Compatibility between railway infrastructure and vehicles

This document gives an overview of known electromagnetic compatibility issues between railway infrastructure and vehicles. The document can serve both as a tutorial and as a checklist for infrastructure modification or vehicle acceptance projects.

Tests with DB's class BR185 and SNCB's class 13 in Wasserbillig, Luxembourg, 2001.

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1 Introduction

1.1 Abstract

In many countries, the introduction of modern semiconductor and computer controlled electrical rail vehicles and locomotives has been anything but a smooth and easy evolution from one technology to the next.

It is the purpose of this document to list and shortly describe the electrical interfaces and the problems of electromagnetic compatibility between the infrastructure (i.e., the power supply and the signalling systems) and the vehicles (locomotives, electric multiple units) of an electrified railway system.

The short descriptions given in the document are generally too brief to serve as more than an introduction to each problem, or a reminder that this problem exists and should be considered for example in a rebuild project or when introducing a new vehicle into the system. More detailled information can be found in the references listed in each chapter, or in the technical reports that are planned to follow of the present report.

The document is roughly organised along the frequency axis, meaning that the first chapter deals with problems related to DC and ultra-low frequencies, and the following chapters with increasingly higher frequency ranges.

Below each section, one or more chapters details the various issues that have been identified. Each chapter contains the following paragraphs:

1.1.1 Description

A short description of the phenomenon.

1.1.2 Symptoms and Consequences

The typical way in which a user may identify that this phenomenon exists, and the consequences of the phenomenon upon safety, reliability, availability, etc.

1.1.3 References

The projects or railways where the phenomenon has occurred, and/or references to litterature, technical articles, standards, etc.

1.1.4 How to avoid

"Best practice", i.e., the things to consider when specifying or designing systems or components for the railway, in order to avoid that the phenomenon occurs at all, or in order to minimise its severity.

Not all paragraphs may be relevant in each chapter. In such cases, the term N/A (not applicable) has been used.

1.2 Definitions and Abbreviations

4QC	Four-Quadrant Converter
AC	Alternating Current
AC-AC	Definition of a rail vehicle that is supplied from an AC line, and equipped with 3-phase AC motors
AT	Auto-Transformer
BT	Booster-Transformer
CFL	Société Nationale des Chemins de Fer Luxembourgeois, Luxembourg State Railways
DB	Deutsche Bundesbahn, German Federal Railways
DC	Direct Current
DSB	Danske StatsBaner, Danish State Railways
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
OHL	OverHead Line
PWM	Pulse Width Modulation
RSF	Right Side Failure (e.g., green signal turning into red)
SNCF	Société Nationale des Chemins de Fer Françias, French State Railways
TGV	Train a Grand Vitesse, French high-speed train
UK	United Kingdom
WSF	Wrong Side Failure (e.g., red signal turning into green)

1.3 Acknowledgements

The general structure of the document, as well as some parts of the text, has been inspired/borrowed/stolen from a similar document written by my good friend and deeply respected colleague Markus Meyer, Emkamatik, in one of our joint projects for the Swedish and Norwegian infrastructure authorities Banverket and Jernbaneverket.

Please visit Markus and his equally nice colleagues Stefan, Thomas, and Markus here.

2 DC and Ultra Low Frequency Currents

2.1 Nearby DC Railways or Metros

2.1.1 Description

The traction return currents from nearby DC-supplied railways, metros, or tram lines, may leak away from the running rails and find their ways into other infrastructure systems.
This can be seen where a DC line runs in parallel to the AC railway, or at the system border where a railway line changes from one supply system to another.

2.1.2 Symptoms and Consequences

Saturation of transformers (supply, booster, AT, locomotive transformers, etc.)
Even harmonics.
DC track circuit WSF or RSF.

2.1.3 References

Deutschmann, P.; Schneider, E.; Zachmeier, M.: Bahnrückstromführung und Erdung bei Bahnanlagen, Teil 1, 2, 3. Elektrische Bahnen 96 (1998), H. 4, S. 85-106.

Deutschmann, P.; Röhlig, S.; Smulders, E.: Parallelbetrieb von AC- und DC-Bahnen: Ziele der neuen EN 50122 Teil 3. Elektrische Bahnen 103 (2005), H. 4-5, S. 191-197.

Cineri, E.; Buffarini, G. G.; Fumi, A.; Salvatori, V.: Interference assessment at the interface between 2 AC 25 kV 50 Hz and DC 3 kV systems. Elektrische Bahnen 102 (2004), H. 12, S. 551-557.

Hofmann, G.; Röhlig, S.; Groeman, F.; Bogaerts, T.: Trennstellen AC 25 kV / DC 1.5 kV im Oberleitungsnetz der Niederländischen Bahnen. Elektrische Bahnen 100 (2002), H. 6, S. 220-225.

2.1.4 How to avoid

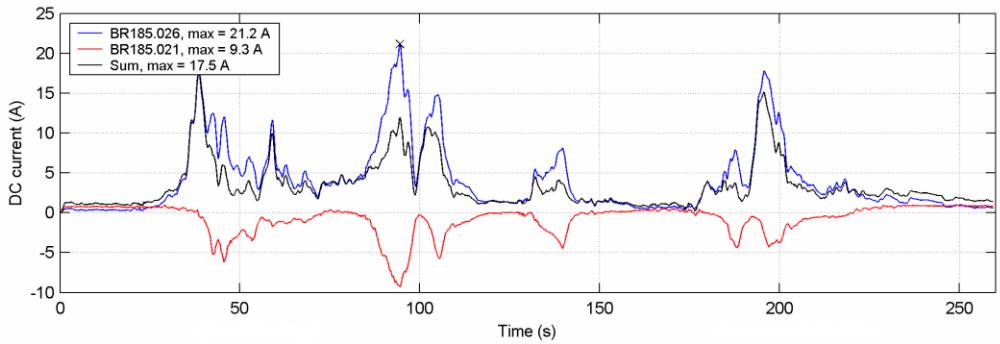
The articles referenced above lists general design rules and experiences.

2.2 Ice on the Overhead Line

2.2.1 Description

Ice or frost on the OHL cause the carbon strip on the pantograph to become separated by a small distance from the cobber contact wire, this in turn causing the formation of an arc. Due to the different electrochemical properties of the materials involved, the voltage drop across the arc is higher in one current direction (i.e., one half period of the 50 Hz fundamental) than the other. This effectively means that the arc forms a small DC voltage source.

The DC current path is closed via the primary winding of the main transformer, the catenary system and return current rail, and the substation transformer. Other trains on the line may also be part of the return path.



Recorded DC components during tests with two BR185 locomotives in multiple operation on CFL's Northern Line.

2.2.2 Symptoms and Consequences

Excessive wear-out of the carbon strip of the pantograph.
Saturation of transformers (supply, booster, AT, locomotive transformers, etc.)
Even harmonics.
DC track circuit WSF or RSF.

2.2.3 References

Buhrkall, L.: DC components due to ice on the overhead contact wire of AC electrified railways. Elektrische Bahnen 103 (2005), H. 4-5, S. 380-389.

2.2.4 How to avoid

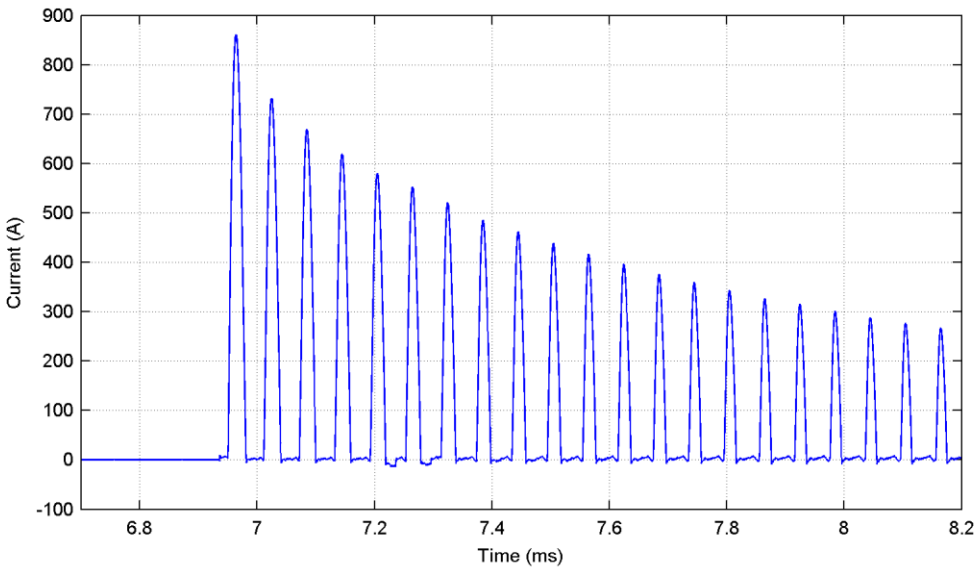
This phenomenon cannot be avoided. The severity may be reduced by running the locomotive with two pantographs raised (if acceptable when crossing neutral sections), by selecting other materials than carbon for the pantograph strip, or by designing the primary winding of the main transformer with a high DC resistance, but both of the two latter remedies have other serious drawbacks (increased contact wire wear-out, power losses)

2.3 Transformer Inrush

2.3.1 Description

If the main circuit breaker of the vehicle is closed at or near the zero-crossing of the supply line AC voltage, the main transformer will become magnetically saturated. This causes the magnetising current waveshape to become very high and greatly asymmetrical, i.e., the current contains a transient DC component of a significant magnitude.

