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Interested committees:

Title: BS EN 50388-2 Fixed installations and rolling stock for railway applications - Technical criteria for the coordination between electric traction power supply systems and rolling stock to achieve interoperability

Part 2: stability and harmonic

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Introduction

This draft standard is based on national and international discussions. Your comments on this draft are invited and will assist in the preparation of the consequent standard.

For international standards, comments will be reviewed by the relevant UK national committee before sending the consensus UK vote and comments to the international committee, which will then decide appropriate action. If the international standard is approved, it is usual for the text to be published as a British Standard.

For national standards, comments will be reviewed by the relevant UK national committee and the resulting standards published as a British Standard.

UK Vote

Please indicate whether you consider the UK should submit a negative (with supporting technical reasons) or positive vote on this draft. Please indicate if you are aware of any reason why this draft standard should not be published as a British Standard.

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Template for comments and secretariat observations

Date: xx/xx/20xx	Document: ISO/DIS xxxx

1	2	(3)	4	5	(6)	7
MB	Clause No./ Subclause No./Annex **(e.g. 3.1)**	Paragraph/Figure/ Table/Note	**Type of comment**	**Commend (justification for change) by the MB**	**Proposed change by the MB**	**Secretariat observations on each comment submitted**
	3.1	Definition 1	ed	Definition is ambiguous and needs clarifying.	Amend to read '...so that the mains connector to which no connection...'	
	6.4	Paragraph 2	te	The use of the UV photometer as an alternative cannot be supported as serious problems have been encountered in its use in the UK.	Delete reference to UV photometer.	

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EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

DRAFT
prEN 50388-2

December 2023

ICS 45.060.01; 29.280 -

English Version

Fixed installations and rolling stock for railway applications - Technical criteria for the coordination between electric traction power supply systems and rolling stock to achieve interoperability - Part 2: Stability and harmonics

Applications ferroviaires - Installations fixes et matériel roulant - Critères techniques pour la coordination entre les installations fixes de traction électrique et le matériel roulant pour réaliser l¿interopérabilité - Partie 2: stabilité et harmoniques

Bahnanwendungen - Ortsfeste Anlagen und Bahnfahrzeuge - Technische Kriterien für die Koordination zwischen Anlagen der Bahnenergieversorgung und Fahrzeugen zum Erreichen der Interoperabilität - Teil 2: Stabilität und Oberschwingungen

This draft European Standard is submitted to CENELEC members for enquiry.
Deadline for CENELEC: 2024-03-15.

It has been drawn up by CLC/SC 9XC.

If this draft becomes a European Standard, CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

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European foreword

This document (prEN 50388-2:2023) has been prepared by CLC/SC 9XC, “Electric supply and earthing systems for public transport equipment and auxiliary apparatus (Fixed installations)”, of CLC/TC 9X, “Electrical and electronic applications for railways”.

It is also relevant to the scope and expertise of CLC/SC 9XB, “Electromechanical material on board of rolling stock”.

This document is currently submitted to the Enquiry.

The following dates are proposed:

• latest date by which the existence of this document has to be announced at national level	(doa)	dor + 6 months
• latest date by which this document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	dor + 12 months
• latest date by which the national standards conflicting with this document have to be withdrawn	(dow)	dor + 36 months (to be confirmed or modified when voting)

EN 50388 “Railway applications – Fixed installations and rolling stock - Technical criteria for the coordination between traction power supply and rolling stock to achieve interoperability” consists of the following parts:

— Part 1: General

— Part 2: Stability and harmonics

This document has been prepared under a standardization request addressed to CENELEC by the European Commission. The Standing Committee of the EFTA States subsequently approves these requests for its Member States.

For the relationship with EU Legislation, see informative Annex ZZ, which is an integral part of this document.

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Introduction

To improve readability, this document is structured as shown in Table 1, which only shows references to the most important sections.

Table 1 — Structure of this document

Topic	Requirements		Tests and documentation	
	Section	**Main requirements**	**Section**	**Most important elements**
Electrical resonance stability	4.1	Definition of a limit frequency f_L - Lowest power system resonance frequency shall not be < f_L - All controlled elements shall be passive for all frequencies > f_L Requirements for filter capacitors	5.1	For controlled elements, in most cases measurement of frequency response of input admittance is required. 5.1.1.2 Defines in which cases input admittance shall be measured and how it shall be measured. 5.1.1.3 Defines the combined test 5.1.1.4 Defines in which cases simulation is sufficient and specifies the requirements for the simulator. 5.1.1.5 Defines in which cases declaration of conformity is sufficient. 5.1.2 Defines the methods to be used to assess the lowest resonant frequency of the power supply.
	A.1	Technical background about electrical resonance stability		
	B.1	Examples of real electrical resonance instability experiences		
Low-frequency stability	4.2	Stable operation shall be demonstrated for predefined operation scenarios of electric traction power supply system and one or several identical traction units at one location.	5.2	Verification either by • time domain simulation (or measurements); or • any other validated method.
	A.2	Technical background about low-frequency stability A.2.1 Background and experiences A.2.2 Acceptance criteria and verification		
	B.2	Examples of experienced low frequency power oscillations		

