Traction System Case Study

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Electrical drives, traction systems, and compatibility

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Case Study?

- Inspiration from Class 357 ”Electrostar”, the Gardermoen Airport Express (Oslo, Norway), and several tender projects.
- Designing a traction package is a multivariable problem and an iterative process – not projects two are equal!
- 6 selected themes that have cost a lot of money!

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Why are trains different?


- Metro trains: All axles driven, small motors
- High speed trains: Locomotives, high power

Q: How many motors, and how much power?

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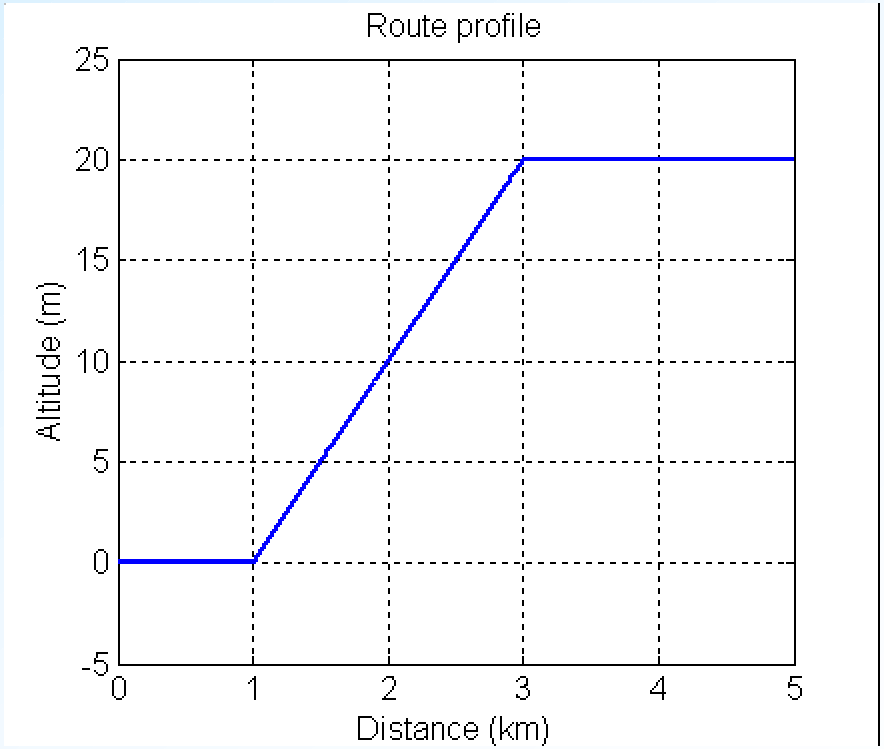
Performance Specification

- 5 km line
- 10 ‰ uphill between km 1 and km 3
- ≤ 4 min run time
- 4 car EMU
- 2 bogies per car
- Max. μ = 15 %
- Max. weight 170 t
  (How do we know that?)



Route profile

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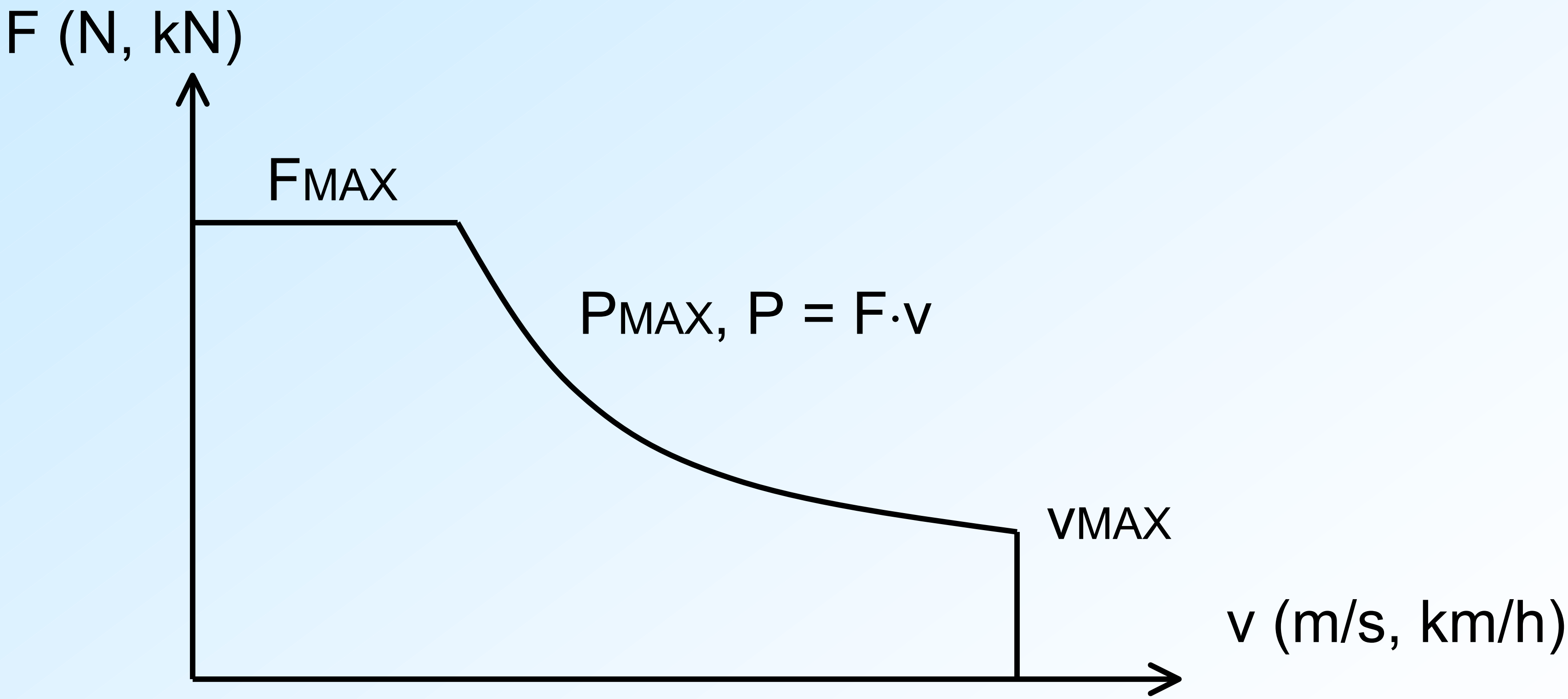
Generic Tractive Effort curve



Determine this curve for 4, 6, and 8 traction motors

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Maximum tractive effort

No. of motors	Total axle load, motorised axles	Maximum tractive effort
n	$m_m = 170\text{-}(16\text{-}n)\cdot 10$ *(10 t on each non-motorised axle, and the rest on the motorised axles)*	$F_{MAX} = \mu \cdot m_m \cdot g$ *($\mu_{MAX} = 0.15$)*
4	50 t	73.6 kN
6	70 t	103 kN
8	90 t	132 kN

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Train resistance

- Running resistance (friction, aerodynamics): Numerous formulas, here Filipović:

  $F_R(v) = m \cdot g \cdot (2.5 \cdot 10^{-3} + 0.33 \cdot (v+15)^2 \cdot 10^{-6})$