The highest DC levels, and also the highest peak currents, are seen if the remanent magnetisation of the main transformer since the last time the main circuit breaker was opened, lies in the same direction as the magnetisation from the first line voltage half-wave.



Inrush current (measured in a 16.7 Hz system)

2.3.2 Symptoms and Consequences

Saturation of transformers (supply, booster, AT, locomotive transformers, etc.)
High peak currents potentially causing protecion systems to be activated
Even harmonics.
DC track circuit WSF or RSF.

2.3.3 References

N/A

2.3.4 How to avoid

The closure of the main circuit breaker may be synchronised to the line voltage waveshape such that the closure takes place at the peak of the sine wave. However,

since the main circuit breakers are mechanical devices with slightly individual characteristics, this is difficult in a 50 Hz system.

If the main transformer is equipped with a filter winding, then the filter will provide a path for a demagnetising current such that the remanent magnetisation is always zero.
The resistance and main inductance of the transformer can, within certain limits, be optimised in order to minimise the magnitude and/or the time durarion of the DC transient.

2.4 Northern Lights

2.4.1 Description

The electromagnetic ’solar storms’ that are also the causes for Northern Ligths can induce ultra low frequency currents in long electric power lines, including railway catenary systems. This has been experienced in both Sweden and Canada.

2.4.2 Symptoms and Consequences

Saturation of transformers (supply, booster, AT, locomotive transformers, etc.).
Even harmonics.
DC track circuit WSF or RSF.

2.4.3 References

N/A

2.4.4 How to avoid

N/A

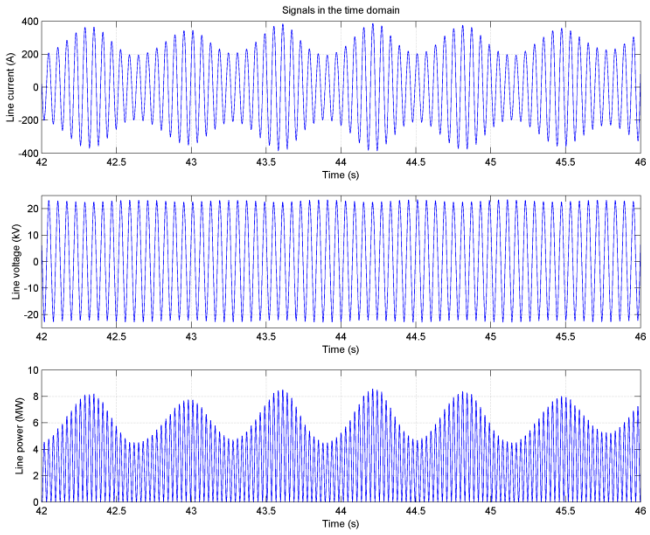
3 Low Frequency Phenomena

3.1 Vehicle Power Control

3.1.1 Description

The control of the power flow to or from an AC-AC vehicle is performed by a closed-loop control system that basically aims for maintaining a constant voltage across the DC link of the converter system at any given power condition. This is basically a constant power control, and has the consequence that the real part of the dynamic or ”small-signal” input impedance of the vehicle is negative. Clearly, adding negative resistance to a system reduces it’s stability margin, and quasi-stable or unstable operation has been observed in many cases. So far, no design rules or standards exist.

These phenomena becomes increasingly more critical as the number of vehicles in any given place increases. Doubling the number of vehicles corresponds to doubling the gain in the feedback loop as well as the negative resistance; i.e., the damping is correspondingly reduced.



Measured time domain signals (current and voltage, power signal obtained by multiplication of the two) from a 16.7 Hz vehicle at severe power oscillation.

3.1.2 Symptoms and Consequences

Amplitude and/or phase modulation of line voltage and current
Power and torque oscillations
Flickering in lights
Longitudinal train oscillations
Mechanical stresses in the bogie and in couplers
Protective shut-down of the vehicle or the power supply

3.1.3 References

Menth, S.; Meyer, M.: Low frequency power oscillations in electric railway systems. Elektrische Bahnen 104 (2006), H. 5, S. 216-221.

Several presentations on the workshops ”Interaction between Power Supply and Rail Vehicles”, Thun 04-05-2006 and 04-06-2009.

3.1.4 How to avoid

Compatibility process according to EN50388
Proper design of control systems, supported by simulations including parameter variations
Tests of actual hard- and software in real time simulators
Type tests to valdate the simulations
Active oscillation damping via the DC link voltage reference

3.2 Repetetive Controller Actions

3.2.1 Description

Several control systems in a vehicle operate in a discontinuous way, e.g., the slip-slide control. The fast torque and power reduction in case wheel slip is being detected causes the power supply to react with a step response which is not critical in itself. However, if the action is continued repetetively and with a frequency close to an eigenfrequency of the supply system or of the mechanical systems, oscillations may occur.

3.2.2 Symptoms and Consequences

Amplitude and/or phase modulation of line voltage and current
Power and torque oscillations
Flickering in lights
Longitudinal train oscillations
Mechanical stresses in the bogie and in couplers

3.2.3 References

N/A

3.2.4 How to avoid

Compatibility process according to EN50388
Proper design of control systems, supported by simulations including parameter variations
Tests of actual hard- and software in real time simulators
Comprehensive tests in order to optimise the performance of the adheson control

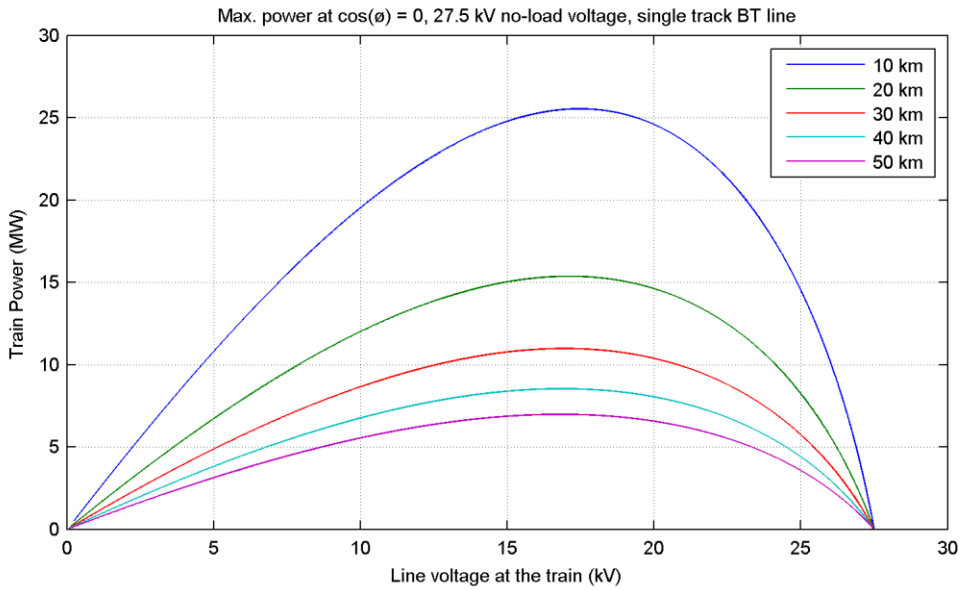
4 Power Transmission

4.1 Supply Power Limitation

4.1.1 Description

The power that can be transferred by the supply line is limited by both the resistive and the reactive voltage drop at the fundamental voltage. Since the cross-section geometry of a OHL system is in general the same for 16.7 Hz and 50 Hz, the series inductances are also more or less equal. However, due to the the 3-fold difference in frequency, the reactive voltage drop tends to be three times higher on 50 Hz lines.

