50 122-1 *Railway applications- Fixed installations Part 1: Protective provisions relating to electrical safety and earthing*, and EN 50 155 *Railway applications Electronic equipment used on rolling stock*.

SWEDEN:



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Antennas for railway vehicles shall satisfy the requirements in Trafikverket's document TDOK 2014:0777 (former BVS 545.43501) Krav på yttre antenner för järnvägsfordon. (Requirements on external antennas for railway vehicles).

#### 3.2.8.3 Verification

NORWAY:

According to relevant standards, EN 50 122-1 and EN 50 155.

#### SWEDEN:

According to TDOK 2014:0777 (former BVS 545.43501) Requirements on external antennas for railway vehicles. Clause 4.1- 4.6. The tests should be performed as a factory type test.

#### 3.2.8.4 **Documentation**

NORWAY AND SWEDEN:

A conformity statement.

#### 3.2.9 **S9: RESISTANCE BETWEEN WHEELSETS**

#### 3.2.9.1 Information

N/A.

#### 3.2.9.2 Requirements

The resistance between wheels of a wheel set must be according to UIC512:1979 (< 0.1  $\Omega$ ).

#### 3.2.9.3 Verification

According to UIC512:1979.

#### 3.2.9.4 **Documentation**

A conformity statement.

#### 3.3 Validation and tests

#### **REQUIREMENTS PRIOR TO TESTS** 3.3.1

NORWAY AND SWEDEN:

Before test runs and/or demonstrations are allowed on the railway lines in Norway or Sweden, certain 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.





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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 Trafikverket 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 already 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.

#### 3.3.1.1 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.

#### 3.3.1.2 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 3.2.7.

#### 3.3.1.3 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 Trafikverket 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.

#### 3.3.1.4 Current or power control at low voltage

Documentation of current limitation as function of voltage is required.

#### 3.3.1.5 Regenerative braking

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

#### 3.3.1.6 Test plan

A test plan shall be presented to Jernbaneverket and/or Trafikverket 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.



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# 3.3.2 COORDINATION WITH TESTS REGARDING COMPATIBILITY WITH THE POWER SUPPLY

The tests specified in the following sections can to a wide extent be coordinated with the tests regarding compatibility with the power supply.

#### 3.3.3 GENERAL TEST PROGRAM

Table 2 below defines the test categories T1-T7, and outlines the minimum number of tests specifically addressing the requirements S1-S6.

Cat.	Condition	Scope and train operation
T1	Closed track, rotating converters	2 LOOP sequences in normal operation, and 1 LOOP sequence in each fault mode.
		(Plus additional tests for P-requirements; the data from these tests must be analyzed also for the S-requirements S1-S6).
T2	Closed track, static converters	<ul> <li>2 LOOP sequences in normal operation, and 1 LOOP sequence in each fault mode, altogether in each end of the line (close to and far away from the substation. I.e., a total of 4 LOOP sequences in normal operation, and 2 LOOP sequence in each fault mode.</li> <li>(Plus additional tests for P-requirements; the data from these tests must be analyzed also for the S-requirements \$1-\$\$6).</li> </ul>
Т3	Mixed traffic	Mainly tests for P-requirements, but the data from these tests must be analyzed also for the S-requirements S1-S6
T4	Transformer inrush (peak AC)	N/A (P-requirement only)
Т5	Transformer inrush (DC, S only)	Minimum 25 successful inrush events
T6	Other tests	According to EN 50 121-3
T7	Non-test approval	N/A

#### Table 2. General test requirements, S-requirements.

The tests of category T1 and T2 can be performed in either country. The tests T3 must be performed in the country/countries where the vehicle is going to operate. Test T5 must be performed in Sweden. Test T6 can be performed anywhere with 15 kV 16.7 Hz supply.

#### 3.3.4 TEST DETAILS

#### 3.3.4.1 Test sites

The following test sites are suggested:

Cat.	Norway	Sweden
T1	Hønefoss-Nesbyen on the Bergen line.	Gemla-Lessebo, Alvesta-Kalmar line.
T2	Lillestrøm-Gardermoen, Gardermoen Airport line.	Eskilstuna-Nykvarn, Eskilstuna-Södertälje line.
Т3	Oslo area.	Borlänge area (Borlänge-Krylbo, Borlänge- Ludvika).
T4	N/A (P-requirement only).	
T5	N/A	Ockelbo.



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T6	Vehicle suppliers own test tracks.
T7	N/A

#### Table 3. Test sites, S-requirements.

#### 3.3.4.2 Power supply configurations

#### CATEGORY T1: CLOSED TRACK, ROTATING CONVERTERS

The test line must be single-end supplied from one or two rotating converters 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 1. Supply conditions for T1 tests, S-requirements.

#### 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 2. Supply conditions for T2 tests, S-requirements.

CATEGORY T3: MIXED TRAFFIC No specific requirements. CATEGORY T5: TRANSFORMER INRUSH Please refer to the detailed description of these tests in chapter 3.3.4.6 below.

#### 3.3.4.3 Train configuration

All tests shall be performed with one vehicle alone and with all configurations of vehicles (i.e. multiple units) for which the approval must be valid. The tests must cover both normal fault-free operation, i.e., with all converters running and all filters etc. in normal mode, as well as all degraded operation modes, i.e., with one or more converter(s) and other subsystems cut-out.

#### 3.3.4.4 Train load

Locomotives must be loaded by a reasonably heavy train ( $\approx$  1-2 t per kN max. tractive effort, or  $\approx$  50-100 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).




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#### 3.3.4.5 Train operation – LOOP sequence

The train must be operated according to the "LOOP" speed profile shown in figure 3 below, during all tests specifically addressing the S-requirements.

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 LOOP sequence must be terminated at a lower speed.



#### Figure 3. LOOP operation sequence.

#### 3.3.4.6 Transformer inrush (DC) test (T5, Sweden only)

NOTE: This is not the same test that is specified for AC inrush currents in section 4.4.