- Gradient resistance:

  $F_G(s) \approx m \cdot g \cdot G(s)/1000$ *(G in ‰, G ≤ 100 ‰)*

- Curve resistance: $F_C(s) = m \cdot g \cdot K/r$ *(K ≈ 0.75)*

- $F_{ACC} = F(v) - F_R(v) - F_G(s) - F_C(s)$

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Performance Simulation

- Define an initial F(v) curve
- Discrete integration gives v(s):

  $v(s)^2 - v(s-\Delta s)^2 = 2 \cdot a \cdot \Delta s$, where

  $a = F(v(s-\Delta s))/m_{dyn}$ and $\Delta s \approx 1$ m
- Time vector t(s):

  $t(s) = t(s-\Delta s) + 2 \cdot \Delta s / (v(s) - v(s-\Delta s))$

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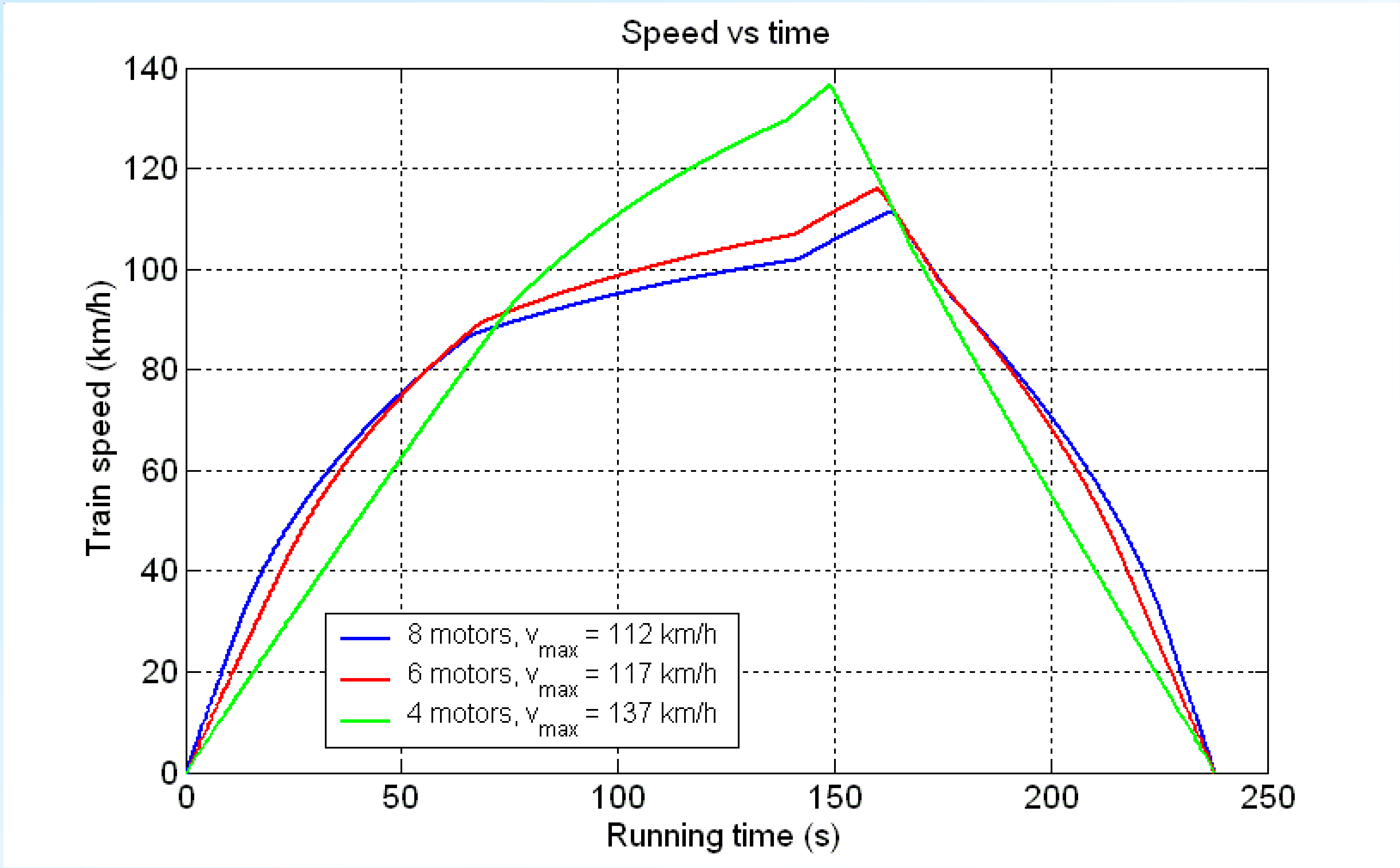
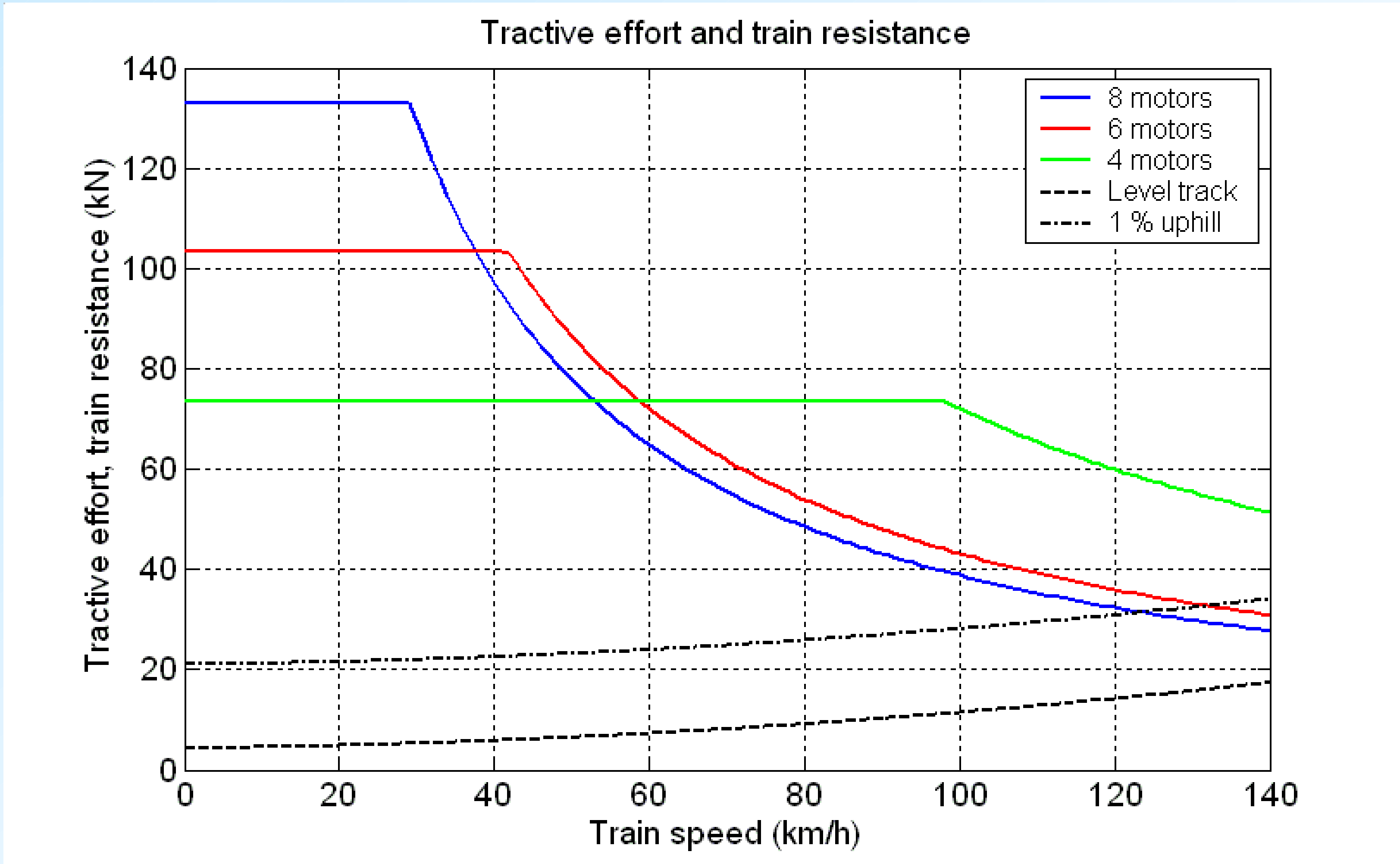
Calculated run times