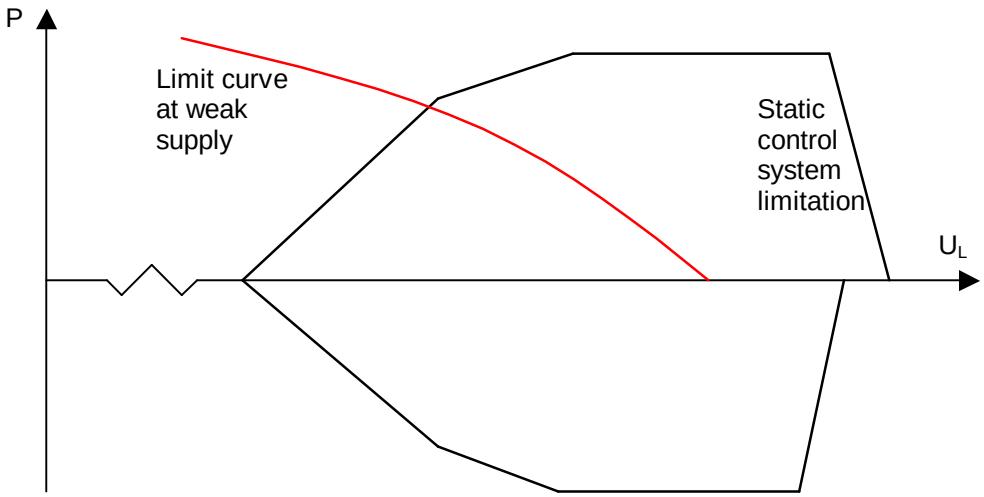
Imagine that a variable resistor is connected at the end of a long feeding section, and then (hypothetically) varied continuously in the range from infinity to zero ohms. This would cause the power losses in the resistor to first be zero (at $R \approx \infty\ \Omega$), then increase and reach a maximum at some intermediate resistance, and then decrease to zero as the resistance becomes 0 Ω. A similar hypothetical exercise can be performed with a generator, generating voltages in phase with the supply voltage and with amplitudes from the no-load level and upwards (i.e., a negative resistance).



Max power at the train at different feeding lengths, cos(φ) = 0.

The control systems of the vehicle are typically designed with limit curves for the vehicle current (or power) vs. frequency. At the lower end of these curves, the current is ramped down quite steeply as the voltage drops. This may lead to power oscillations if, for some reason, the voltage suddenly drops (e.g., due to another vehicle). The reduced voltage causes the first vehicle to rapidly reduce its power. This in turn reduces the voltage drop across the supply impedance, and the voltage increases. The vehicle increases the power again, the voltage drops, and the sequence repeats.

In order to ensure a stable operation, the dP/dU slope in the vehicle control must not be too steep.



Line power limit at weak supply, and static limitations in the control system

The line voltage drop and thus the maximum power that can be transferred depends also on the cos(φ) of the load, as discussed in the next section.

4.1.2 Symptoms and Consequences

Line voltages outside the specified range
Line voltage collapse
Reduced system performance
Damage to components and subsystems

4.1.3 References

N/A

4.1.4 How to avoid

Improved infrastructure (e.g., more parallel feeder and return current conductors, shorter feeding distances, autotransformer systems)
Cos(φ)-control (see next section)

4.2 Cos(φ) Control

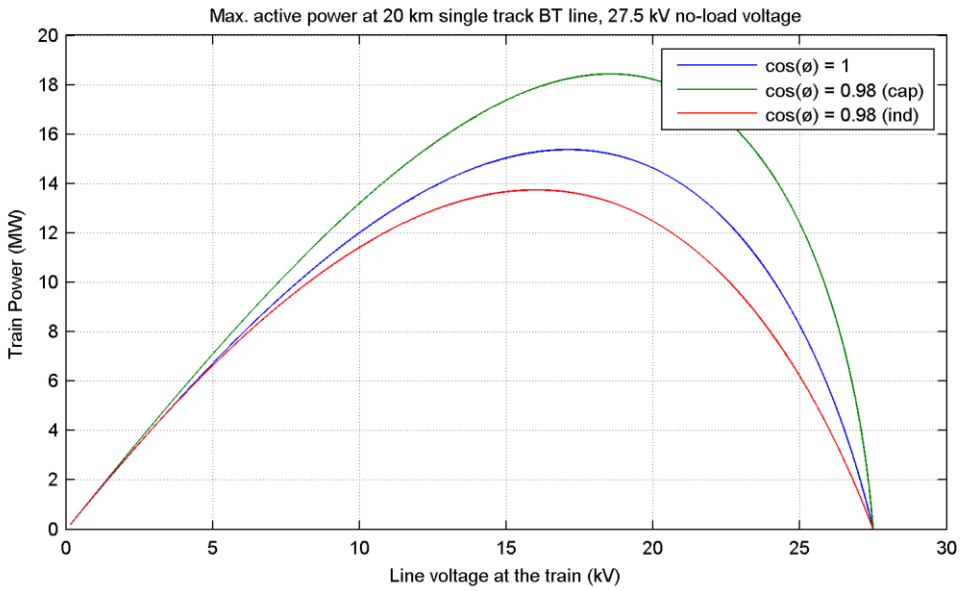
4.2.1 Description

AC-AC vehicles equipped with 4QC line converters are capable (in principle) of a free control of the phase angle φ between the line voltage and line current fundamentals, within the voltage and current limits of the system. Normally this is utilised to achieve a cos(φ) close to unity, but other control strategies may be beneficial:

- Consuming reactive power (inductive operation) in electric braking keeps the line voltage lower, compared to cos(φ) = -1
- Generating reactive power (capacitive operation) in driving acts as an ordinary phase compensation

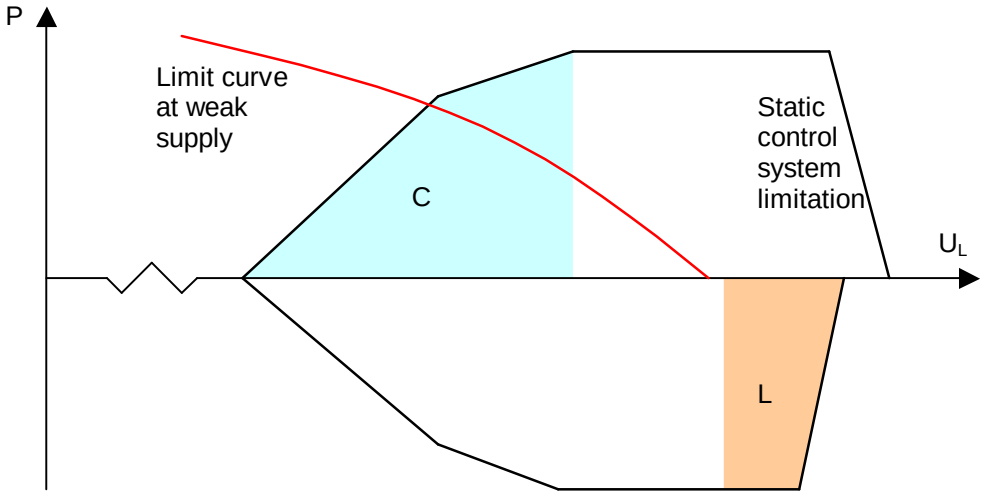
Capacitive operation in regenerative braking is normally not desirable, due to issues with both the voltage level and the protection systems (distance relays).

Inductive operation in driving leads to a reduction of the power transmission performance of the supply system, and is normally not preferred.



Cos(φ)-control in driving

The inductive braking and capacitive driving should be limited to the situations where it is required, i.e., at high line voltages in braking and low line voltages in driving.



Reasonable areas for inductive and capacitive operation.

Please notice that the terms 'inductive' and 'capacitive' in this context applies to the fundamental only, and says nothing about the characteristics or the behaviour of the vehicle at other frequencies. In other words, capacitive operation at the fundamental does not generally turn the vehicle into the equivalent of a capacitor. The active control makes it possible (and is used accordingly) to apply different characteristics at (in principle) any frequency[1].