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Topic	Requirements		Tests and documentation	
	Section	**Main requirements**	**Section**	**Most important elements**
Overvoltages caused by harmonics	4.3	4.3.2 Rolling stock Defines the limit of the overvoltage and specifies the calculation method by using line current spectrum, bandpass filtering, summation methods and standardized power supply impedances. 4.3.2.3 Overvoltage detection. Suggests methods of overvoltage detection. 4.3.3 Defines applicability and the overvoltage limits for static converter stations. 4.3.4 Infrastructure related topics	5.3	5.3.1 Demonstration of compliance for rolling stock by: - Calculation of line current spectrum including plausibility check by measurement - Calculation of harmonic voltage assessment using the method given in 4.3 - Check of interlacing between units as specified in 4.3.2.2 - Check of overvoltage protection as specified in 4.3.2.3 - If diode rectification is used to reduce risk of overvoltages check of correct transition between pulsing and blocking of line converter 5.3.2 Demonstration of compliance for static converters by: - Assessing the overvoltage by combining the converter with a line of variable length - defining the assessment method in time domain - plausibility check of the simulation model by measurement
	A.3	Technical background relating to overvoltages caused by harmonics including example calculations for rolling stock		
	B.3	Examples of real overvoltage experiences caused by harmonics		
Topics related to all phenomena	A.3	Depot cases		
	Annex C	Data related to the compatibility study of harmonics and dynamic effects		
	Annex D	Examples experienced in DC systems		

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1 Scope

This document is linked to EN 50388-1:2022, which describes the general technical criteria for the coordination between power supply and rolling stock to achieve interoperability.

This Part 2 establishes the acceptance criteria according to EN 50388-1:2022, 10.2 for compatibility between traction units and power supply, in relation to:

— co-ordination between controlled elements and also between these elements and resonances in the electrical infrastructure in order to achieve network system stability.

— co-ordination of harmonic behaviour with respect to excitation of electrical resonances.

The following electric traction systems are within scope:

— railways;

— guided mass transport systems that are integrated with railways;

— material transport systems that are integrated with railways.

Public three-phase grid networks are out of scope, but grid networks which are dedicated to railways are included.

This document is applied in accordance with the requirements in EN 50388-1:2022, Clause 10. It does not apply retrospectively to rolling stock or railway power supply elements already in service.

It is the aim of this Part 2 to support acceptance of new elements (rolling stock or infrastructure) by specifying precise requirements and methods for demonstration of compliance. This document acts as “code of practice” quoted in EN 50388-1, 10.2. However, it is still admissible to use the process as defined in EN 50388-1:2022, 10.3 instead.

This version of the standard only applies to AC systems. Later versions might include similar effects in DC networks in addition, see Annex D.

The main phenomena identified and treated in this document are:

— electrical resonance stability.

— low frequency stability.

— overvoltages caused by harmonics.

The interaction with signalling (including track circuits) is not dealt with in this document.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

CLC/TS 50238-2:2020, *Railway applications - Compatibility between rolling stock and train detection systems - Part 2: Compatibility with track circuits*

EN 50388-1:2022, *Railway Applications - Fixed installations and rolling stock - Technical criteria for the coordination between electric traction power supply systems and rolling stock to achieve interoperability - Part 1: General*

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EN 50163:2004,[1] *Railway applications - Supply voltages of traction systems*

EN 50160:2010, *Voltage characteristics of electricity supplied by public electricity networks*

3 Terms, definitions, abbreviations and symbols

For the purposes of this document, the terms and definitions given in EN 50388-1:2022 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1 Terms and definitions

3.1
new element
new, rebuilt or modified traction unit or power supply component (hardware or software) having a possible influence on the harmonic or dynamic behaviour of the power supply system

Note 1 to entry: This new element can be integrated in an existing power supply network with traction units e.g. for fixed installation:

— transformer;

— HV cable;

— filters;

— converter.

Note 2 to entry: Depot areas are a combination of equipment listed in note 1 associated with a large number of traction units and therefore very prone to harmonic and dynamic effects.

Note 3 to entry: New means also introduction of an existing element on another infrastructure system, i.e. “new to this infrastructure”.

3.2
power system
system which includes generation, distribution and consumption of electrical power, i.e. equal to the power supply system plus power circuits of all trains

3.3
power supply system
electrical power generation or distribution system for trains

Note 1 to entry: In railway systems this includes power stations and frequency converters, transmission lines, substations including HV impedance at the point of common coupling and contact line system as well as the return current circuits.

3.4
plausibility check
check of theoretical and calculation methods of assessment, generally based on measurement, to confirm that assessment predictions are credible and realistic

[1] As impacted by EN 50163:2004/A1:2007, EN 50163:2004/Corrigendum May 2010, EN 50163:2004/AC:2013, EN 50163:2004/A2:2020, EN 50163/A3:2022.

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3.5
anti-control
use of negative feedback control systems to reduce and limit the amplitude of a given harmonic frequency

3.6
static converter
converter having no moving parts and notably using semi-conductor rectifiers

Note 1 to entry: For the purpose of this document, this definition is used for fixed installations side only, example given frequency conversion, phase compensation, energy conversion.

[SOURCE: IEC 60050 811.19.05 – Modified: Note 1 to entry is added]

3.7
line converter
converter connected to the line or a line transformer which creates an intermediate link, mainly to supply a traction converter

Note 1 to entry: Derived from EN 61287-1:2014, 6.2.

3.8
active
behaviours of circuit elements which bring energy into the system at a defined frequency or frequency range

Note 1 to entry: In the given context, “active“(and also “passive“) is always defined for the small-signal behaviour only.

3.9
passive
behaviours which do not bring energy into the system at a defined frequency or frequency range

Note 1 to entry: The above definitions of “active” and “passive” apply throughout this document and differ from other definitions where “active” is used to designate a controlled element.