TE curves



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Spec compliant systems

No. of motors	v_{MAX}	P_{MAX}
4	137 km/h	2.0 MW
6	117 km/h	1.2 MW
8	112 km/h	1.08 MW

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Quick Comparison

No. of motors	4	6	8	8
No. of inverters	2	3	4	2
No. of motors/inverter	2	2	2	4
Peak power	-	+	+	+
Redundancy	-		+	-
Cost DC-supply only	(+)	(+)	-	
Additional cost AC-supply			(+)	+

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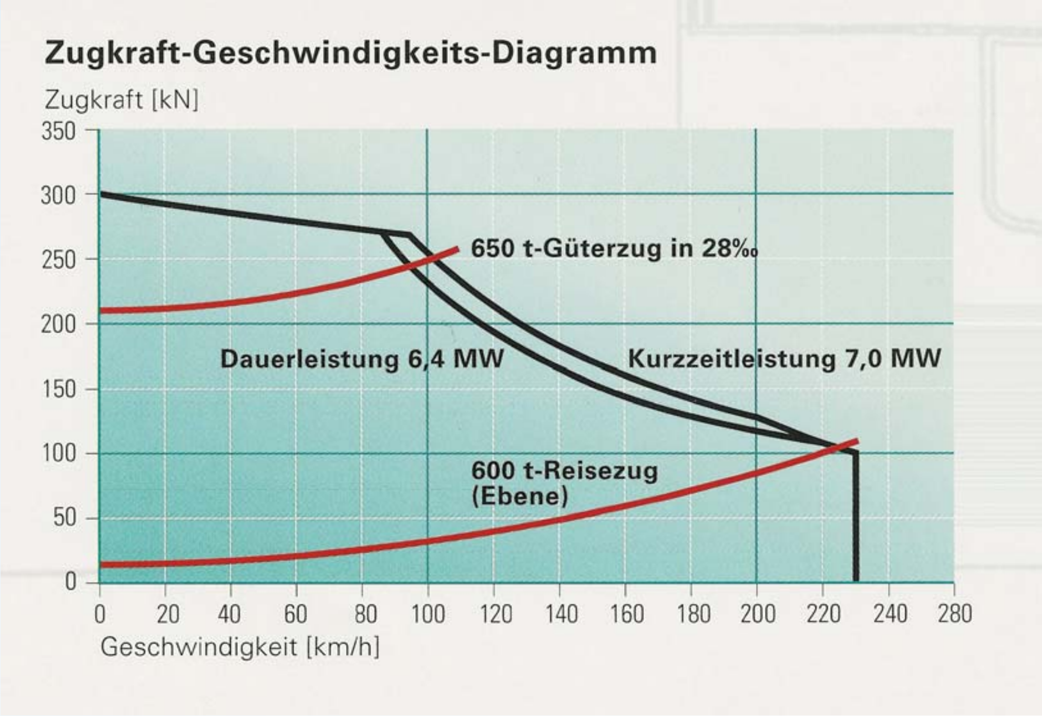
Motor and inverter size



Why is the short-term power reduced at high speeds?

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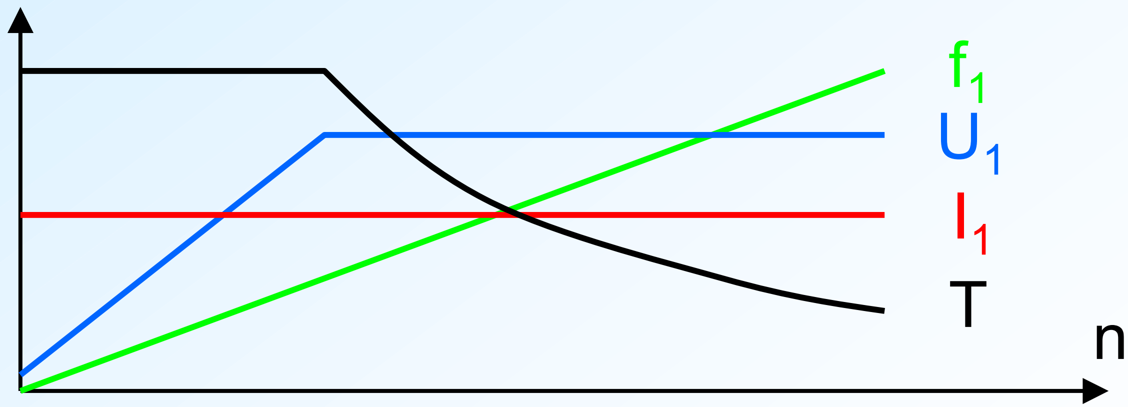
Basic control of the 3-phase drive

The ASM supplied from a 3-phase inverter:

- $n \sim f_1$
- $U_1/f_1 \sim\cdot$ constant up to f_{BASE} (constant flux)
- $P \sim U_1 \cdot I_1$, $T \sim P/n$



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Motor torque

$T = k_1 \cdot V_{ROTOR} \cdot J \cdot B \cdot \cos(\text{ø}_i)$, where

V_{ROTOR} = active rotor volume

J = stator current surface density

B = air gap flux density *(saturation!)*

ø_i = angle between J and B vectors

(increases at increasing J, $\Rightarrow$ pullout!)