4.2.2 Symptoms and Consequences

A poorly adjusted cos(φ) control may lead to too low line voltage levels at the train, and even line voltage collapse.
Reduced train and system performance.
Excessive power losses due to reactive currents

4.2.3 References

Appun, P.; Lienau, W: Der Vierquadrantensteller bei induktivem und kapazitivem Betrieb. EtzArchiv Bd. 6 (1984) H. 1

4.2.4 How to avoid

Apply a careful cos(φ)-control that depends on line voltage and operation mode:
Capacitive operation at low line voltages and driving
Inductive operation at high line voltages and regenerative braking

[1] Another common misundestanding is that cos(φ) = 1 turns the vehicle into a resistor, the value of which can be calculated as $R = U^2/P$, and which can be used as an equivalent at all frequencies. This is not correct, the resistor analogy is only valid exactly at the fundamental.

4.3 Filters and Reactive Power Compensators

4.3.1 Description

Filters and other capacitive components in the network (including long cables, or passive filters in for example vehicles that are parked with raised pantograph) may lead to overcompensation and overvoltages, in particular at no-load situations and in the end of long feeding sections.

4.3.2 Symptoms and Consequences

Line voltages outside the specified range
Reduced system performance
Damage to components and subsystems

4.3.3 References

N/A

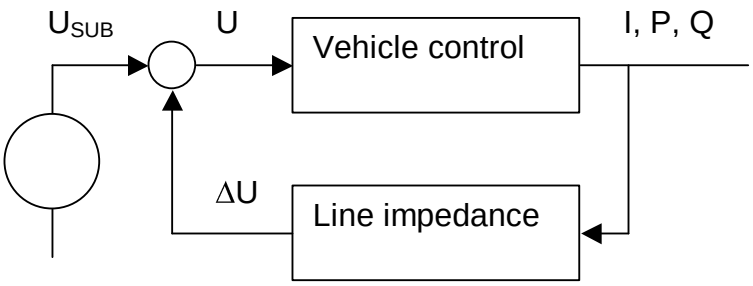
4.3.4 How to avoid

Vehicle designs with reduced filter capacitance in parking mode
Careful system analysis when introducing new components such as cables

4.4 Feedback Loop Effects

4.4.1 Description

Limitations and controllers that act on the line voltage and/or frequency form a closed feedback loop together with the line impedance, i.e., both the number of vehicles and the line impedance directly affects the gain of the closed loop. Care must be taken in the design of the converter control systems such that the vehicle can operate at all relevant feeding conditions. It is not possible to design a control system that can work with any line impedance regardless of its value.



Feedback loop including the line impedance

4.4.2 Symptoms and Consequences

Instability and low frequency power oscillations
Reduced system performance
Protective shutdowns of vehicles and/or power supply systems

4.4.3 References

Meyer, M.: Wechelwirkungen Energiversorgung-Triebfahezeug bei AC-Bahnen. Elektrische Bahnen 103 (2005), H. 4-5, S. 213-218.

4.4.4 How to avoid

Prober specification of the operational limits of the system in terms of line impedance (feeding lengths, network configurations) and of maximum number of vehicles at any given location.
Simulations and other analysis
Prober testing

5 Line Impedance Characteristics

5.1 Overhead Supply Line

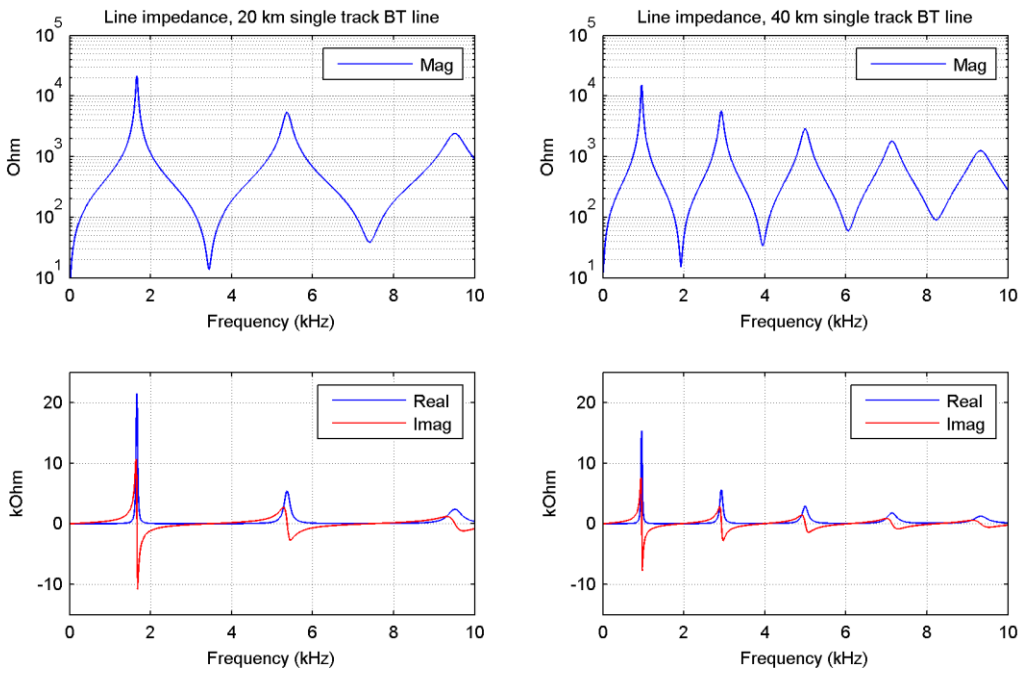
5.1.1 Description

The impedance of the overhead supply line (OHL) is characterised by the per-unit-length values of the parasitic components of the conductors:

- The (frequency dependant) series resistances
- The self and mutual inductances
- The capacitances to earth and between conductors at different potential
- The conductance to earth of conductors at potential

A typical feeding section of a 50 Hz electrified railway has the substation in one end, possibly connected via underground cables, and a neutral section in the other end. This system forms a multiconductor transmission line with subsequent series and parallel resonance points along the frequency axis, and standing voltage and current waves may occur.

The resonance frequencies are basically inversely proportional to the feeding section length. The resonance frequencies ar also strongly dependant upon the detailed configuration of the line (single or double track, BT or AT, etc.).



Line impedance characteristics, single-track BT line.

The line impedance characteristic shows that the line is the equivalent to an inductor when going in the direction of the frequency axis from a series to a parallel resonance (the impedance increases with frequency), and the equivalent of a capacitor when going from a parallel to a series resonance (the impedance decreases as the frequency increases).

Splitting the complex impedance characteristic in it's real and imaginary parts shows that the real part is very small at the series resonance points (basically only the physical ohmic resistance of the conductors), whereas it is very high at the parallel resonance points.

5.1.2 Symptoms and Consequences

Amplification of voltage and current harmonics generated by the vehicles (section 7.3)
Excessive line interference currents, e.g., psophometric currents
Protective shut-downs of trains due to filter overcurrents caused by other vehicles
Overvoltages causing damage to components
Audible noise in supply transformers

5.1.3 References

N/A

5.1.4 How to avoid

Short feeding sections and strong supply
Filters in the power supply
Prober vehicle design (see sections 7.3 and 7.4)
Side tracks, small station areas, and other 'irregularities' that make the transmission line less ideal are generally reducing the severity of the resonance, while large station areas may do the opposite

5.2 Substation and Feeding Cables

5.2.1 Description

The transformer that connects the 50 Hz public supply grid (e.g., 220 kV or 150 kV) to the 25 kV (typically) railway power supply is in many cases effectively a low-impedance termination point of the OHL transmission line. However, if the substation is located some distance away from the railway, and the feeding arrangement includes cables between the substation and the track, then the cable capacitance may become significant and must be considered.

Also cables elsewhere in the system may introduce significant capacitance and move the resonance frequencies downwards such that they coincide with frequencies where the vehicles have an ’active’ behaviour (see section 6.1).

5.2.2 Symptoms and Consequences

Lower resonance frequencies in the system
Potential instabilities

5.2.3 References

N/A

5.2.4 How to avoid

Careful system analysis when introducing new components such as cables

5.3 Reactive Power Compensators and Passive Filters

5.3.1 Description

Some 50 Hz electrified railway systems, for example at SNCF, are equipped with phase compensating capacitors and/or tuned 3rd and 5th harmonic filters installed in the substations. Other railways (e.g., the West Coast Main Line in the UK) have harmonic filters at the far end of the feeding sections.