3.10
controlled element
electrical component or subsystem that has internal feedback loops controlling its output towards a set point

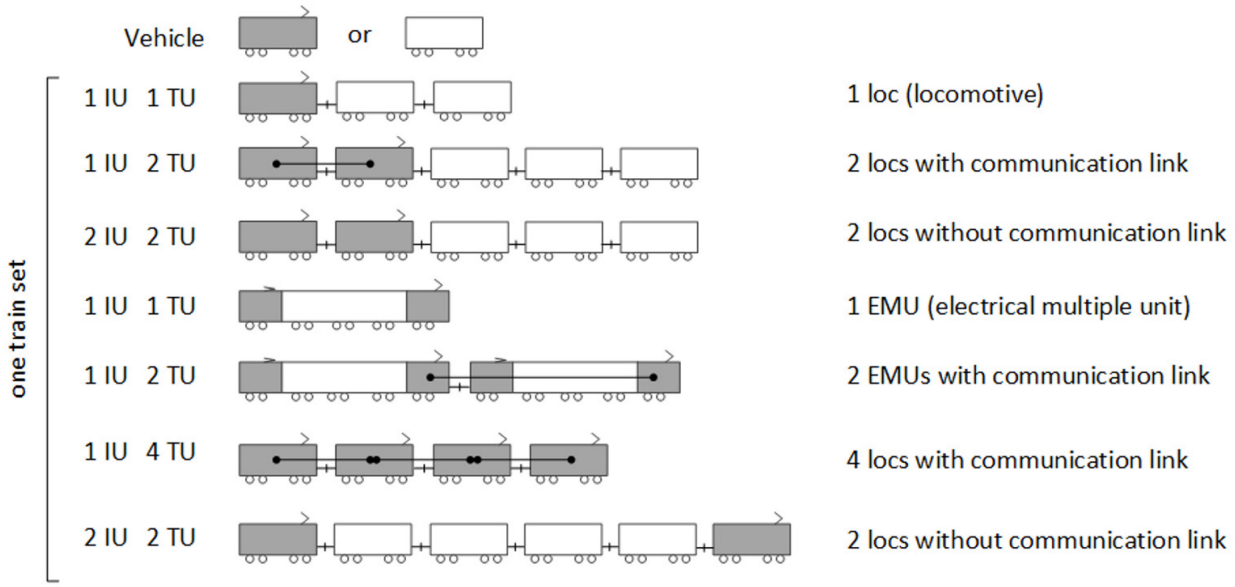
Note 1 to entry: In the scope in this document, controlled element will typically be power electronic converters on infrastructure or rolling stock. Controlled element can be active or passive at different frequencies.

3.11
traction unit
locomotive, motor coach or train unit

Note 1 to entry: Within this Part 2 a traction unit specifically comprises all traction subsystems including auxiliary supplies, which can be collectively switched off by one current collector / pantograph.

[SOURCE: IEC 60050-811:2017, 811-02-04, modified – The Note 1 to entry has been added.]

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Key

motor vehicles shown in solid grey

unpowered vehicles shown in white

NOTE In the case of an EMU, motorized axles are typically distributed throughout vehicles.

Figure 1 — traction unit and influencing unit

3.12
influencing unit
set of traction units forming a train which has a communication link in the on-board control system for the purpose of interlacing between the traction units

Note 1 to entry: One influencing unit (IU) may consist of several traction units (TU). TUs and IUs are defined slightly different from CLC/TS 50238-2. Only those TUs which are controlled from or get their reference values from one single master control unit are part of one IU. Independently controlled TUs (individual train driver, or different vehicle type) are not part of one single IU.

3.13
auxiliary converter
system with power conversion from one frequency (power supply system) to another (traction motor, auxiliary systems) by means of devices with fast control, such as PWM (pulse width modulation)

3.14
train line
conductor which extends throughout the whole length of each vehicle of a train with couplers to maintain electric continuity throughout the train

[SOURCE: IEC 60050-811:2017, 811-25-21]

Note 1 to entry: Practically, for the understanding of this document, UIC train busbar, heating train line, train power supply line are similar. See also UIC leaflet 552 (Electrical power supply for trains – standard technical characteristics of the train line).

3.15
AT system
traction power supply system in which energy transmission is at double the overhead line voltage and uses autotransformers (AT) to feed the overhead line

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3.2 Abbreviations and symbols

For the purposes of this document, the following abbreviations apply.

A/D	Analog/digital
AC	Alternating Current
AT	Autotransformer
DC	Direct Current
EMU	Electrical Multiple Unit
EC	European Commission
EU	European Union
ETCS	European Train Control System
HV	High Voltage
IGBT	Insulated Gate Bipolar Transistor
IM	Infrastructure Manager
IU	Influencing Unit
LRAS	Load Reference-Arrow System
MIMO	Multiple Input Multiple Output
PWM	Pulse width Modulation
RMS	Root mean square
RINF	Register of infrastructure
RL	Resistance of an Inductance,
RC	Resistance of a Capacitance
TSI	Technical specification for interoperability
TU	Traction Unit
U_{max2}	Highest non-permanent voltage defined in EN 50163:2004, 3.5
U_{max1}	Highest permanent voltage defined in EN 50163:2004, 3.4
U_n	Nominal voltage defined in EN 50163:2004, 3.3
U_{min1}	Lowest permanent voltage defined in EN 50163:2004, 3.7
U_{min2}	Lowest non-permanent voltage defined in EN 50163:2004, 3.8
v	Velocity

Other terms in the document are defined at the point of use within this document.

4 Requirements

4.1 Electrical resonance stability

Electrical resonance stability concerns the following phenomenon. The controllers of the line converters of rolling stock, but also the controllers of other line converters, containing feedback loops, which may make these systems active at certain frequencies. If such frequencies of active behaviour coincide with resonance frequencies of the power supply system, stability of the power system can be lost, depending on the damping at these frequencies.

The power system includes the power supply system with all its components in addition to all trains including running trains and parked trains with filters or cables which are connected directly to the power supply system. The requirements affect both design and operation of the power system (including degraded / emergency modes of feeding). Background information and examples can be found in A.1 and B.1.

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In order to prevent electrical resonances in the power systems from being excited to oscillations and corresponding overvoltages, the following requirements shall be fulfilled:

— The lowest resonance in the power system shall not fall below the limit frequency f_L.