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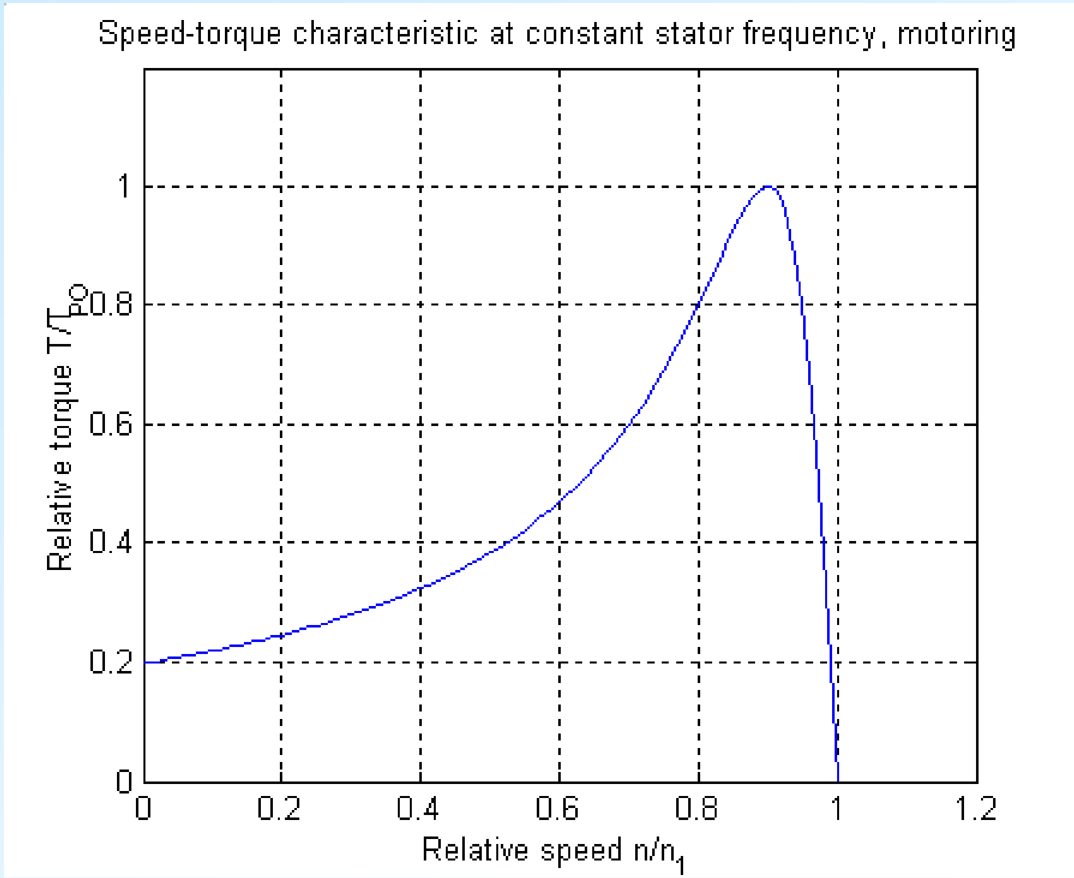
Pullout torque



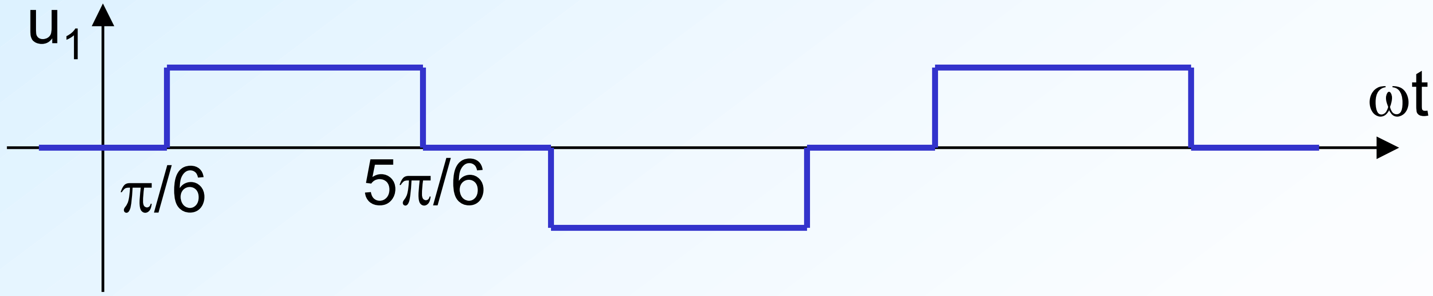
Speed-torque characteristic at <u>constant</u> stator frequency

Pullout torque limit at high speed

Pullout torque vs. voltage and frequency:

$T_{PO} = (k_2/L_\sigma)\cdot(U_1/f_1)^2$,

where $f_1 \sim v$, while U_1 is limited by the DC link voltage:



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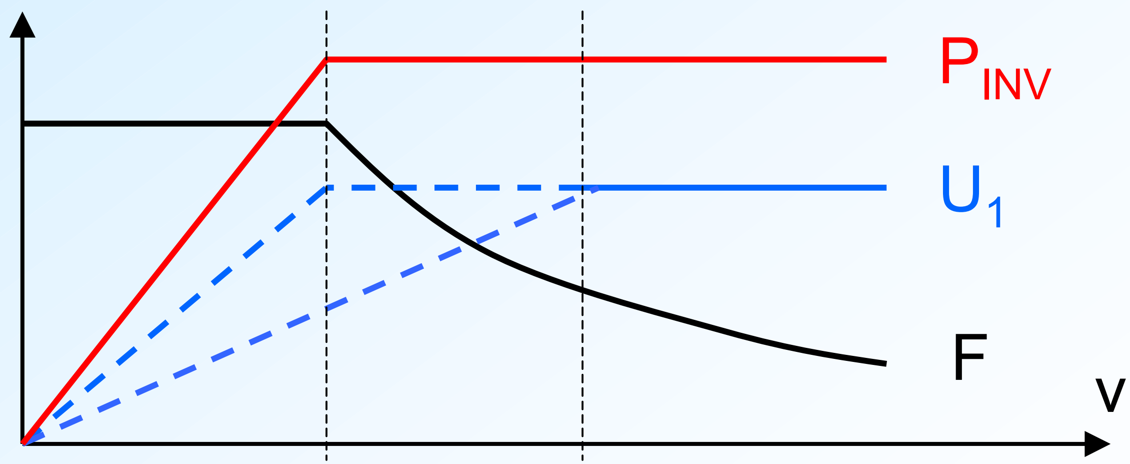
Inverter power and current

- Inverter power: $P_{INV}(v) = F(v)/(v \cdot \eta)$
- Try 2 different base speeds (different U_1/f_1 characteristics)
- Current: $I_{INV}(v) = P(v)/(\sqrt{3} \cdot U_1(v) \cdot \cos(\varphi))$