The train must be located just beyond the first booster transformer, seen from the converter station, as seen in figure 4 below.

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 25 trials of breaker closures shall be performed, preferably more. All trials must be within limits for acceptance.

The DC-component shall be calculated as the mean value over one period of the fundamental, moving average calculation. The transducer must handle the frequencies from DC and upwards. The whole course of the inrush current shall be recorded.

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# current test. For booster transformer data, please refer to Appendix 1, section A1.2.3, A1.2.4 and A1.5.6.

#### 3.3.5 MEASUREMENT INSTRUMENTATION AND METHODS

## 3.3.5.1 Measurement instrumentation – requirements S1-S6

All measurements shall be performed with adequate voltage and current transducers (transformers and/or active transducers such as Rogowski coils and Hall transducers. Hall transducers are particularly required for DC measurements).

Sampling instruments as shown in figure 5 below 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 3.3.5.2 below.

The figure 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.

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Figure 5. Transducer position and recommended measuring equipment.

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  $\pm$  1% at the fundamental, and less than  $\pm$  5% of any of the stated interference requirements, is expected.

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.

## 3.3.5.2 Data analysis – requirements S1-S6

The recorded data must be processed and analysed in accordance with the interference requirements S1-S6. 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
- RMS line voltage
- Train speed
- DC current (Sweden only)
- 95 Hz and 105 Hz RMS current (Norway only)
- RMS currents in each of the 16 TI 21 channels (Norway only)
- RMS current in each of the 4 FTGS46 channels, and each of the 8 FTGS 917 channels (Norway only)
- RMS current in the broad-band interference channels. The lower channel should be split in three bands, such that the levels in the following frequency bands are presented separately: 33 Hz 150 Hz, > 150 Hz 300 Hz, > 300 Hz 7 kHz, > 7 kHz 9 kHz, > 9 kHz (Norway only)





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 (number of converters in operation, software revision etc.)
- Distance covered during the test sequence
- 99%-percentile of the psophometric current

If the psophometric current varies significantly with speed (e.g., in the case of a rectifier vehicle), the test report must additionally present a plot of the psophometric current versus speed.

Figure 6 below shows the suggested analysis method, based on a sampling frequency of the raw data of 50 kHz.

For FFT analysis, Hanning windows are recommended.

It is suggested that the psophometric currents are determined by means of a digital IIR filter with a characteristic equal to that specified by Appendix 9. It must be documented that the gain of the filter complies with the tolerance specified in ITU-T O.41 throughout the frequency band 50 Hz – 6 kHz. The recommended RMS integration time is 140 ms.

If FFT methods are used, the psophometric weighting function according to ITU-T (see Appendix 9) shall be applied on the FFT bins according to the formula in section 3.2.5. For FFT bins between the frequencies for which the weighting factors are specified, linearly interpolated values shall be used. The recommended FFT window length is 120 ms. At least 50% overlapping is required. The applicant shall describe how he deals with spectral leakage and frequency variations.

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 6. Suggested post-processing of the recorded data.





#### 3.3.5.3 Data analysis – S1-requirement (transformer inrush)

The current and voltage waveforms, as well as the 60 ms moving average value of the current, around each inrush event must be plotted, and the time for the 60 ms moving average value of the current exceeding plus or minus 25.0 A must be noted. Each plot must have information about the test date, the exact location of the test, and the data recording ID(s).

#### 3.3.5.4 Measurements and analysis – S7-reqiurement

Measurements procedures and instrumentation are in accordance with EN 50 121, part 2 and 3-1.

## 3.4 Documentation

#### 3.4.1 GENERAL

All documentation shall be in English. 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.



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#### Power supply 4

#### 4.1 References

#### 4.1.1 NORMATIVE REFERENCES

No.	Standard	Applica	ble to
		Signalling	Power
1.1	EN 50 110-1: Operation of electrical installations. CENELEC, European Standard.		Х
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.		Х
1.4	EN 50 128: Railway applications – Communications, signalling and processing systems – Sofware for control and protection systems. CENELEC, European Standard.	Х	
1.5	EN 50 153: Railway applications – Protective provisions relating to electrical harzards. CENELEC, European Standard.		Х
1.6	EN 50 155: Railway applications Electronic equipment used on rolling stock. CENELEC, European Standard.	Х	
1.7	EN 50 163: Railway applications – Supply voltages of traction systems. CENELEC, European Standard.		Х
1.8	EN 50 207: Railway applications – Electronic power converters for rolling stock. CENELEC, European Standard.		Х
1.9	EN 50 215: Railway applications – Test of rolling stock after completion of construction and before entry into service. CENELEC, European Standard.	Х	Х
1.10	EN 50 238: Railway applications – Compatibility between rolling stock and train detection systems. CENELEC, European Standard.	Х	
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.		Х
1.13	UIC 552: Electrical power supply for trains – Standard technical		Х



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	characteristics of the train line.		
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.	Х	
1.15	UIC 512: Conditions to be fulfilled in order to avoid difficulties in the operation of track circuits and treadles.	Х	
1.16	TDOK 2014:0777 (former BVS 545.43501): Requirements on external antennas for railway vehicles (only published in Swedish: "Krav på yttre antenner för järnvägsfordon"). Trafikverket. Only normative for Sweden.	Х	
1.17	ITU-T Recommendation O.41: Psophometer for use on telephone- type circuits.	Х	

#### 4.1.2 OTHER REFERENCES

No.	Standard	Applica	ble 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.	Х	Х
2.2	Characteristics of infrastructure. Document JD 590. Jernbaneverket, 01.02.2005.	Х	Х
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. Trafikverket, July 2004.	Х	Х
2.4	Rotating converters TRV/JBV: Description of simulation model. emkamatik document 06-0132, ver. 1. Stefan Menth, emkamatik, 18.9.2006.		Х
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

#### Safety with respect to electricity 4.2

#### 4.2.1 **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, Trafikverket will define restrictions for parking the vehicle under live overhead contact line.