— If it is not reasonably practicable to avoid resonances below f_L (e.g. due to harmonic filters or reactive power compensators), sufficient damping shall be provided, based on a stability analysis (see A.1.2) for the specific case.

— All controlled elements shall be passive for all frequencies higher than f_L, which means that the phase for its frequency dependent input admittance lies between ± 90°. See non-restricted and forbidden areas in Figure 2.

NOTE 1 There is no need for a stability margin since experience has shown that this sufficiently takes into account inaccuracies from measurements.

The above requirement concerns rolling stock, traction units, auxiliary converters connected to the train line as well as static converters in fixed installations feeding the power supply system.

— For equipment connected to the train line (1 000 V, 16,7 Hz or 1 500 V, 50 Hz), CLC/TS 50535 already makes reference to EN 50388-1 and EN 50388-2 for stability. In this case, the requirement is applicable for the input admittance seen between train line and ground. For Electrical Multiple Units (EMUs) with networks for auxiliaries with internal supply and return current, only the requirement at the pantograph of the EMU is applicable.

The limit frequency f_L is defined in Table 2 as follows:

Table 2 — limit frequency for resonance stability

Power supply frequency	16,7 Hz	50 Hz
Limit frequency f_L for resonance stability	87 Hz	300 Hz

NOTE 2 These values correspond to the 5th harmonic plus some tolerance for control and prediction of resonances in real systems. The following reasons justify the limit at the 5th harmonic:

— Strong line voltage distortions at 3rd and 5th harmonic can be present today. This is mainly due to the operation of vehicles with line commutated rectifiers. These line voltage distortions can lead to excessive harmonic voltage components in the DC-link voltage on inverter vehicles. In order to prevent the excessive harmonic voltages, it shall remain possible to actively reduce larger distortions of the line voltage up to the 5th harmonic. This active reduction can make rolling stock active around these frequencies. Thus, it is not possible to reduce the limit frequency to the 5th harmonic or below.

— With weakly damped networks with resonance near the 5th harmonic (or lower) switching on / energizing under no-load conditions can lead to continuous oscillations which are excited by the non-linearity of transformers (saturation of the iron core).

— Experience has shown that the bandwidth between the 5th harmonic and the f_L needs to be larger for 50 Hz power supply than 16,7 Hz, hence the limit frequency is 300 Hz rather than 270 Hz for 50 Hz power supply frequency.

Infrastructure managers may specify higher values of f_L in case compatibility between rolling stock and signalling equipment can only be reached by anti-control on board of rolling stock (which normally makes traction units active). Also in these cases, one single f_L is always valid as requirement for the whole infrastructure segment (power supply, rolling stock, operation). If an f_L value higher than the above needs to be chosen by the infrastructure manager, justification shall be given.

NOTE 3 Examples for different values for f_L in 16,7 Hz systems are:

— f_L = 103 Hz if 100 Hz track circuits are present

— f_L = 120 Hz in networks where old signalling equipment requires anti-control of the 7th harmonic

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Explanation: f_L = 103 Hz is necessary in case of networks having 100 Hz track circuits (100 Hz is a natural harmonic of the line frequency, which may lead to large harmonic currents during transients). In case of 95 Hz or 105 Hz_track circuits, no anti-control is needed, and f_L can remain on the standard value of 87 Hz.

Figure 2 illustrates the requirements for the frequency response of a traction unit.

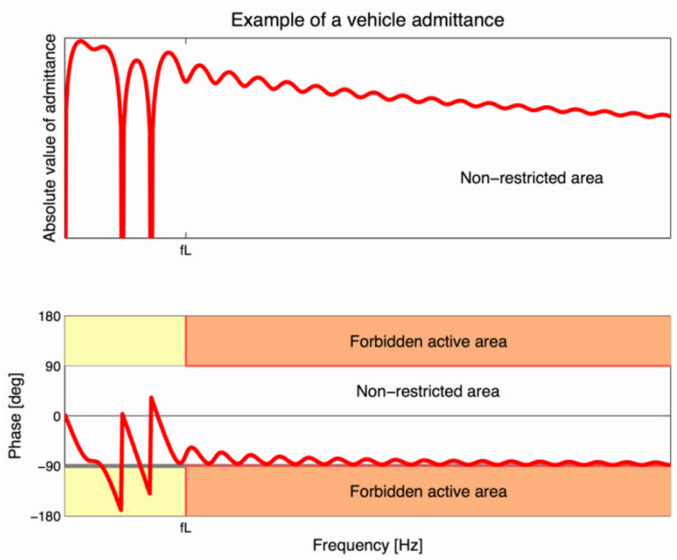


Figure 2 — Example of a frequency response of input admittance of a traction unit and forbidden zones of phase angle

With respect to line filter capacitors on board of rolling stock the following requirement applies to new rolling stock only (no modification on existing rolling stock as long as no problems are observed):

If there are no pulsed line converters in operation, the value of the effective capacitance per unit power (C_L) shall not exceed the value as defined in Table 3.

C_L is defined by the following formula using the imaginary part of the admittance at f_L and the installed power at wheel.

$C_L = \mathrm{Im}(Y(f_L)) / (2 \cdot \pi \cdot f_L) / P_{installed}$

Table 3 — Limits for C_L

Network frequency [Hz]	C_L [nF / MW] at f_L
16,7	210
50	25

NOTE 4 This requirement will be necessary in order to guarantee that, for example, parked trains do not lower the critical resonance frequency of a network too much. Values are selected so that the resonance frequency in a critical network (resonance around f_L) is not lowered by more than 3,4 Hz (in 16,7 Hz network) or 10 Hz (in 50 Hz networks) if the ratio between total installed power at wheel and substation power rating is 4. See A 4.2.

For infrastructure where compatibility with track circuit limits requires the installation of larger filters on vehicles, or if a large number of trains are stabled that have filters and/or cables which are connected directly to the power supply system, larger values of C may be allowed. If this is the case, the power supply might have to be adapted accordingly in order to maintain an acceptable value of f_L. This decision is the responsibility of the infrastructure manager.