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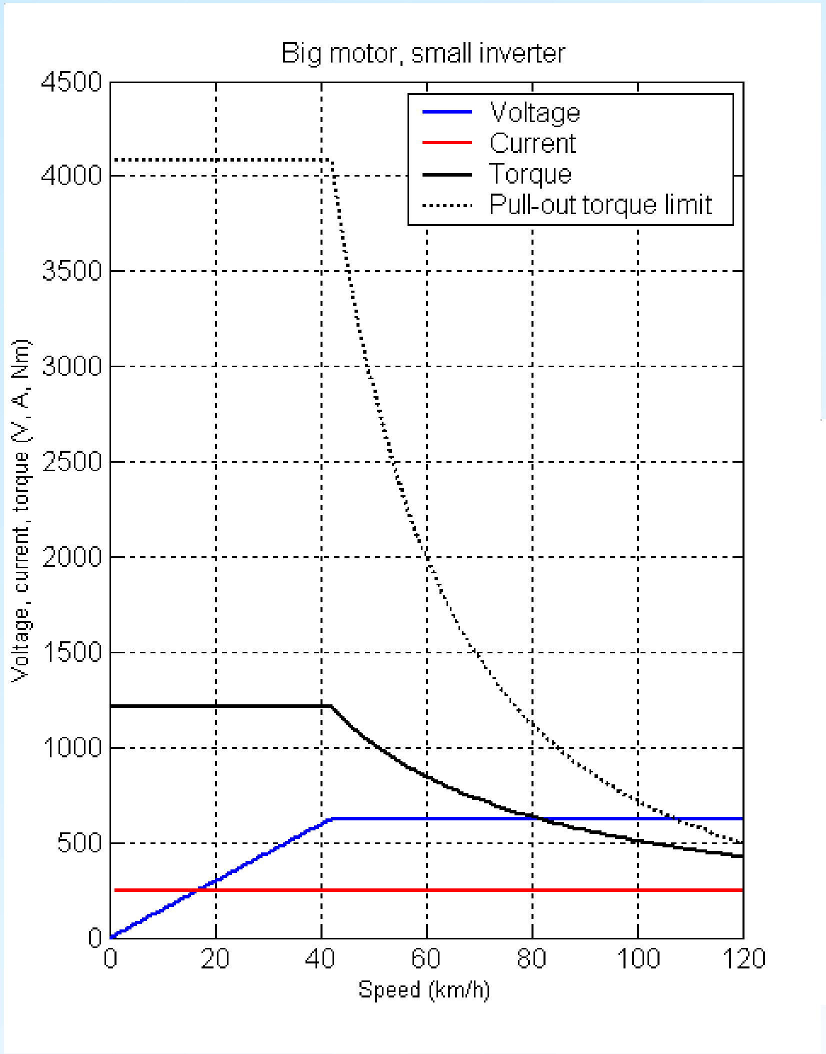
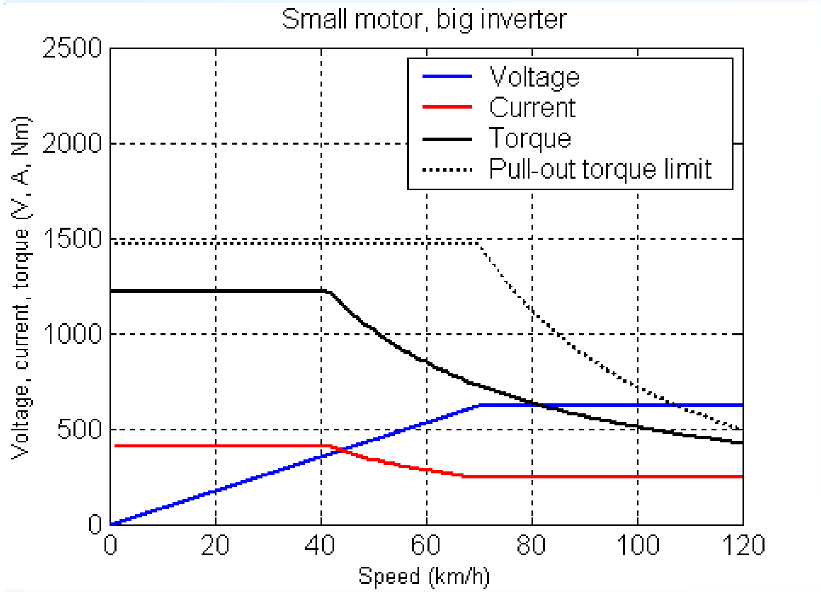
Two different designs, equal performance



- Motor size ~ max. torque
- Inverter size ~ $U_{MAX} \cdot I_{MAX}$



Comparison of the two designs

	Big motor, small inverter	Small motor, big inverter
Relative motor size (V_{ROTOR})	*2.8*	*1*
Relative inverter size ($U_{MAX} \cdot I_{MAX}$)	*1*	*1.7*
Requirements on motor cooling	*Low*	*High*

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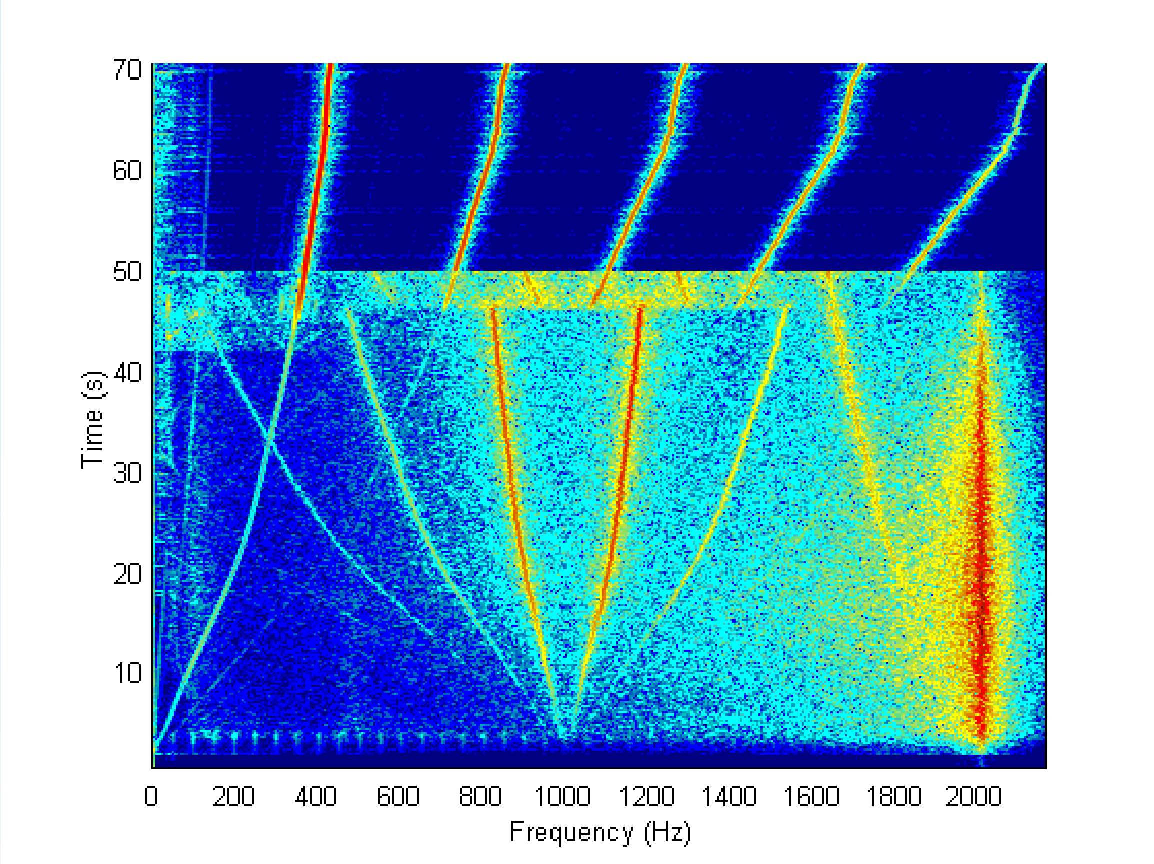
DC Traction and Line Filters



How do we avoid that this nasty current spectrum causes interference with wayside systems?