#### 4.2.2 REQUIREMENTS

Requirements are in accordance with EN 50 153:



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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 <a href="http://www.dsb.no/">http://www.dsb.no/</a>

#### SWEDEN:

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

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 Trafikverket 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.

#### 4.2.3 VERIFICATION

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

#### 4.2.4 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  $U_{mean useful}(zone)$  and  $U_{mean useful}(train)$  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  $\pm$  0.033 Hz and under special conditions the variation is  $\pm$  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:



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$$THD_{U} = \frac{\sqrt{U_{2}^{2} + U_{3}^{2} + \dots + U_{n}^{2}}}{U_{1}}, n = 4, 5, 6, \dots$$

 $U_1$  = 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.

	i) Percentile		
Parameter	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
3 <sup>rd</sup> harmonic, RMS	3.4 kV	4.0 kV	4.7 kV
5 <sup>th</sup> harmonic, RMS	1.8 kV	2.7 kV	3.6 kV
7 <sup>th</sup> harmonic, RMS	0.4 kV	0.7  kV	1.3 kV
THD <sub>U</sub>	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  $(3^{rd}, 5^{th}, and 7^{th})$  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 3<sup>rd</sup> 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 5<sup>th</sup> harmonic.

Figure 7 below shows examples of measured line voltage waveshapes.







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 4.3.10 *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.



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## 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,  $\lambda$ , 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  $\cos(\varphi)$  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  $\cos(\varphi)$  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.



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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  $\cos(\varphi) \ge 0.95$  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  $\cos(\phi)$  control is used in the vehicle, the corresponding control characteristics shall be documented. If capacitive  $\cos(\phi)$  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  $\cos(\phi)$ -control (if present) in order to keep the voltage within limits.



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## 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  $cos(\phi)$  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.



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#### 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



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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  $(\cos(\varphi)-\operatorname{control})$ , 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  $\rightarrow$  reactive power  $\rightarrow$  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  $cos(\phi)$ 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  $\approx$  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  $\approx$  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 Trafikverket 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:





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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**

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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.

#### **P9: ELECTRICAL RESONANCE STABILITY** 4.3.9

#### 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.

#### Requirements 4.3.9.2

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.

fg 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.



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#### 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.



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Harmonics	3	5	7	9
Current level, % of I <sub>N</sub>	5%	3%	3%	3%

#### Table 5. Limits for individual current harmonics.

 $THD_I$  shall not exceed 8% (0.08), where

$$THD_{I} = \frac{\sqrt{I_{2}^{2} + I_{3}^{2} + \dots + I_{n}^{2}}}{I_{N}}$$

 $I_N$  = 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<sub>I</sub> -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:
  - $\,\circ\,$  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  $640 \Omega$ . 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 <u>not</u> 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.



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#### 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 singlephase 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.



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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  $cos(\phi)$  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  $\cos(\varphi)$ -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.





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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.



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#### 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 Trafikverket 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 Trafikverket.

#### 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.





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#### 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.



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#### 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 Trafikverket 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





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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 3.2.7, *S7: Radiated interference*.

## 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 Trafikverket 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 Trafikverket 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 <u>minimum</u> number of <u>successful</u> tests specifically addressing the requirements P1-P13.

Cat.	Condition	Scope and train operation
T1	Closed track, rotating converters	<ul><li>4 ABAB sequences and 2 ARO-sequences in each end of the line, all in each train configuration.</li><li>(Plus additional tests for S-requirements; the data from these tests must be analyzed also for all relevant P-requirements).</li></ul>
T2	Closed track, static converters	4 ABAB sequences and 2 ARO-sequences in each end of the line, all in each train configuration.



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		6 voltage jump tests. (Plus additional tests for S-requirements; the data from these tests must be analyzed also for all relevant P-requirements).
Т3	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
Т5	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.	
Т3	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 ( $\approx 2 \text{ t per kN}$  max. tractive effort, or  $\approx 100 \text{ t}$  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.



in the supply end

the far end, at maximum power of the vehicle under test



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#### Figure 17. Voltage jump test.

#### 4.4.4.8 Transformer inrush (AC) test (T4)

NOTE: This is <u>not</u> 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 4.3.14, *P14: Train preheating systems*.

Verifications shall be made by tests of at least 25 trials of inrush current tests, apart from the description mentioned in clause 4.3.14, 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  $\pm$  1% at the fundamental, and less than  $\pm$  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  $\cos(\varphi)$  and  $\tan(\varphi)$  (1.2 s)
- 3<sup>rd</sup>, 5<sup>th</sup>, 7<sup>th</sup>, and 9<sup>th</sup> line voltage harmonics
- 3<sup>rd</sup>, 5<sup>th</sup>, 7<sup>th</sup>, and 9<sup>th</sup> current harmonics, and the current THD

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



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- 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<sup>rd</sup>, 5<sup>th</sup>, 7<sup>th</sup>, and 9<sup>th</sup> 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.
- $Tan(\phi)$  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.





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• 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 Trafikverket 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 ( <i>curve resistance</i> )=CR0/(( <i>curve radius</i> )-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) <sup>2</sup> ] on straight track as function of speed [km/h] in the formula ( <i>running resistance</i> )= $RRA+RRB\cdot v+RRC\cdot v^2$
4.5.2.10	Adhesion coefficients ADH1 [km/h] and ADH2 [km/h] in adhesion formula ( <i>adhesion</i> )= <i>ADHCOEFF</i> + <i>ADH1/(speed</i> + <i>ADH2)</i> . 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





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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  $\ensuremath{\mathbb{R}}$  and the additional module TRACFEED  $\ensuremath{\mathbb{R}}$  Simulation are used.