The first type of filter is mainly used in systems with a high number of phase-angle controlled vehicles, such as the first generation of TGV trains. These filters reduce the levels of the lower-order current harmonics that are injected into the public supply grid.

The second type is mainly installed in order to damp the OHL resonances such that the higher-order harmonics generated by AC-AC vehicles are not amplified. This type of filter is an alternative to filters installed in the vehicle, see section 7.4.

Whichever is the case, any kind of filter in the infrastructure need to be considered when designing vehicles and system rebuilds.

5.3.2 Symptoms and Consequences

Lower resonance frequencies in the system
Potential instabilities

5.3.3 References

N/A

5.3.4 How to avoid

Careful system analysis when introducing new components such as filters

5.4 High Voltage Transmission Networks

5.4.1 Description

In general, the 220 kV or 150 kV high voltage network at the primary side of the substation transformers have so high short-circuit power that the impedance characteristics can be neglected, i.e., the equivalent impedance can be assumed to be zero.

However, a few exceptions from this general rule have been observed, one being a former substation in Luxembourg (where the primary supply had a comparably low short-circuit power), and another being a substation at the Swedish side of the Øresund Link (where a special cable feeding arrangement introduces distinct resonance points in the 132 kV network).

5.4.2 Symptoms and Consequences

Resonance points in the power supply that differ from the expected
Excessive harmonics in the railway power supply, or in the primary high voltage network

5.4.3 References

N/A

5.4.4 How to avoid

Tuned filters in the substation (Øresund case)

6 Linear Stability

6.1 4QC Control

6.1.1 Description

The control system for the 4-quadrant converters of a modern AC-AC vehicle has a bandwidth that goes far beyond the 16.7 Hz or 50 Hz fundamental. This means that the closed-loop feedback effects described in section 4.4 applies to a wider frequency range.

A closed-loop system is stable if the total damping is positive for all frequencies. Otherwise a self excited oscillation will build up. One way to analyse this is to look at the complex input admittance characteristics of A) the vehicle seen from the power supply, and B) the line and power supply seen from the vehicle.

Since the power supply is entirely made up of passive components, it has a positive damping for all frequencies, meaning that the real part of it's admittance characteristic is always positive (or in other words, the phase angle of the admittance is always between ± 90°). If the same thing applies to the vehicle, then the combined system is guaranteed to be stable.

However, it is probably not feasible to design the 4QC control systems such that this requirement can be met at all frequencies. All known existing AC-AC vehicles have input admittance characteristics that goes outside the ± 90° limits in certain frequency bands above the fundamental frequency. The vehicle is said to be ”active” in these areas where the real part of it's input admittance becomes negative. If such a vehicle operates on a line that has a parallel resonance in an ”active” frequency band, there is a risk that the whole system becomes instable. (The real part of the line admittance is very small at a parallel resonance point).

Seen from any single vehicle, it is not only the line and the power supply that determines the ”external” admittance characteristics. Also all other vehicles and any other components such as filters within the feeding section must be considered.

Traditional stability analysis and criteria such as Nyquist have been found to be inadequate for this type of analysis. The Input Admittance (IA, a.k.a. ”ESCARV”) criterion for stability says that the sum of the real parts of the admittances (vehicle + external) must always be greater than zero at frequencies where the sum of the imaginary parts equals zero.

However, more recent work has suggested that even the IA criterion is insufficient (because it does not take harmonic imtemodulaton into account, see section 8) and suggests instead an analysis method based on what is called a Harmonic Transfer Matrix (*Pröls and Strobl*).

Practically, it is of great importanc to keep the first line resonance frequency as high as possible, and the highest ”active” vehicle frequency as low as possible, such that these frequencies cannot coincide.

6.1.2 Symptoms and Consequences

Precense of line voltage (inter-) harmonics that are normally not generated by any vehicle
Overvoltages, damage to components
Protective shut-downs, stopping of all trains in the actual area
Potential interference with signalling systems

6.1.3 References

Lörtscher, M.; Meyer, M.; Schneeberger, A.; Henning, U.: Kompatibilitäts-untersuchungen am schweizerischen 16.7 Hz Bahnstromnetz. Elektrische Bahnen 99 (2001), H. 6-7, S. 292-300.

Pröls, M.; Strobl, B.: Stabilitätskriterien für Wechelwirkungen mit Umrichteranlagen in Bahnsystemen. Elektrische Bahnen 103 (2005), H. 4-5, S. 213-218.

6.1.4 How to avoid

Prober vehicle design with a low ”highest active frequency”
Prober infrastructure design and configuration with a high ”lowest resonance frequency”
System studies, modelling, and analysis
Compatibility process according to EN 50388

6.2 Harmonic Anticontrol

6.2.1 Description

The fully (in principle) controllable 4-quadrant converter gives the possibility of active anticontrol of certain line current harmonics. This is typically done in order to keep the line current sinusoidal even if the line voltage contains for example significant 3rd and 5th harmonic components, but it is also sometimes used in order to suppress critical frequencies for the signalling systems (e.g., 42 Hz and 100 Hz in Germany).

However, anticontrol implies ”active” vehicle behaviour according to the definition in the previous section, and should only be used with care at higher frequencies.

6.2.2 Symptoms and Consequences

Reduced levels of low-order line current harmonics
Potential risk of system instabilities

6.2.3 References

N/A

6.2.4 How to avoid

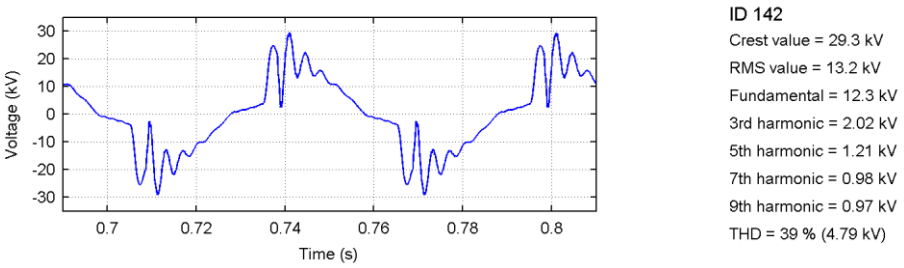
System studies, modelling, and analysis
Compatibility process according to EN 50388

7 Line Harmonics

7.1 Phase Angle Controlled Vehicles

7.1.1 Description

Phase angle controlled vehicles, and also vehicles with tap changers and diode rectifiers, generate high levels of low-order odd current harmonics (3rd, 5th, 7th, etc.). The levels are more or less proportional to the fundamental current, i.e., strongly dependant on the operation point of the vehicle.



Example of a heavily distorted line voltage due to a phase-angle controlled locomotive on a weak supply line, measured in a 15 kV 16.7 Hz network.

7.1.2 Symptoms and Consequences

High levels of low-order current and voltage harmonics
Additional losses in the power supply system
Distortion of the line voltage
AC-AC vehicles must have harmonic anticontrol

7.1.3 References

N/A

7.1.4 How to avoid

The problems due to the line voltage distortion must be considered at the design stage of a new vehicle
Strong power supply