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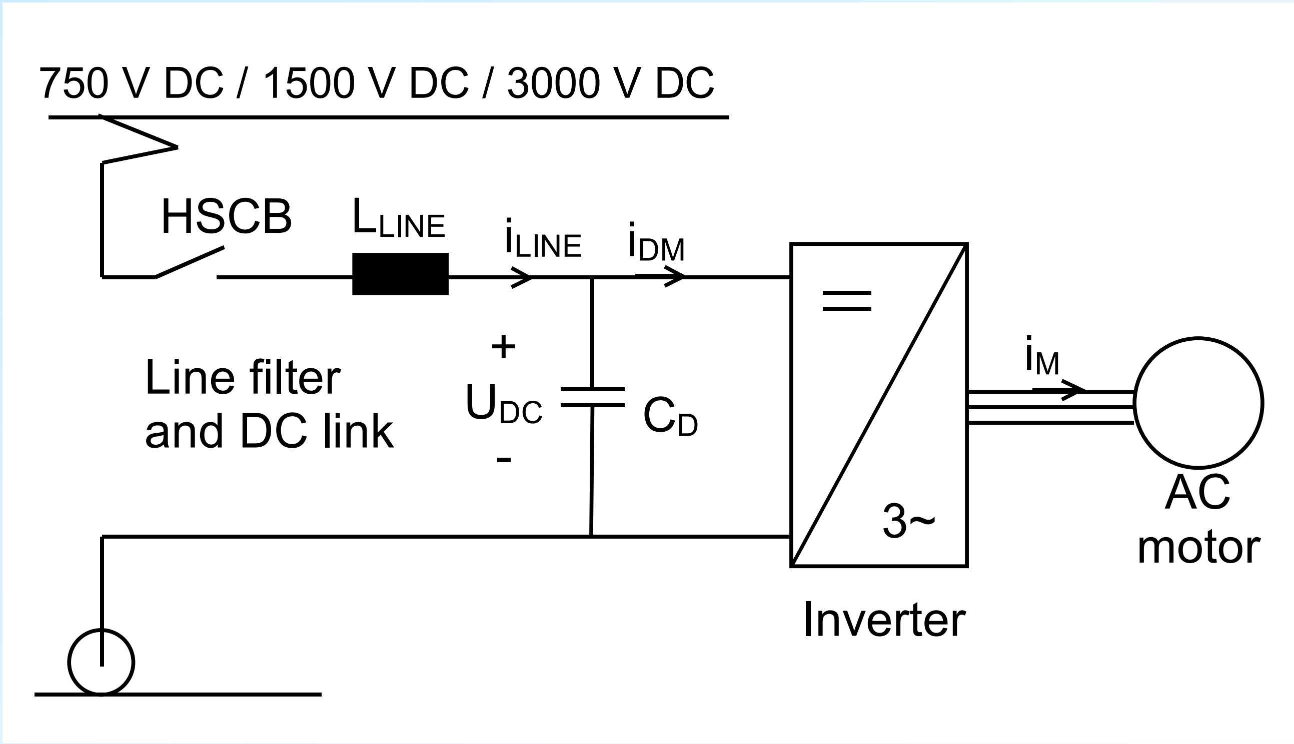
DC Traction Systems



Interference current generation mechanisms, motor/inverter combination, and line filter design

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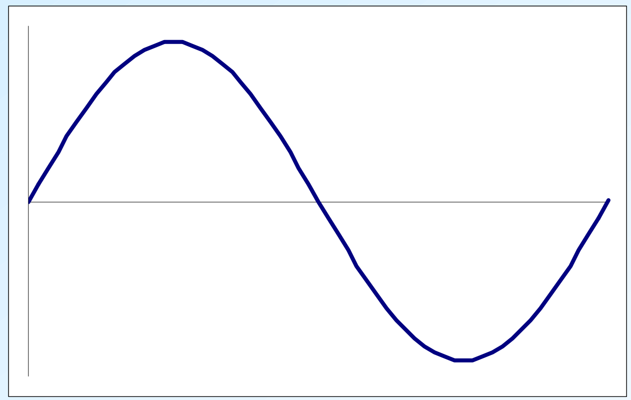
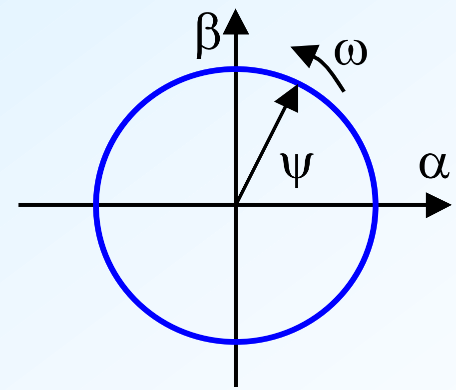
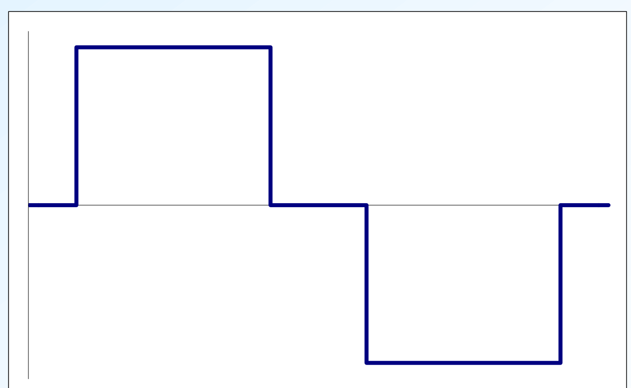
Trajectory of the stator flux vector

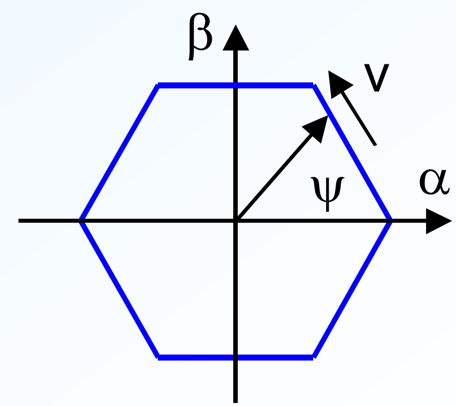
- Sinusoidal voltage ⇒ Circular flux trajectory





- Squarewave voltage ⇒ Hexagon flux trajectory





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Base frequency and Reed track circuit interference

- Hexagon flux polygon $\Rightarrow$
  Current components with $f = 6 \cdot f_S$ in i_{DM}
- Reed frequencies: 363 Hz – 423 Hz
- $f_{BASE} \leq 70.5$ Hz *(i. e., big motor, small inverter)* $\Rightarrow$
  The 6th harmonic interferes with the Reed band!