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7 Appendices till bilaga 1: NES TS 02 appendices – Technical specification: Requirements on rolling stock in Norway and Sweden regarding EMC with the electrical infrastructure and coordination with the power supply and other vehicles. NIM NES 2009-07-01

NES	TECHNICAL SPECIFICATION	TS 02 APPENDICES
POWER CO-	FROM THE NES	PAGES: A138
OPERATION	GROUP	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

APPENDICES





## 1 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.

#### 1.1 Main data

Data	Norway	Sweden
Owner	Norwegian National Rail	Swedish National Rail
	Administration	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	9882 km, of which 1734 km are
	double track	double track or more
		(11 697 km track length)
Length of electrified railway	2500 km, of which 220 km	7638 km, of which 1734 km are
network	double track	double track or more (9543 km
		track length)
Мар	See appendix 2	See appendix 3
Modifications planned in future	Rebuilding of weak main lines	New single track lines on the
	and construction of some new	east coast in the north of
	lines (double track) that will	Sweden (Botniabanan and
	increase capacity and cut travel	Haparandabanan)
	time between existing railway	New city lines double track in
	destinations around Oslo	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.	



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## 7.1 Power generation

Data	Norway	Sweden
Direct supply from public	No	No
network		
Supply from public utility via	Yes	Yes
rotary frequency converters		
Supply from public utility via	Yes	Yes
static frequency converters		
Railway owned power stations /	Yes, but one hydro power	No
generators	station owned by other	
	company (Statkraft SF)	
Supply network structure	Decentralized, but a small	Decentralized, including a 132
	centralized 55 kV network	kV-feeding system which
	exists in the region south west	connects 8 converter stations
	of Oslo	
Frequency and phase stiffness	Synchronous to public utility.	Synchronous to public utility.
	See section 6.1.2 in the report.	See section 6.1.2 in the report.
	Transient deviation in frequency	Transient deviation in
	may occur due to changing load.	frequency may occur due to
	Phase:	changing load.
	For both rotary and static	Phase:
	converters phase angle depends	For both rotary and static
	on load demand. For a load at	converters phase angle
	$\cos(\phi) = 1.0$ the phase normally	depends on load demand. For a
	lags 36° at converters at rated	$r_{0}$ to at $cos(\phi) = 1.0$ the phase
	10au.	at roted load

### 1.1.1 CONNECTION TO PUBLIC UTILITY

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



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commissioned.

#### 1.1.2 POWER STATIONS

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

#### 1.1.3 ROTARY FREQUENCY CONVERTERS

Data	Norway	Sweden
Converter name	ASEA Q24, Q38, Q48 and	ASEA Q24/Q25
	NEBB 7 MVA and 10 MVA	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	min: 1	min: 2
station	typ: 2	typ: 3
	max: 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	Damping windings in
	generator-machine, none in	generator-machine, none in
	motor-machine	motor-machine
Railway side connected to	Contact line for all, but also to	Contact line
	55 kV distribution network in	
	two stations	
Regeneration capability	Yes	Yes
Rated converter power per unit	min (Q24): 2.4	min (Q24): 2.4
[MVA]	typ (Q38): 4	typ (Q38): 4
	max (Q48): 10	max (Q48): 10
Continuous power per unit	min (Q24): 3.1	min (Q24): 3.1
(respectively) [MVA]	typ (Q38): 5.8	typ (Q38): 5.8
	max (Q48): 10	max (Q48): 10
Typical short circuit impedance	min (Q48): j7.0	min (Q48): j7.0
of generator+	typ (Q38): j14.35	typ (Q38): j14.35
Transformer [Ohm]	max (Q24): j33.1	max (Q24): j33.1

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Voltage negalation	Stiff on alightly dealining with	Stiff on alightly dealining with
voltage regulation	Still of slightly declining with	Sum or singhtly declining with
	increasing reactive power	increasing reactive power
	demand.	demand.
Capacity	The number of active units in	The number of active units in
	each station is adapted to	each station is depending on
	hourly variation in power	the actual load and adaptive
	demand	load statistics.
Overloading capacity	Up to +40 % of continuous	Up to +40 % of continuous
	power for 6 minutes and	power for 6 minutes and
	+100 % of rated power for 2	+100 % of rated power for 2
	seconds	seconds
If overloaded	Converter is instantaneously	Converter is instantaneously
	disconnected	disconnected
Modifications planned in future	Static and brushless excitation	Brushless exciters may be
_	may be implemented. Maybe	introduced in the future.
	increasing the number of	
	converters in each station.	

#### 1.1.4 STATIC FREQUENCY CONVERTERS

Data	Norway	Sweden
Converter name	ABB PWM converter	ASEA Cyclo-converter: YOQC
	ABB/Adtranz PWM converter:	ASEA/ABB PWM-converter:
	MegaMacs	TGTO
	Siemens	ABB/ADtranz PWM-converter:
		MegaMacs
		ALSTOM PWM-converter
Number of converter stations	6	18
Number of converters units per	min: 2	min: 2
station	typ: 2	typ: 3
	max: 3	max: 4
		6 in future
Type of converter	PWM converter: Line voltage	15 cyclo converters and 37
	converter (rectifier) and pulse	PWM conveters
	width modulated inverter	
	connected together with DC-	
	link	
Filters on railway side	Yes, broad band and	Normal filter configuration for
	psofometric filter	cylco converters and
		MEGAMACS is a wideband
		filter. Normal filter
		configuration for other PWM
		converters is 6 <sup>th</sup> and 8 <sup>th</sup> and
		wideband
Other filters	DC-link: 2 <sup>nd</sup> , 4 <sup>th</sup> , 6 <sup>th</sup> and	DC-link: 2 <sup>nd</sup> , 4 <sup>th</sup> , 6 <sup>th</sup> and 8 <sup>th</sup>
	$8^{\text{th}}/9^{\text{th}}$ .	and wideband in MEGAMACS
	Utility grid: Yes	converters
		Utility grid: Yes
Regeneration capability	Only one station, in others the	All cyclo converters can
	phase angle is shifted to push	regenerate to the 50 Hz-grid.