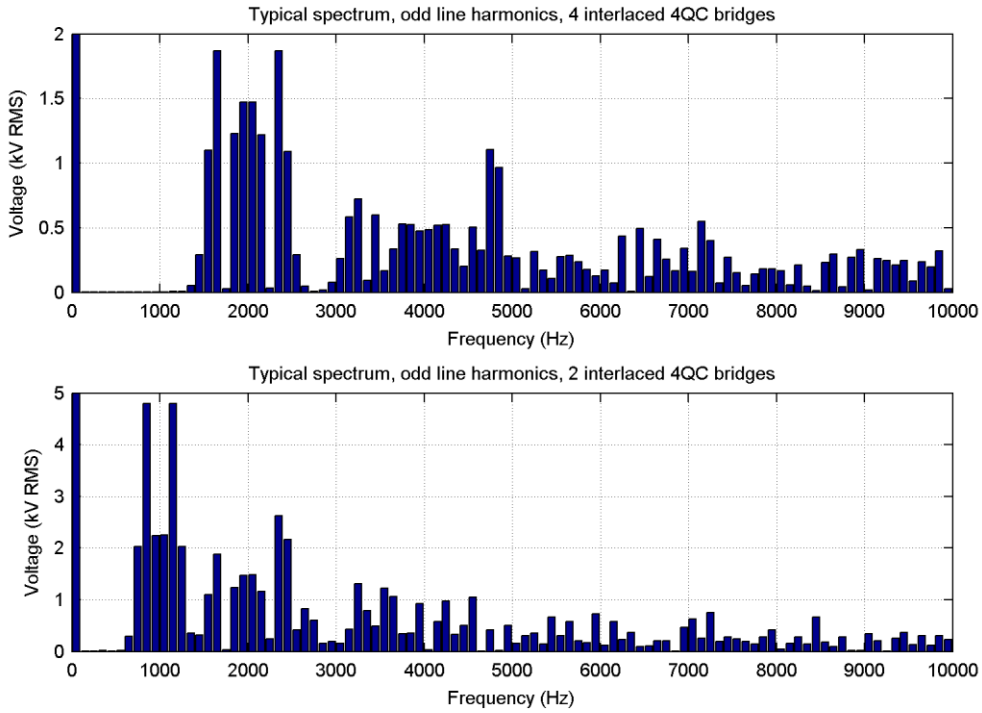
7.2 AC-AC (or 4QC) Vehicles

7.2.1 Description

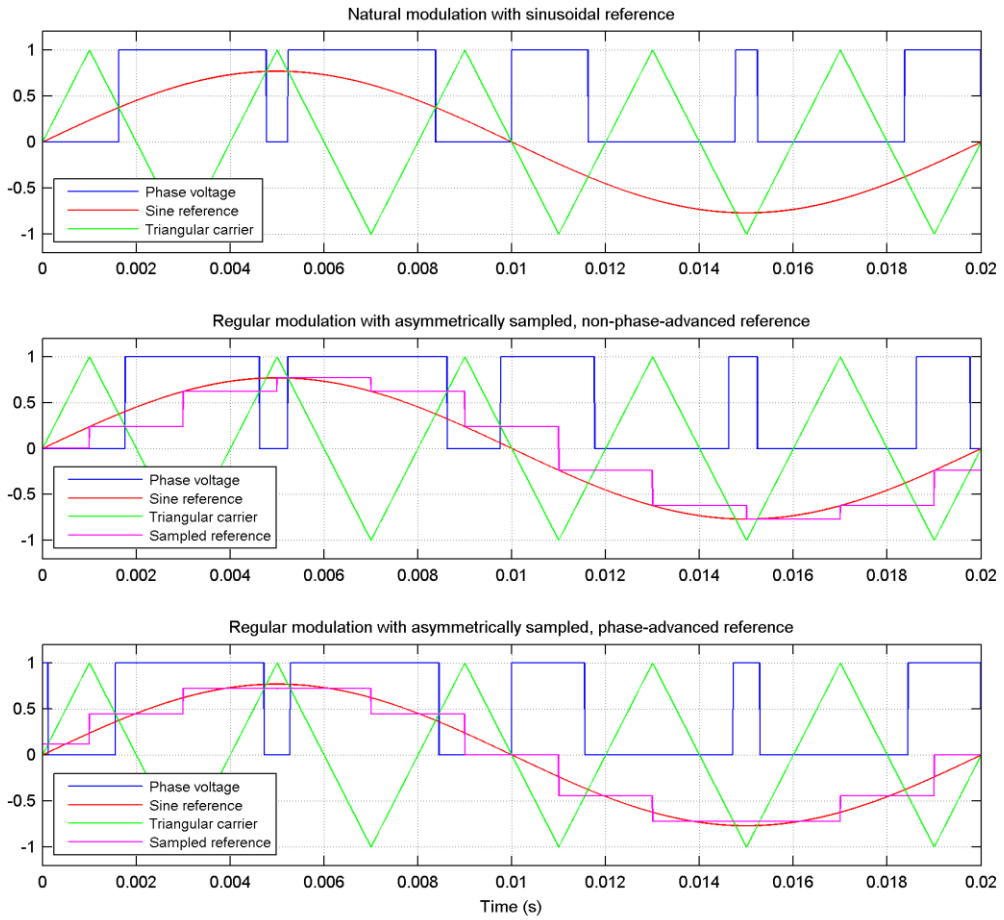
The 4-quadrant converters of an AC-AC vehicle constitutes a voltage source that generates higher-order odd line voltage harmonics. The levels and frequencies of these harmonics depends on several factors:

- The switching frequency f_{SW} per 4QC phase leg
- The number n of interlaced 4QC bridges
- The operation point of the vehicle (actual voltage and power)
- The power imbalance between independent systems, e.g., for each bogie
- The modulation strategy in the 4QC control

In general, the first main burst of harmonics are located as sidebands to the frequency $f_{RES} = 2 \cdot f_{SW} \cdot n$. Another general rule of thumb says that the amplitudes of this first burst of harmonics are inversly proportional to n.



Example of the "inner" 4QC voltage spectra in the case of four (upper plot) and two (lower plot) interlaced converter bridges.



Examples of modulation strategies, all leading to different voltage spectra. Also other strategies exist, e.g., lock-up tables with predetermined switching angles

As a first approximation, the levels of the line current harmonics i(f) are determined as the voltage harmonics v(f) divided by the leakage reactance $X_L(f)$ of the main transformer in the vehicle. However, the precense of line-vehicle resonances can strongly amplify the current harmonics, while on the other hand a filter can greatly reduce the levels.

7.2.2 Symptoms and Consequences

Line voltage and line current harmonics
Psophometric currents
Excessive external magnetic fields (EN 50121)
Interference with signalling equipment or telecommunication

7.2.3 References

N/A

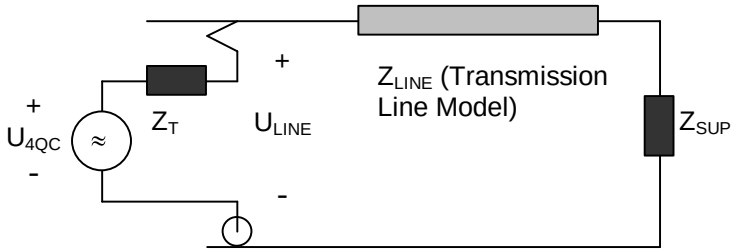
7.2.4 How to avoid

The optimal vehicle has ”many” interlaced 4QC bridges, a high switching frequency, high transformer leakage reactance, and a modulation strategy that reduces the harmonics to a minimum.

7.3 Line-Vehicle Resonances

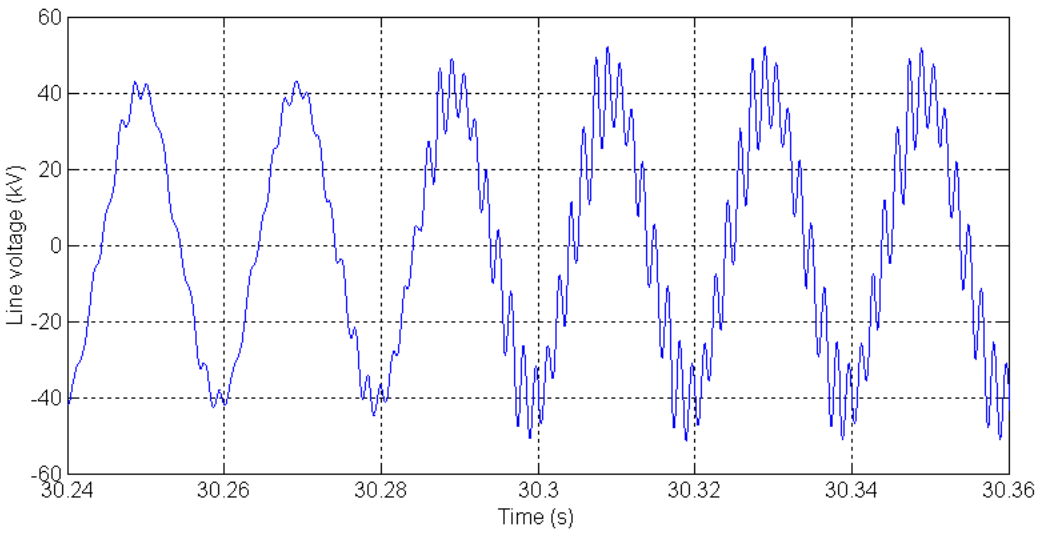
7.3.1 Description

Seen from equivalent 4QC voltage source, the mainly inductive transformer is connected in series with the line and supply system which, as shown in section 5.1, has an impedance characteristic that is subsequently inductive and capacitive.