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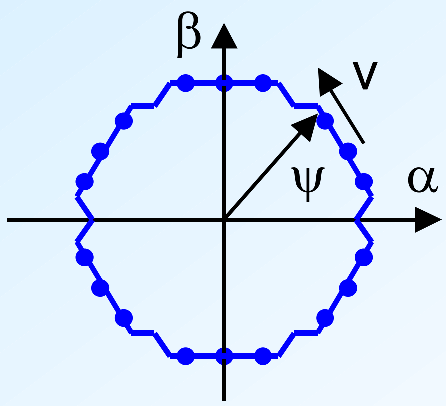
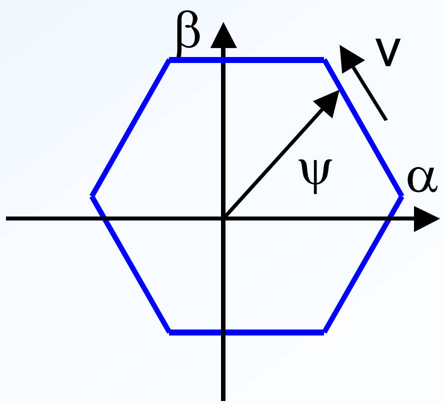
Low speeds

- Stop points below base speed
- Aim for a circular flux polygon
- Harmonics due to stops and shape



Irregular harmonics

- Asymmetries and main circuit imperfections displaces the polygon and/or bends it out of shape
- Stator frequency in i_{DM}!



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DC line filter

- Gain of 2nd order L-C filter:
  $i_{LINE} = i_{DM}/(1-\omega^2 LC)$
- Typical values:
  - Reed limit = 10 mA at 363 Hz
  - 6th harmonic = 200 A *(big motor, small inverter)*
- If C = 15 mF, then L $\geq$ 260 mH !!!
- Use small motor / big inverter combo, or 4th order filter, and/or cornerfolding

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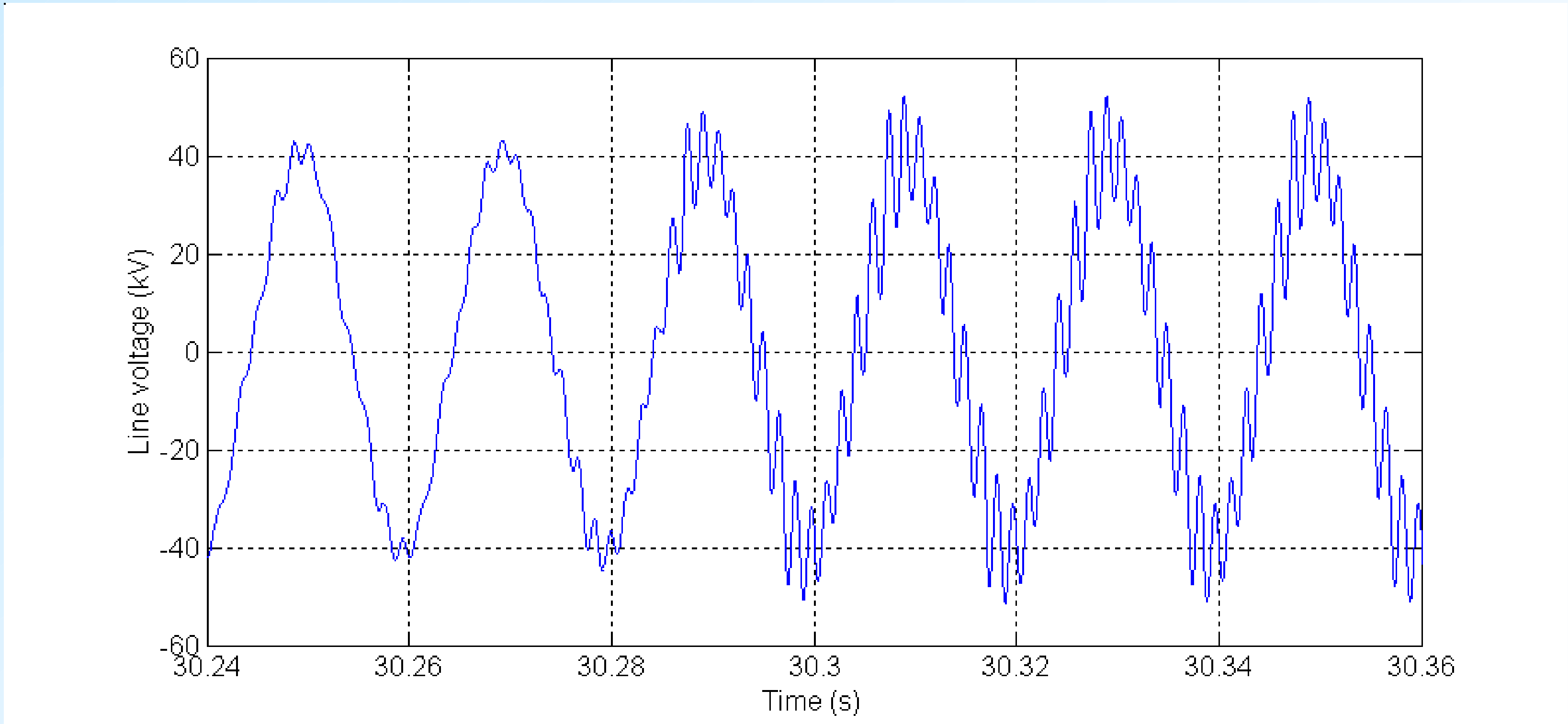
Line side circuits for AC-AC traction systems



How do we avoid this line voltage wave shape?

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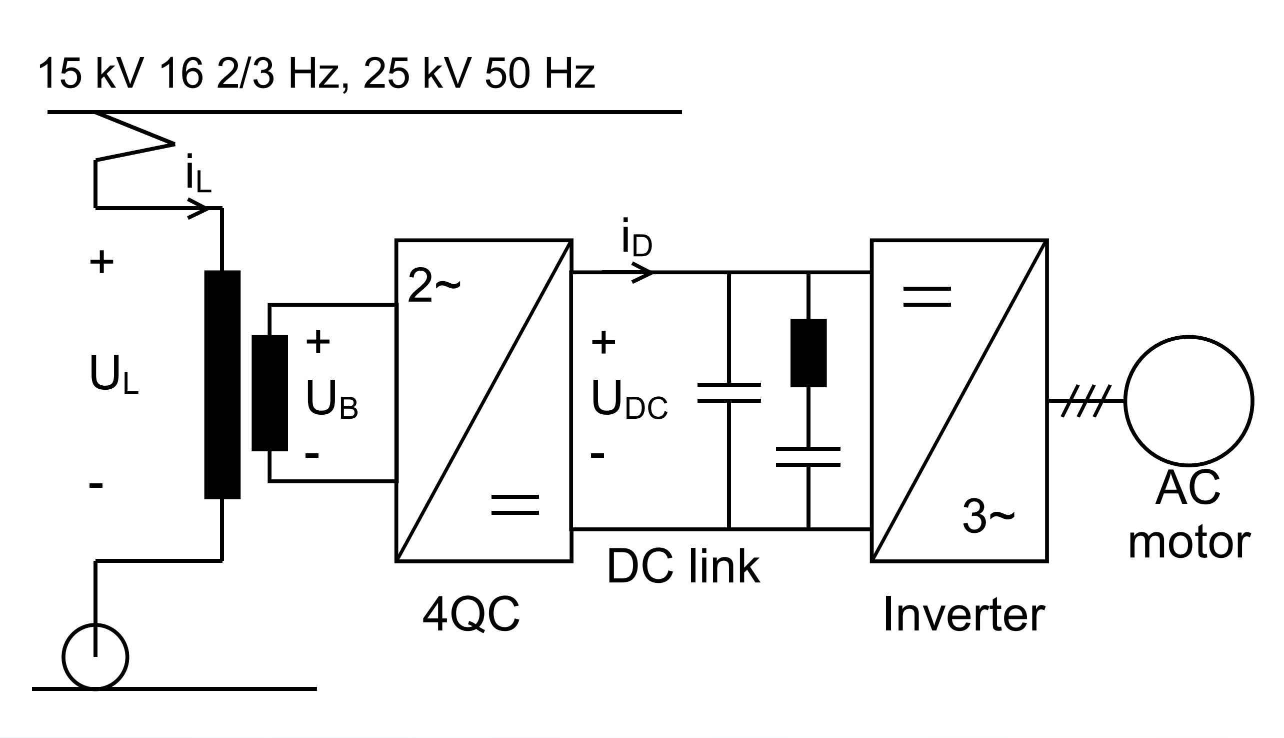
AC-AC Traction