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	regenerated energy forward to other trains or stations. Some	2 converter stations with PWM-converters can
	stations have a resistor for	regenerate to the 50 Hz grid.
	taking care of short term	(Alingsås and Järna). All other
	feedback power.	PWM converters have resistors
	-	to take care of short term
		feedback power.
Rated converter power per unit	min: 6	min: 6
[MVA]	typ:	typ: 15
	max: 15	max: 15
Typical short circuit impedance	0.013+j0.0677 pu	0.83+j13.0 but can vary a lot:
of output transformer [%]		0.83% > ur >1.49%
		7.94% > ur >13.0%
Voltage regulation	Stiff or slightly declining with	Stiff or slightly declining with
	increasing reactive power	increasing reactive power
	demand. Static converters	demand. Static converters
	imitate the dynamical response	imitate the dynamical response
	of a rotary converter (ASEA	of a rotary converter (ASEA
	Q48) due to software	Q48) due to software
	parameterisation. The 1~	parameterisation. The 1~
	phase voltage angle depends	phase voltage angle depends
	therefore of the 3~ phase	therefore of the 3~ phase
	angle.	angle.
Frequency regulation	Synchronization with the 50	Synchronization with the 50
	Hz grid is kept by means for	Hz grid is kept by means for
	phase-locked loops	phase-locked loops
Capacity	The number of active units in	The number of active units in
1 5	each station are automatically	each station is depending on
	adapted to variation in power	the actual load and adaptive
	demand	load statistics.
Overloading capacity	No short time exceeding of	Normally no overload capacity
	rated power	but MEGAMACS have a short
	-	time capacity of 17 MVA
If overloaded	If current limit is reached,	If current limit is reached,
	voltage will be reduced. The	voltage will be reduced. The
	voltage will then not be sine	voltage will then not be sine
	adapted.	adapted.
Extensions planned in future		7 new static converters are
•		under commissioning,
		in operation 2007-2008

#### 7.2 Power distribution

#### 1.1.5 GENERAL DATA

Data	Norway	Sweden
Railway owned power	Yes at 16.7 Hz, in one limited	Yes at 16.7 Hz
distribution network exists	area	
Nominal voltage [kV]	55 (2 x 27.5 kV)	132 kV (2x66 kV)
Number of phases	2	2



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Purpose	Connecting one hydro power	To reduce number of converter
	station, 2 rotary converters and	stations and have a more even
	3 substations	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	No information available.	Normally 100 -130 Hz.
frequency [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

#### 1.1.6 TRANSFORMER STATIONS

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

#### 1.1.7 TRANSMISSION LINES

Data	Norway	Sweden
Typical transversal section	55 kV (2x27.5 kV) normally	132 kV lines (2x66 kV) are
(cross section)	made up with concrete poles	normally built with wooden
	and with the phase height of	poles with a phase height of
	9.2 m and phase spacing of 3.5	10.8 m (sags included) and a
	m.	phase spacing of 4m. Earthed



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		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 mm² FeAl
Conductor cross section (s)	4x35, 4x50, 2x50 and 2x70	See above.
[mm2]		
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.

#### 1.1.8 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:	Per phase:
	0.16 µF/km	0.16 µF/km
Modifications planned in future	No significant modifications	None known.

## 7.3 Substations

#### 1.1.9 GENERAL DATA

Data	Norway	Sweden
Мар	Se appendix 2	Se appendix 3
Number of substations	38	See section 1.1.4 and 1.1.6.
Type of substations	Transformers only: 3	See references above
	Converters feeding contact	
	line: 35	
	Hydro power station: 1	
Nominal power rating of	min: 2x0.625	See references above
complete substation [MVA]	typ: 2x5.8	
	max: 3x15	
Feeding of railway lines	Single side	Single and double sided
	Double side	feeding.
	Multiple side (2 T-	
	connections)	
Distance between substations	min: 12	See section 1.1.15.
[km]	typ: 80	
	max: 92	



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Distance of single fed line [km]	min:	See section 1.1.15.
	typ:	
	max: 63	
Normal operation of network	Interconnected	Interconnected
Separation of feeding areas	Seldom sectioned, but	Normally no separation of
(neutral sections)	depending on operation of	feeding areas.
	utility grid	
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)

#### 1.1.10 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:	uk = 0,4 %, 57.53° (or
	typ: 0.4 max:	0.184+j0.117 Ω)
Distance between trafos [km]	min: 8	min: 8
	typ: 10	typ: 10
	max: 12	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.



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#### 1.1.11 PASSIVE FILTERS AND COMPENSATORS

Data	Norway	Sweden
Passive filters exist	Yes	No, only at converter stations
		with static converters, see 1.1.4
Type of filter	Series capacitor and shunt	N.A.
	capacitor	
Schematics etc.	No information available.	N.A.
Resonance frequencies	Series: No significant effects on	N.A.
	resonance frequencies.	
	Shunt: No information	
	available.	
Where in service	Series capacitor between	N.A.
	converter stations on weak	
	lines, shunt capacitor in heavy	
	load area (Oslo S)	
Purpose	Series capacitor for voltage	N.A.
	increase and shunt capacitor	
	for reactive power feeding	
Rating	Series cap -j7.35 [Ohm]	N.A.
	Shunt cap 4 [MVAr]	
Modifications planned in future	Series capacitors will probably	More filters built when new
	be removed when line is	converters are built
	reinforced/rebuilt with AT-	
	system	

#### 1.1.12 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.

#### 1.1.13 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



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### 1.1.14 OTHER EQUIPMENT

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

## 7.4 Railway lines

#### 1.1.15 LONGITUDINAL CHARACTERISTICS

Data	Norway	Sweden
Мар	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.