Equivalent scheme, vehicle, line, and supply. If the line impedance is replaced by a capacitor, it is evident that this is a series resonant circuit.

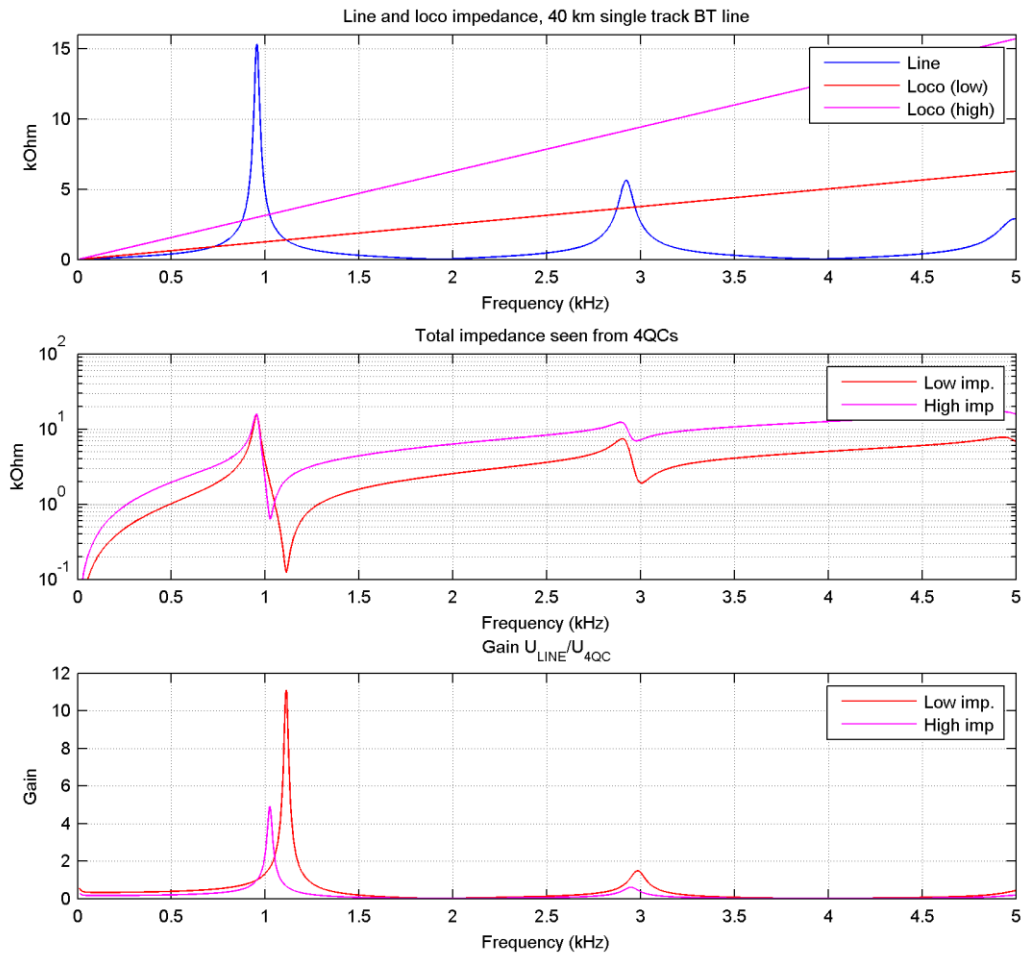
In the general case (the exceptions being transformers with very high leakage reactances, and very short feeding distances), at least one frequency exists where the magnitudes of the imaginary parts of the transformer impedance and of the line impedance are equal, but with opposite sign. In other words, the reactive components cancel out, and the harmonic currents are only limited by the real part of the line and transformer impedance. Seen from the 4QC, this corresponds to a series resonance between the transformer inductance and the equivalent line capacitance.



Distorted line voltage (measured) due to line-vehicle resonance. The 4QCs are activated at t ≈ 30.285 s

If this occurs close to a line series resonance point where the real part of the line impedance is low, then the overall impedance seen from the 4QC voltage source will also be low, generally much lower than the impedance of the transformer itself at the

actual frequency. If the 4QC voltage spectrum contains a significalt harmonic at exactly this frequency, very high interference currents will be the result.



Comparison between resonance conditions with a vehicle with low (red) and high (pink) transformer leakage reactance. The higher impedance reduces the severity of the resonance as the impedance at the resonance point increases by more than the difference in transformer impedance as such.

7.3.2 Symptoms and Consequences

Very high line voltage and line current harmonics
Interference with signalling equipment, telecommunication, etc.
Excessive external magnetic fields (EN 50121)
Damage to other vehicles and systems due to overvoltages

7.3.3 References

N/A

7.3.4 How to avoid

Design the main transformer with a high leakage reactance, such that the real part of the line impedance is higher at the line-vehicle resonance point
More substations, shorter feeding sections such that the lowest line rsonances move to higher frequencies
Filters in the vehicle or the infrastructure

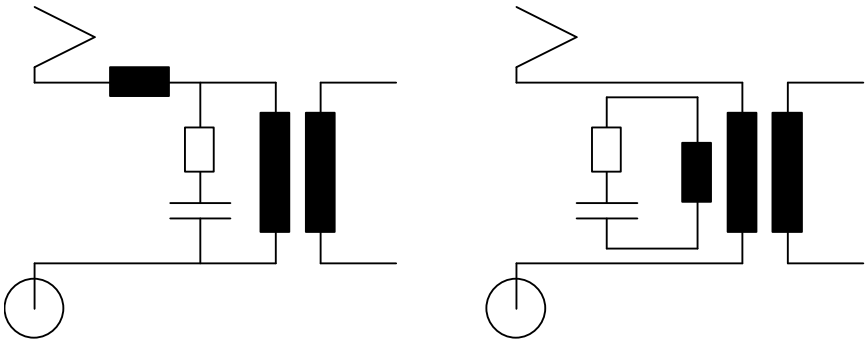
7.4 Passive Filters in Vehicles (”Psophometric Filters”)

7.4.1 Description

Passive filters towards the line-side of AC-AC vehicles serve two purposes:

- The filter may act as a shunt path for the interference currents generated by the 4QC
- The filter provides resistance that can damp the vehicle-line resonances

The drawback of a filter is the reduced input impedance of the vehicle, such that it may potentially ”vacuum-clean” current harmonics that are generated by other vehicles or systems. In addition, the filter introduces new resonance points, and if designed wrongly (e.g., with excessive capacitance and/or insufficient damping), this may create new problems that are just as severe as the problems the filter was meant to solve.



High voltage filter (left), and filter connected to a separate transformer vinding (right)

7.4.2 Symptoms and Consequences (of a non-optimal filter design)

Line overvoltages far away from substations
Filter overcurrents
Protective shut-downs of locomotives
Overheating of components
Damage to equipment