For assessment of the above stipulated requirements, see 5.1.

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4.2 Low-frequency stability

4.2.1 Introduction

Low-frequency stability concerns oscillatory stability on frequencies below the line frequency (16,7 Hz or 50 Hz) due to feedback control loops. In the time domain, the resulting oscillations are amplitude and/or phase modulation of the fundamental AC voltage and current.

Such instability can appear when traction units with controlled line side converters are combined with power supply system impedances. The experienced consequences of such instability have been serious service interruptions even if no limit of overvoltages as defined in EN 50388-1:2022, 10.3 Table 6 is reached.

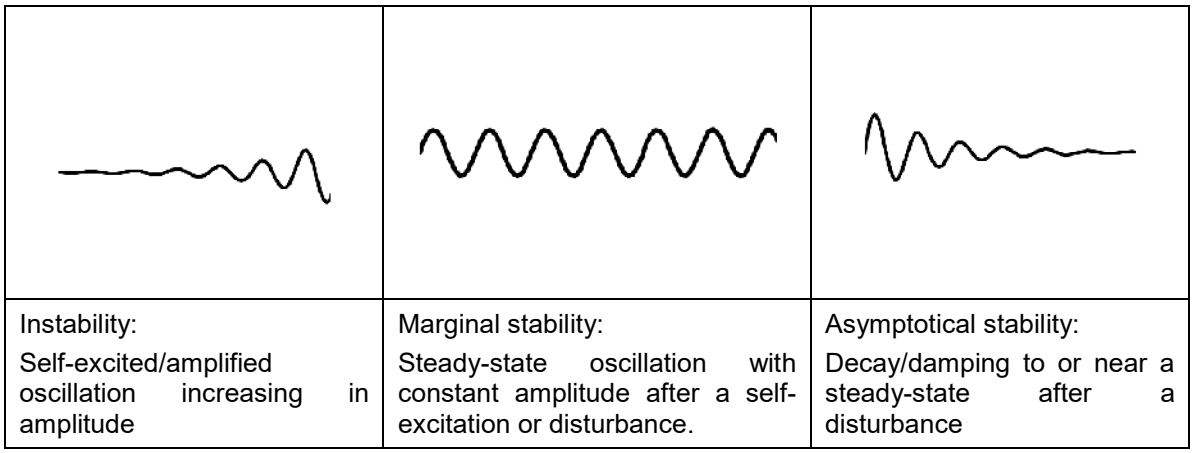
Background information and examples can be found in A.2 and B.2.

This clause treats low-frequency oscillations ~~stability~~ in general. Low-frequency stability due to continuous feedback control loops in generic traction power systems are in focus. Low-frequency oscillations due to repetitive and discontinuous controller actions, e.g. by protection functions, is only covered to a limited extent in the present version of this document. There are also networks having special low-frequency behaviour that need additional special attention as part of a compatibility study as required in EN 50388-1:2022, Clause 10.

NOTE One example of a network having special low-frequency behaviour is the Norwegian and Swedish railway fed by the rotary frequency converters without explicit motor damper windings and having a poorly damped electromechanical eigenfrequency.

4.2.2 General requirements

The general requirement is that the traction units and power supply system combined shall operate in a stable manner. This implies there shall be sufficient margins to instability, i.e. where self-excited and large steady-state oscillations can occur (see the qualitative illustration and explanation in Figure 3). The requirement applies to all electrical quantities, i.e. voltages and currents, and is illustrated for DC and RMS of AC quantities.



Instability:	Marginal stability:	Asymptotical stability:
Self-excited/amplified oscillation increasing in amplitude	Steady-state oscillation with constant amplitude after a self-excitation or disturbance.	Decay/damping to or near a steady-state after a disturbance

Figure 3 — Qualitative illustration of degree of stability

The acceptance criterion is that stable operation shall be ensured by traction units and infrastructure. To ensure stability, the two following requirements apply for realistic worst-case scenarios:

— The minimum decay shall be 1/4.

NOTE 1 As a target for future, stability is improved by having a decay of ½ or higher.

The decay is defined as the oscillation amplitude decay from one oscillation peak (x_n, y_n) to the next (x_{n+1}, y_{n+1}) of same sign as calculated by

$\Delta y = (y_n - y_{(n+1)})/(y_n - y_\infty)$

with y_∞ the final steady state value.

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— The peak-to-peak value of a steady-state oscillation in the RMS line voltage shall not exceed 1 % of *Un* (see EN 50163).

The predefined scenarios in Table 4 are expected to represent generic and realistic worst cases for a simplified railway system. This system is illustrated in Figure 4 with the following definition:

— a voltage source with fundamental frequency f_n and RMS voltage U_0;

— a linear network impedance *Z* with resistance *R* and inductance *L*; and

— one or several traction units of identical type at one location.

— in different operation modes and total load *Pl* given for power at wheel as defined in Table 4; No auxiliary power to be considered.

and

— with a minimum value of total installed maximum power at wheel P_{max} in the most powerful configuration it is intended to operate as a single train set (see Figure 1). For traction units having lower installed power, the number of traction units shall be scaled up to meet this least condition as it is intended to work in the specific operation mode and configuration.