#### 1.1.16 CROSS CONNECTIONS ON DOUBLE-TRACK LINES

Data	Norway	Sweden
Cross connection is done	Never in normal operation but	Exists on some lines (Tranås-
	one shorter line where the two	Malmö) as normal operation.
	tracks are operated n parallel	On other lines only during
	(connected in the ends)	fault conditions or
		maintenance.
Cross-connections (if existing)	Switchable, but just in use in	Switchable.
are	fault situations	
Distance between connections	min:	Normally 7-10 km.
(if existing)	typ: very variable	
	max:	
Modifications planned in future	No information available.	More lines using cross
		connections are under
		investigations

#### 1.1.17 CROSS SECTIONS OF LINES

Data	Norway	Sweden
Number of tracks on open line	Mostly single track, but double	Normally single track but



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(i.e. outside stations/yards)	and multiple track exist	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 <sup>2</sup> Al	Yes, normally two 212 mm <sup>2</sup> Al
Auto-/booster wires	No information available.	BT-systems: Booster wire is normally (212 mm <sup>2</sup> 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.



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#### 1.1.18 CABLE SECTIONS

Data	Norway	7	Sweden
Length of cable connection	typ:	0.1	0.1 – 4 km, typical value 300
substation to contact line [km]	max:	5	m.
Length of feeder cable parallel	typ:		Exist only in the Stockholm
to railway line (e.g. tunnels,	max:	short	area (4 cable feedings). Typical
urban areas) [km]			length : 13 km.
Specific impedance [Ohm/km]	min:	0.10+j0.03	For cables in the Stockholm
	typ:	0.12+j0.06	area:
	max:		0.12 + j 0.054 and
			0.15 + j 0.036
Specific capacitance [µF/km]	min:		For cables in the Stockholm
	typ:	0.26	area:
	max:		0.16 and 0.26 μF/km.
Modifications planned in future	Introduc	ing AT-system may	Under investigation
	cables fo	r negative and positive	(Citybanan in Stockholm).
	feeder in	tunnels may be	
	necessar	у	

#### 1.1.19 RETURN CURRENT ARRANGEMENT

Data	Norway	Sweden
Rail types	S49: 2700 km	Normally UIC 50 and UIC 60
	S54: 750 km	or corresponding.
	UIC60: ca. 200 km	
Rail info	Normally welded, isolated	One rail welded (S-rail) and
	gaps/joints exists	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 1.1.17.	See section 1.1.17.
Earth wire	On some lines, both sectioned	See section 1.1.17.
	and interconnected (typical	
	distance between connections	
	to rail is 3 km) exist	
Track transformers	No	No
Other characteristics	No	No
Earth resistivity [Ωm]	Railway lines are very often	Earth resistivity is high. A
	build on bedrock ground or	usable value is 2500 $\Omega$ m.
Wet soil: 20-200	rocky ground. A usable value is	
Humus/clay: 50-200	2500 Ωm.	
Wet sand: 100-300		
Dry sand: 1000-50000		
Mountains: 1000-10000		
Future modifications plans	No information available.	None



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#### 1.1.20 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 1.1.23.
Modifications planned in future	No information available.	3-windings boosters may be introduced if ATBT-systems are introduced.

#### 1.1.21 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 stationsmin:60typ:180max: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

#### 1.1.22 INTERACTION AC/DC RAILWAYS

Data	Norway	Sweden
Infrastructure segment lies	Yes	Yes
adjacent to DC-		



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railways/tramways		
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

#### 1.1.23 NUMERICAL VALUES BT SYSTEM

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

#### 1.1.24 NUMERICAL VALUES AT SYSTEM

Data	Norway	Sweden
Fixed impedance at feeding or	Not yet decided or calculated.	min: 0.189+j0.343
starting points [Ohm]		typ:
		max: 0.468+j0.755
		(see note below the table)
Line impedance on single line	Not yet decided or calculated.	min: 0.0335+j0.031
track [Ohm/km]		typ:
		max: 0.0715+j0.066
		(linear approximations



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		including AT's)
Line impedance on double line	Not yet decided or calculated.	Not calculated.
track [Ohm/km]		
Specific capacitance, single	Not yet decided or calculated.	
track [nF/km] (caternary–		typ: 11.9 – 13.5
earth)		
Specific capacitance, double	Not yet decided or calculated.	Not calculated.
track [nF/km]		
(caternary–earth)		
Lowest resonance frequency	typ: 450 Hz global	typ: 400 Hz global
(contact line network) double	typ: 350 Hz local	typ: 250 Hz local
side feeding [Hz]		
Lowest resonance frequency	typ: 200 Hz local	typ: <200 Hz local
(contact line network) single		
side feeding [Hz]		
Modifications planned in future	Exact system design not	No
	decided yet	

**NOTE** that the values for AT-systems in Sweden regard 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.

#### 7.5 Signalling equipment

#### 1.1.25 TRACK CIRCUITS

Data	Norway	Sweden
DC track circuits	Only on non-electrified lines	DC track signalling circuits
	and at one electrified railway	exists on nearly the whole
	station (Filipstad)	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	Do not exist
	lines. 95 and 105 Hz only,	
	uncoded.	
Reed frequency (275-1000Hz)	Do not exist	Do not exist
Lower audio frequency (1-4	Exist on a small part of the	Do not exist
kHz)	network. Bombardier TI 21 (1.5	
	- 2.6 kHz), digital processor	
	based and not transmitter	
	signal coded.	
Upper audio frequency (4-20	Exist on a part (110 km) of	Do not exist
kHz)	network. Siemens FTGS (4.7-	
	16.5 kHz), digital and	
	transmitter signal coded.	
Other	Do not exist	Train radio or radio blocking of
		trains on some none electrified



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		low traffic lines
Modifications planned in future	No information available.	More radio block systems are
		planned for low traffic lines.