7.4.3 References

El17 in Norway
EA3000 in Denmark

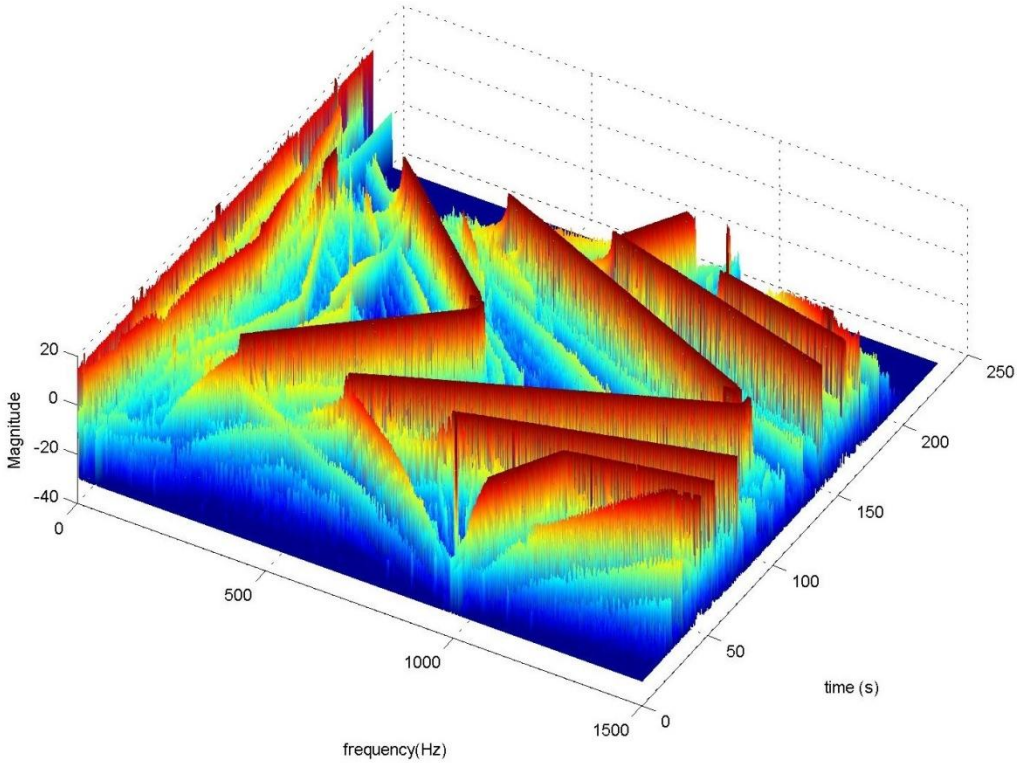
7.4.4 How to avoid

The filter must be designed with sufficient damping and impedance
System analysis and calculations including the supply, lines, other vehicles, etc.

8 Interharmonics and Harmonic Modulation

8.1.1 Description

The 3-phase PWM inverter for the AC motors generates currents towards it's DC side, i.e., into the DC link filter, over a wide range of frequencies. Both the current level and the frequencies vary with speed. This leads to a variable-frequency voltage ripple across the DC link capacitor. The ripple frequencies are then modulated by the reference signal for the 4QCs, such that they appear as voltage (inter-) harmonics in the 4QC voltage spectrum.

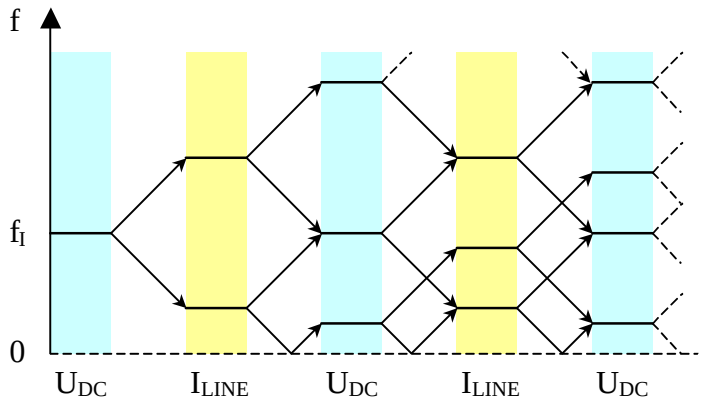


Example of the DC link harmonics during an acceleration-brake load cycle

The frequencies of the currents injected into the DC link by the 3-phase inverter depends on the PWM principle that is used, and as such, they vary strongly with speed and power. Also different vehicle types from different manufacturers use different modulation principles. But in general, at least the following can be expected, with f_S being the actual stator frequency of the 3-phase motors, and f_{SW} being the switching frequency of one phase leg of the 3-phase inverter:

- $\frac{1}{2}\cdot f_S$, f_S, $2\cdot f_S$, $4\cdot f_S$: These so-called irregular harmonics are due to various asymmetries in the inverter and it's control equipment
- $6\cdot f_S$, $12\cdot f_S$, $18\cdot f_S$, . . .: These are the regular harmonics due to the square-wave shape (with or without additional notches) of the 3-phase voltage at higher speeds
- 1, 3, 5, . . times $f_{SW} \pm 3\cdot f_S$, $\pm 9\cdot f_S$, . ., and 2, 4, 6, . . times $f_{SW} \pm 6\cdot f_S$, $12\cdot f_S$, . .: These are the regular harmonics of the 3-phase inverter at lower speeds

The modulation through the 4QCs towards the AC side causes a frequency shift of ± 50 Hz of the DC link ripple frequencies (at 50 Hz network), and also ± 150 Hz and ± 250 Hz in case 3rd and 5th harmonic anticontrol is used. If for example a significant DC link ripple exists at 82 Hz, then the 4QC AC-side voltage will have voltage components at 32 Hz and 132 Hz, and also (if 3rd harmonic anticontrol is used) at 68 Hz (= |82-150|) and 232 Hz. This modulation process goes both ways, such that a line current component at say 65 Hz will cause DC link ripple at 15 Hz and 115 Hz after the modulation through the 4QC.



Example showing how the modulation by 50 Hz through the 4QC is capable in principle of forming new frequencies from the initial DC link ripple frequency f_I.

These effects become even more complicated due to the fact that strong feedback loops exist from the DC link voltage via the control system to the reference signals for the 4QC pulse pattern generation. Such effects have been observed to provide a significant amplification of the modulated DC link ripple, compared to ”open-loop” calculations with constant reference signals.

A special case is related to the signalling frequencies at 75 Hz (or 77 Hz) and 125 Hz. First, the DC link filter of a 50 Hz AC-AC vehicle may typically have an impedance peak close to 125 Hz, due to the parallel connection of the DC capacitor and the 2nd harmonic filter. This means that it is likely that the DC link voltage ripples at this frequency. Second, the ± 50 Hz modulation forth and back through the 4QCs leads to current and voltage components at the frequencies 25 Hz, 75 Hz, 125 Hz, and so on, at both the AC and the DC sides, forming what has been described as a ”harmonic avalance”.

As described in section 6.1, the interharmonic modulation may even play a role in the system stability.

8.1.2 Symptoms and Consequences

Interharmonic components in the line current
Potential interference with signalling systems

8.1.3 References

Pröls, M.; Strobl, B.: Stabilitätskriterien für Wechelwirkungen mit Umrichteranlagen in Bahnsystemen. Elektrische Bahnen 103 (2005), H. 4-5, S. 213-218.

8.1.4 How to avoid

The DC link should be designed with adequate damping

The modulation strategies for the 3-phase inverters should be optimised in order to match the requirements of the signalling systems, in such a way that no high levels of DC link ripple are seen in ± 50 Hz distance from a carrier frequency of a signalling system

The 4QC control must not have feedback loops which amplify the modulation products

9 Close-Up Effects

9.1 Magnetic Fields Below the Vehicle

9.1.1 Description

The currents through traction motors, main transformer, power cables, and other components mounted in the underframe or in the bogies of a rail vehicle, may generate magnetic field levels in excess of the susceptibility limits of trackside systems such as axle counters and other signalling equipment.

9.1.2 Symptoms and Consequences

Excessive magnetic fields
Interference with signalling equipment

9.1.3 References

N/A

9.1.4 How to avoid

Adequate magnetic screening of components and cables
Routing of cables in screening cable ducts

9.2 Common Mode Currents

9.2.1 Description

The 3-phase inverter voltages that are generated by the PWM switching pattern contains a common-mode component that is effectively applied across the stator-winding-to-frame capacitance of the traction motors. This generates a common-mode current that somehow has to find it's way back to the traction inverter DC links – across the motor bearings, over the earth brushes and the rails, or via whatever is the lowest-impedance path.

In order to provide a return path back to the 3-phase inverter, it has become common practice to A) use screened motor cables with the screens earthed both at the motor and the inverter, and B) mount decouling capacitors from earth to the DC link. However, this may lead to resonances between the said capacitors and the leakage inductance of the cables, cable screens, and other return paths.

Such resonant common-mode currents have been reported to be the cause of malfunctioning of axle counters and other infrastructure systems.

For this reason, it is important to damp the resonant circuit, e.g., by means of adequate resistors in series with the capacitors.

This is particularly important in the 4-rail system of London Underground, where the track circuits and other systems that are connected to the running rails are not designed to cope with any traction return current.

9.2.2 Symptoms and Consequences

Interference with axle counters and other infrastructure systems
Bearing failures due to common mode currents

9.2.3 References

N/A

9.2.4 How to avoid

Provide defined and well-damped return paths of the common-mode currents directly from the motor frame to the inverter, via cable screens or screening conductors, and via decopling RC circuits from earth to DC link potential