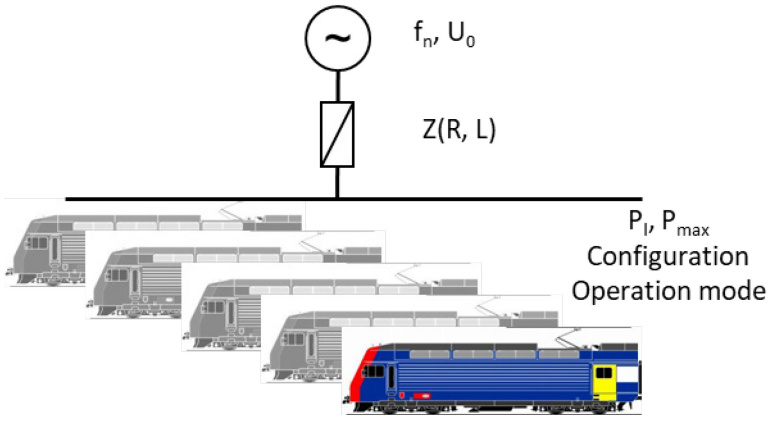


Figure 4 — Simplified combined system with scaling of number of traction units to fulfil least requirement on total installed maximum power at wheel.

Table 4 — Parameters for low-frequency stability scenarios with pulsing traction unit line converters

				Infrastructure			Traction unit	
ID	Traction unit operation mode : Description	f_n [Hz]	U_0 [kV]	R [Ω]	L [mH]	Z [Ω]	P_l [MW]	P_{max} [MW]
A1	Traction: Medium impedance	16,7	16,5	3,7	58,8	7,2	5	> 6
A2	Braking: Medium impedance	16,7	16,5	3,7	58,8	7,2	−4	> 6
A3	Traction: High impedance	16,7	16,5	10,9	130	17,5	1	> 6
A4	Braking: High impedance	16,7	16,5	10,9	130	17,5	−1	> 6
A5	No-load: Very high impedance	16,7	16,5	21,8	237	33,1	0	> 6
A6	Parking mode: Depot	16,7	16,5	0,13	23,8	2,5	0	200
A7	Parking mode: Small depot	16,7	16,5	22,9	312	40	0	18
B1	Traction: Medium impedance	50	26,5	5,2	66,1	21,4	5	> 6
B2	Braking: Medium impedance	50	26,5	5,2	66,1	21,4	−4	> 6

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B3	Traction: High impedance	50	26,5	9,47	108	35,2	2	> 6
B4	Braking: High impedance	50	26,5	9,47	108	35,2	−2	> 6
B5	No-load: Very high impedance	50	26,5	18,0	191	62,8	0	> 6
B6	Parking mode: Depot	50	26,5	0,24	14,3	4,5	0	150

NOTE 2 For practical consideration of scenarios the parameters in Table 4 can be adopted by altering the linear network impedance (Z) and traction unit power (P_I and P_{max}) if their products ($Z.P_I$ and $Z.P_{max}$) and the impedance's R/L ratio remains unchanged. Example for A6: $Z.P_{max}$ = 2,5 × 200 = 500 MW. Ohm equivalent to $Z.P_{max}$ = 100 × 5 MW.Ohm.

NOTE 3 Higher values of $Z.P_{max}$ are under investigation and might be necessary for future revision of this document, see A.2.3.

NOTE 4 Simple interface requirements for single components or subsystems is an open point for future revisions of this document. Until then, additional specifications to components or subsystems are detailed in 4.2.3 to 4.2.5.

NOTE 5 Stability of several different types of traction units together is an open point for future revisions of this document and are until then considered covered by these identical type scenarios.

NOTE 6 Stability of rolling stock together supplied by more complex infrastructure, e.g. static frequency converters or compensators, is an open point for future revisions of this document and are until then considered covered by Table 4 and 4.2.4.

NOTE 7 Specific scenarios for special charging tracks for onboard energy storage for traction purposes is an open point for future.

For assessment of the stipulated requirements, see 5.2.

4.2.3 Rolling stock

For parked traction units in depot parking mode the following applies:

To reduce the low-frequency dynamics and improve stability of the power system, parked traction units should switch-off line converter pulsing and apply diode rectification. This is specifically beneficial when consumed power (e.g. for auxiliaries) is lower than 15 % of the maximum power at wheel, see A.4.3.

— Rare and random events on individual traction units forcing line converter short-term pulsing are still acceptable and depot scenarios in Table 4 are not applicable. Examples are starting a compressor or shunting.

— Frequent or synchronised events on several traction units forcing line converter short-term pulsing shall still be treated according to the scenarios in Table 4 with pulsing converters. Examples are reacting to line-side DC currents saturating the transformer or violating harmonic current limits, short-term pulsing periods of line-side converters, or start of pulsing at high power given by ambient temperature.

To avoid low-frequency oscillations during traction and braking due to repetitive and discontinuous controller actions, e.g. by protection functions, traction units may be able to reduce power fast, but only ramp up power again slowly.

4.2.4 Static converters

Specific requirements for static power supply system converters and static compensators are not yet covered by this document. The compatibility process in EN 50388-1:2022, Clause 10 shall be followed.

NOTE The main contributor to low-frequency dynamics and instability in the scenarios specified in Table 4 are experienced to be the traction units. Experience has shown that converters qualitatively provide far better stability (damping) than required and targeted in 4.2.2.

4.2.5 Infrastructure

If the scenario under consideration is outside the frame given by the product of linear network impedance (Z) and total installed maximum power at wheel (P_{max}) set by the worst-case scenarios in Table 4, the compatibility process in EN 50388-1:2022, Clause 10 shall be followed.

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NOTE Examples are given as application of Table 4:

— A depot having tracks for 10 traction units of 10 MW is designed. Pmax is then 100 MW 16,7 Hz power supply impedance is 2 Ohm. The product $Z.P_{max}$ is 200 MW.Ohm. The expected rail operation under consideration is within the given frame in Table 4 scenario A6 ($Z.P_{max}$ = 2,5 × 200 = 500 MW·Ohm).

— A depot having tracks for 20 traction units of 10 MW is designed. Pmax is then 200 MW 16,7 Hz power supply impedance is 3 Ohm. The product $Z.P_{max}$ is 600 MW.Ohm. The expected rail operation under consideration is outside the given frame in Table 4 scenario A6.