#### 1.1.26 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

## 1.1.27 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)



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#### 1.1.28 INTERFERENCE MONITORS

Data	Norway	Sweden
Philosophy of application	Monitors recommended.	DC-current monitor on new
	Monitors needed if safety case	electrical traction vehicles is
	cannot be fulfilled otherwise	required.
Purpose	Monitored frequencies: 95 and	To monitor the DC-
	105 Hz.	component, a component
	Trip level 2 A rms.	which can have an influence on
	Filter characteristics ±3 Hz.	the track signalling circuits.
	Response time 1 sec.	
Type(s) in service	95 and 105 Hz monitor for	DC-monitors are in operation
	warning and disconnection of	on some new vehicles.
	main circuit breaker.	
Modifications planned in future	No information available.	None

#### 1.1.29 INTERFERENCE LIMITS

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

#### 1.1.30 DATA TRANSMISSION AND REMOTE CONTROL SYSTEMS

Data	Norway	Sweden
System(s)	Various communication	Various communication
	systems exist, such as PCM	systems exist, such as PCM
	(pulse code modulation, BF	(pulse code modulation, BF
	(frequency carrier), etc, on Cu-	(frequency carrier), ADSL, etc,
	cable. Also ordinary telephone	on Cu-cable. Also ordinary
	lines on Cu-cables exist. Opto-	telephone lines on Cu-cables
	communication is the	exist. Opto-communication is
	dominating transmission for	the dominating transmission
	long distances communication.	for long distances
	GSM-R is being introduced in	communication. Transmission
	the whole country.	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.



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#### 7.6 Operational conditions

1.1.31 LINE FREQUENCY

See section 6.1.2.1 in the report.

1.1.32 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.



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#### 1.1.33 LINE VOLTAGE SPECTRUM

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

## 

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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.



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#### 1.1.34 **REGENERATIVE BRAKE**

See clause 6.8 in the report.

#### 1.1.35 POWER FACTOR

See clause 6.3 in the report.

#### 1.1.36 EARTHING

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

#### 1.1.37 TRAFFIC INFORMATION/CHARACTERISATION

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

See respective Network Statement.

#### 1.1.38 NETWORK OPERATION

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



#### 1.1.39 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	$V_{1:} U_{max2} = 17500 V$
	50163:2004	
	V2: $U_{min2}$ =10000 V and	
	U <sub>min1</sub> =11000 V	
Maximum current limitation	C1: I <sub>max</sub> = 900 A	Max current per train is 900 A
		in tractive mode. Higher values
	C2: $I_{max} = 700 \text{ A}$	in braking mode can be
		accepted.
	C3: $I_{max} = 450 \text{ A}$	
Regenerative braking	B1: I <sub>max</sub>	No classes defined.
	B2: 10 MW / 600 A	
	B3: 8 MW / 500 A	
-	B4: 5 MW / 300 A	
Low frequency power	Under investigation.	Under investigation.
oscillations		

### 7.7 Existing electrical vehicles

Passive filters refer 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

#### 1.1.40 ELECTRICAL LOCOMOTIVES IN NORWAY AND SWEDEN

Operator	Vehicle (no of vehicles in op. in brackets.)	Туре	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

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MTAB	Dm 3	(19)	Tap changer	No	No
МТАВ, ТКАВ	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 / BF	R 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 Ro	e 7 (356)	Phase angle control	Yes	No
Green Cargo AB	Rm	(6)	Phase angle control	Yes	No

#### 1.1.41 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 ("IC 70")	(16)	Inverter	No	up to about 300 Hz
Flytoget AS	Class 71 ("FPT")	(16)	Inverter	No	up to about 850 Hz
NSB AS	Class 72	(36)	Inverter	No	Unknown
NSB AS	Class 73 Identical to cla	(22) ss 71	Inverter	No	up to about 850 Hz
SL	X1	(94)	Phase angle control	Yes	No
SJ	X2 ("X 2000")	(43)	Inverter	Yes	up to 216 2/3 Hz
Arlanda Banan AB	X3 ("Arlanda Expr	(7) ress")	Inverter	No	unknown
SJ and SL and other regional operators	X10 to X14 (13)	7)	Phase angle control	yes	No
SJ, TKAB	X20 to X23	(3)	Tap changer, diode rectifier	unknown	No



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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 <u>www.jarnvag.net</u>)



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#### Appendix 2: Network map Norway 2





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#### **Appendix 3: Network map Sweden** 3










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## 4 Appendix 4: Additional information for stability studies

#### 7.8 Low frequency power oscillations

#### 4.1.1 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.

#### 4.1.2 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 1.1.23 and 1.1.24 of this document).
  - Substation (rotary converters). The dynamic behaviour is provided by the infrastructure manager, see chapter 5 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





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static converters if they are compatible with the rotary ones for all required operational conditions.

#### 4.1.3 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



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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.

## 7.9 Electrical resonance stability

#### 4.1.4 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.



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#### 4.1.5 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.

#### 4.1.6 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.



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# 5 Appendix 5: dynamic behaviour of rotary converters

## 7.10 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.

## 7.11 Examples of converter unit response to changes in load

#### 5.1.1 INTRODUCTION

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.

#### 5.1.2 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)
DA Golimi	Angle of pontograph voltage at 60km from the converter station when every

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.



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#### 5.1.3 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  $\Delta P_1$  and the response in 3-phase power  $\Delta P_3$  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, $\Delta P3/\Delta P1$ , for sine shaped change in single-phase power $\Delta P1$ .

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

#### 5.1.4 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.



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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



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

Power step in	Max. Oscillation	
train	U 60km	PA 60 km
0 – 3.50 MW	≈ 690 V	$\approx 13^{\circ}$
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.

#### ACTIVE POWER RAMP RESPONSE 5.1.5



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 (ran	p) steepness as follows:
	(··· F ···· · · · · · · · · · · · · · ·		F	r, r

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	$5\mathrm{V}$	(Shown in Figure A5-4)





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Comment:

Do Т

• 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.

#### 5.1.6 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:	Ma	x. 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.



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#### 5.1.7 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:

<b>Reactive power step:</b>	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.

#### 7.12 Voltage phase angle variation with load

During increasing load the converter units' power angle and thus the phase angle for generated singlephase 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:





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

 $\Psi_0$  = angle difference between the 50 Hz and 16.7 Hz at no load on the converter and

$$\Psi_{\text{conv}} = -\left[\frac{1}{3}\arctan(x_{qM} \cdot i_G \cdot \cos\varphi_G) + \arctan(\frac{x_{qG} \cdot i_G \cdot \cos\varphi_G}{1 + x_{qG} \cdot i_G \cdot \sin\varphi_G})\right]$$
  
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<sub>G</sub> is the current of the converter generator [A]

 $I_{n\_G}$  is the rated current of the converter generator [A]

 $\varphi_{\rm G}$  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  $\cos(\phi) < 1$ . In the figure  $\Psi_0$  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.