4.3 Overvoltages caused by harmonics

4.3.1 General

Overvoltages caused by harmonics concern the following phenomenon: Harmonic currents, produced by the pulsing of line converters in rolling stock or by the pulsing of static converters, can be amplified by electrical resonances in the power systems, which can result in overvoltages. For this overvoltage phenomenon no feedback loop effect is present. Background information and examples can be found in A.3 and B.3.

4.3.2 Rolling stock

4.3.2.1 Area of application

The following requirements apply to new rolling stock with conventional transformers and PWM line converters. In case overvoltages occur in the presence of traction units with phase angle-controlled converters, the situation shall be analysed, and mitigation measures shall be defined, using the compatibility process of EN 50388-1:2022, Clause 10. If, with non-conventional new propulsion systems, the stipulated requirements cannot be met, they shall be treated according to the compatibility process of EN 50388-1:2022, Clause 10.

4.3.2.2 Generation of harmonic currents

This chapter aims to define design limits for rolling stock by specifying overvoltage requirements which need to be met in several representative scenarios.

In order to prevent overvoltages caused by harmonics occurring in AC railway power systems, the following requirements shall be fulfilled by rolling stock:

For a number of *N* independent influencing units (IU) of identical type, the expected RMS value for the harmonic line voltage $U_H(f0)$ for a range of possible resonance frequencies *f0*, with $f_L \leq f0 \leq f0max$ (f_L = 87 Hz or 300 Hz respectively, same values for as for resonance stability)shall be calculated as follows in this chapter and shall be below U_{maxH} according to the values in Table 5:

Table 5 — Values for U_{maxH}

Power supply system	15 kV 16,7 Hz	25 kV 50 Hz
U_{maxH}	3,2 kV	6,4 kV
NOTE The stated values for U_{maxH} are derived from: $U_{maxH} = U_{peak}/\sqrt{2} - U_{max2}$ and U_{peak} = max. allowed peak voltage of the supply system according to EN 50388-1:2022, 10.6. Short-term limits are applied since the current spectrum of a vehicle changes over time as well as the position of the vehicle along the line. U_{max2} = max. voltage according to EN 50163.		

This limit applies to an IU in all its operation modes. Requirements for degraded modes (e.g. one bogie out of operation due to a hardware failure) are relaxed by means of a different definition of factor *N* (number of IUs).

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N is calculated from the maximum power at wheel of the influencing unit P_{max} and rounded to the next higher integer number. The IU shall hold the limit for all six representative cases contained in Table 6.

Table 6 — Definition of *N* number of influencing units (IU) for the calculation cases

	Impedance at resonance Z_{res}	
Number of IUs	**200 Ω Interconnected network [a]**	**2 000 Ω Isolated network [b]**
***N* (normal operation)**	150 MW / P_{max}	50 MW / P_{max}
***N* (degraded operation)**	6	1
***N* (standstill and no tractive effort; applies for pulsed line converters only)**	200 MW / P_{max}	150 MW / P_{max}
NOTE Two representative values of power supply impedances are considered for the different conditions in an interconnected or an isolated network, for further details see also A.3.1. [a] Interconnected network: where substations are interconnected via the contact line. [b] Isolated network: where substations are not interconnected via the contact line.		

$U_H(f0)$, the expected harmonic voltage at resonance, is calculated as follows:

$$U_H(f0) = Z_{res} \cdot I_{IU0}(f0) \cdot k_Z(f0) \cdot k_N$$

with

Z_{res} = standardized value for the maximum impedance at resonances; this is resistive (no imaginary part) (see Table 6).

$I_{IU0}(f0)$ = bandpass-filtered line current of the influencing unit (see below).

$k_Z(f0)$ = reduction factor, modelling the feedback effect via the line impedance in a simplified way (see below)

k_N = factor taking account summation of harmonics between different IUs

$I_{IU0}(f0)$ is calculated as follows:

— simulation of the total line current of the IU, at nominal voltage and ideal sinusoidal supply voltage with zero line impedance, and operation at maximum power and with maximum regulated DC link voltage.

NOTE 1 The simulation of the total line current needs to consider the different operation modes normal operation, degraded operation and standstill

— the effect of on-board line filters shall be included

— subtraction of the fundamental harmonic (line frequency) component from the total line current

— multiple bandpass filtering as follows:

  — each bandpass filter with centre frequency *f0*, and *f0* shall be increased to sweep the range from f_L up to $f0_{max}$

  — difference between two *f0* sufficiently small so that no higher values for $U_H(f0)$ are disregarded for frequencies between them

  — $f0_{max}$ sufficiently high to guarantee that $U_H(f0)$ can only decrease below already reached values if *f0* is further increasing

NOTE 2 In typical rail vehicles the peak of $U_H(f0)$ is reached at the first or second characteristic switching frequency band, see also A.3.3.

  — 2nd order (= 2 . 1st order) bandpass filter, with 3 dB bandwidth = 0,1 x *f0*.

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NOTE 3 This characteristic is adapted to typical resonances in the railway power supply system, see also A.3.2.

Since the 2nd order bandpass filters with a bandwidth of 0,1 x *f0* include several line harmonics (for which the superposition requires correct amplitude and phase information), the evaluation shall be made in time domain from the line current.

— $I_{IU0}(f0)$ is then the highest value reached over one line period in steady-state of the bandpass filtered current divided by square root of 2, for each centre frequency *f0*

$k_Z(f0)$ is calculated as follows:

$$k_Z(f0) = |Z_{veh}(f0)| / (N.Z_{res} + |Z_{veh}(f0)|)$$

— Z_{res} = standardized impedance at resonance (see above)

— $Z_{veh}(f0)$ = impedance as seen from the power supply into the IU, with internal voltages set to zero (considering only passive elements of the IU). Filters of the IU aimed to filter the line current shall be included. Roof cable capacitances connected directly to the line voltage as well as parasitic effects inside the line circuits (e.g. transformer capacitances) shall be neglected, since their influence is included in the general effect of resonance amplification. $Z_{veh}(f0)$ shall be based on a frequency extrapolation of the impedance at the fundamental frequency.

— *N* is the required number of IUs (see Table 6)

NOTE 4 The purpose of k_z is to calculate the actual line current of the IU injected in the network, denoted by I_{IU} in Figure 5 as a function of I_{IU0}: $I_{IU} = k_z \cdot I_{IU0}$. The calculation of $k_Z(f0)$ can be illustrated for the simplified equivalent circuit diagram for *N* IUs (left), combined into one single unit with modified line parameters (right). The voltage at pantograph U_L is identical in both cases.

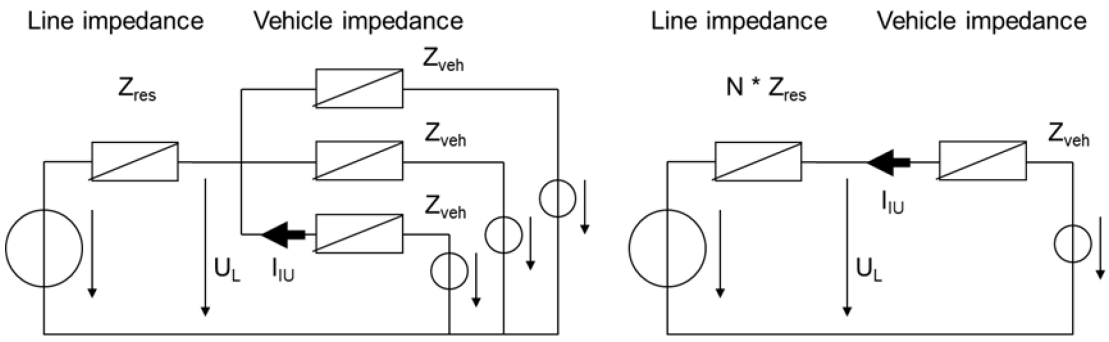


Figure 5 — Illustration of $k_z(f0)$

k_N is defined as follows:

— if random displacement of the switching angles between different IUs is applied, k_N is shown in Table 7)

Table 7 — Values for k_N if random displacement of the switching angles between different IUs is applied

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
k_N	1	1,95	2,76	3,38	3,86	4,27	4,63	4,98	5,30	5,60	5,90	6,17	6,44	6,68	6,91	7,12

if *N* > 16: k_N results from linear interpolation of *N* = [16, 1600] and k_N = [7,12; 71,2] in a double-logarithmic scale

NOTE 5 These factors for $N \leq 16$ are identical to the factor *kI* for superposition of harmonics with equal magnitude, but random phase as defined in CLC/TS 50238-2:2020, B.8.2.

— if no random displacement is applied: $k_N = N$

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4.3.2.3 Overvoltage detection

The overvoltage detection defined in this subclause is recommended for all rolling stock equipped with line voltage measuring devices which are not showing resonances at the characteristic harmonics band of the line side converters.

Traction units should be equipped with protection against peak voltages on the supply voltage. If the peak voltage (defined as the highest value during one half of a fundamental period of the line frequency) continuously (i.e. in each line period) exceeds the value defined in Table 8 for more than the defined time t_1, the traction converters should stop pulsing, and a diagnosis message should be recorded. Line converters can be restarted after some time t_2 (this time can be coordinated with other protection functions of the traction converter). If the exceedance repeatedly occurs for more than t_3, the line converters should be blocked. Otherwise, there is a risk that surge arrestors may be overloaded and cause short circuits in the supply system. A restart should be possible after manual intervention by the train driver.

NOTE 1 The handling of such a case by the driver is defined in the relevant operational procedures of the network.

Table 8 shows the limits for the peak voltage for both network frequencies.

Table 8 — Limits for the peak voltage monitor

Network frequency	Periodic peak voltage for protection	Time duration t_1	Time duration t_2	Time duration t_3
16,7 Hz	32 kV [a]	1 s [b]	3 s ... 5 s	20 s
50 Hz	53 kV [a]	1 s [b]	3 s ... 5 s	20 s

[a] Values are derived from max. allowed values according to EN 50388-1:2022, 10.3, Table 6 plus about 6 %

[b] This value allows for pantograph bouncing without further intervention

Existing voltage sensors can be used on board rolling stock. No installation of precision sensors with a high accuracy and / or high bandwidth is required. Parameters for the protection functions in the software should be selected to guarantee the best possible correspondence with the voltage defined in Table 8, for a frequency range up to about 5 000 Hz, as far as existing measuring devices allow it. This detection can also be realized by undersampling and does not require a sampling rate of 10 000 Hz (theoretically necessary for precise detection).

NOTE 2 This protection mechanism will:

— Prevent surge arresters from taking too much energy and fail in critical cases.

— provide data to Inform the infrastructure manager about the presence of such critical cases, which would be otherwise undetected and could lead to faults in the power systems later (premature ageing, disruption of operation).

4.3.2.4 Diode rectification

In order to lower the risk of overvoltage caused by harmonics, following measure should be used. When the power of a traction converter is low, and the vehicle is at standstill and does not require tractive or electric braking effort, the line converters should stop pulsing, and only the freewheel diodes shall carry the load current. If this operation mode is chosen, it shall be applied if the power is lower than the value defined in Table 9 (for the background see Annex A). A hysteresis can be applied to avoid repetitive start and stop of pulsing of the line converters already due to low variations in consumed power.

Table 9 — use of diode rectification

Network frequency	Instantaneous power divided by the maximum power at wheel
16,7 Hz	15 %
50 Hz	15 %

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