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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  $\cos(\phi)$ -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.

## 7.13 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.



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#### 5.1.8 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.

#### 5.1.9 MODEL STRUCTURE

Chapter 7.11 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.





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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:

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

where

- $\circ$   $f_N = 16\frac{2}{3}Hz$  is the nominal line frequency,
- $\circ$  A(t) the amplitude and
- $\circ \varphi(t)$  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

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

 $U_{Gen}^{*}(t) = A(t) \cdot \cos(2\pi f_{N}t + \varphi(t))$  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):

$$\varphi(s) = \left[G_0(s) + k(P) \cdot G_1(s)\right] \cdot P(s)$$

where

P(s) is the Laplace transformed time domain signal P(t).

$$G_0(s) = \frac{A_0}{T_0^2 s^2 + 2d_0 T_0 s + 1}$$
 is an "oscillation component".  

$$G_1(s) = \frac{A_1}{T_1 s + 1}$$
 is a "static component", which is combined with



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$$k(P) = \varphi_0 + k_{\varphi} \cdot abs(P)$$

 $G_2(s) = \frac{A_2s}{T_0^2s^2 + 2d_0T_0s + 1}$ 

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:

 $G_i(s) = \frac{A_i}{T_i s + 1}$ 

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

$$A(s) = U_N + [G_2(s) + G_3(s) + G_4(s)] \cdot P(s) + [G_5(s) + G_6(s)] \cdot Q(s)$$
$$U_N = \sqrt{2} \cdot 16.5kV \qquad \text{is the nominal line voltage amp}$$

is the nominal line voltage amplitude,

is an "oscillation component" (same denominator as  $G_0(s)$ )

with i = 3 ... 6 represent transient effects.





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#### 5.1.10 MODEL PARAMETERS

The following parameter sets have been determined and allow the reproduction of the step responses shown in chapter 7.11 with good accuracy:

	Q 38 weak 3-phase network
$A_0$	-12.25°/5.8 MW
	$= -3.6863 \cdot 10^{-8} W$
$T_0$	$\frac{1}{2-1.5 H_{\odot}} = 0.1061 s$
. *	$2\pi \cdot 1.5Hz$
$d_0$	0.045
$A_{l}$	1
$T_{I}$	0.05s
$\varphi_0$	-1.3541.10-7
k <sub>\varphi</sub>	6.0184 · 10 <sup>-15</sup>
$A_2$	$1.5 \cdot 10^{-5} V/W$
$A_3$	$-2.0 \cdot 10^{-4}$
$T_3$	0.05 <i>s</i>
$A_4$	$2.0 \cdot 10^{-4}$
$T_4$	1.5s
$A_5$	$1.5 \cdot 10^{-3}$
$T_5$	0.25s
$A_6$	$-1.5 \cdot 10^{-3}$
$T_6$	0.001 <i>s</i>

#### \* Remark:

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

#### 5.1.11 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 1.1.23. 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  $Z_{{\it Line}}$  = 10.8 + j 11.4  $\Omega_{\odot}$ 





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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.

#### SIMULATIONS WITH VEHICLES 5.1.12

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).



#### 5.1.13 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:





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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:

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

#### 5.1.14 VALIDATION EXAMPLES

The simulation model shown in this chapter, 7.13, 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<sub>Gen</sub>, Q<sub>Gen</sub>)
- Lower left plot: active and reactive power at line end  $(P_{60km}, Q_{60km})$
- Upper right plot: line voltage at line end (U<sub>60km</sub>)
- Lower right plot: phase angle of voltage at line end (PA<sub>60km</sub>).

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.



#### 5.1.14.1 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 5.1.4.

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#### 5.1.14.2 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.

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







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#### 5.1.15 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:
  - $\circ~$  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.
  - $\circ~$  Line power limitation due to low or high pantograph voltage in traction and braking.

#### 7.14 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.



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# Appendix 6: Typical cross section of a booster transformer line in sweden 6









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#### Appendix 7: cross section of EXISTING 7 AT-system lines in sweden





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#### Appendix 8: cross section of new standard for AT-systems 8 lines in Sweden





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Frequency	Weighting factor, Pfn	
[Hz]		
16,66	0,056	
50	0,71	
100	6,91	
150	35,5	
200	89,1	
250	178	
300	295	
350	376	
400	484	
450	582	
500	661	
550	733	
600	794	
650	851	
700	902	
750	955	
800	1 000	
850	1 035	
900	1 072	
950	1109	
1 000	1 122	
1 050	1 109	
1 100	1 072	
1 150	1 035	
1 200	1 000	
1 250	977	
1 300	955	
1 350	928	
1 400	905	
1 450	881	
1 500	861	
1 550	842	
1 600	824	
1 650	807	
1 700	791	
1 750	775	
1 800	760	

# 9 Appendix 9: Psophometric weighting factors according to ITU-T

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1 850	745
1 900	732
1 950	720
2 000	708
2 050	698
2 100	689
2 150	679
2 200	670
2 250	661
2 300	652
2 350	643
2 400	634
2 450	626
2 500	617
2 550	607
2 600	598
2 650	590
2 700	580
2 750	571
2 800	562
2 850	553
2 900	543
2 950	534
3 000	525
3 100	501
3 200	473
3 300	444
3 400	412
3 500	376
3 600	335
3 700	292
3 800	251
3 900	214
4 000	178
4 100	144,5
4 200	116
4 300	92,3
4 400	72,4
4 500	56,2
4 600	43,7
4 700	33,9
4 800	26,3
5 000	20,4
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> 6 000	7,1



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# Ändringslogg

Fastställd version	Dokumentdatum	Ändring	Namn
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