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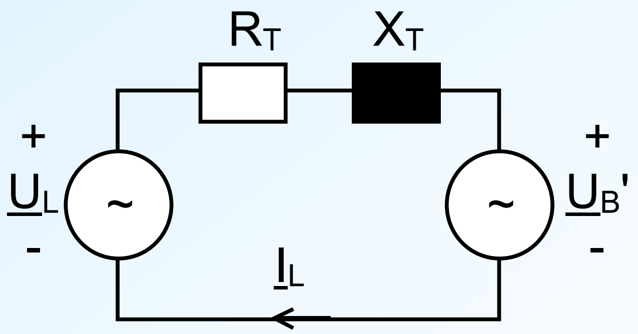
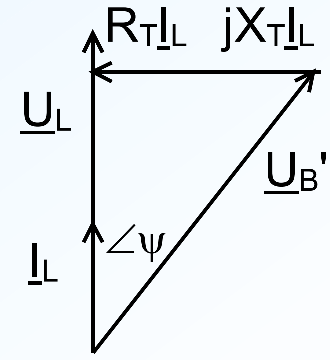
The short circuit impedance of the main transformer – a key parameter

- $\underline{I}_L = (\underline{U}_L - \underline{U}_B')/(R_T + jX_T)$
- $\underline{U}_B$ is controlled to give cos(ø) = 1:
  - amplitude
  - relative angle Ψ
- $P \sim I_L \sim \Delta U_T$





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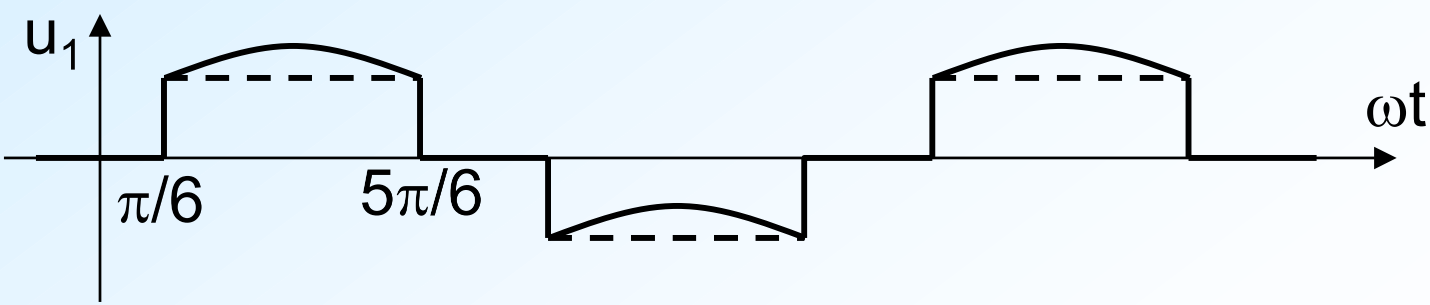
2nd harmonic current

- Power balance across the 4QC $\Rightarrow$ $i_D(t) = I_{D,DC} + \hat{\imath}_{D,2nd} \cdot \sin(2\omega t)$
- The 3-phase drive consumes a constant power
- DC link ripple cause torque pulsations:



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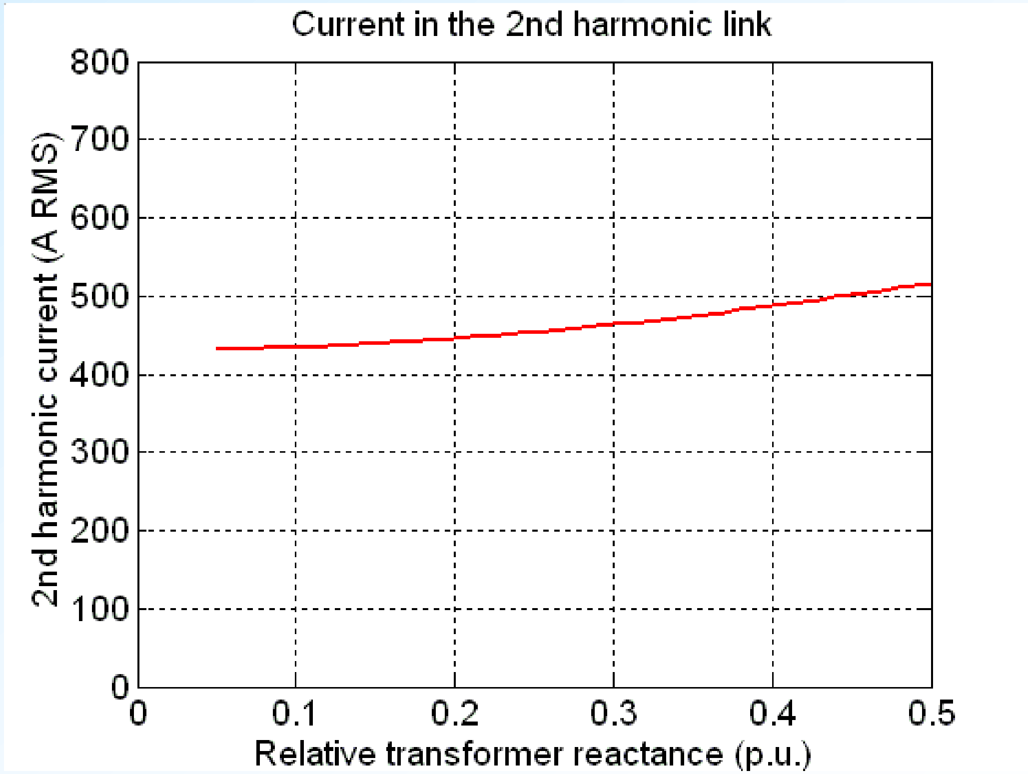
2nd harmonic link

- Low impedance at the 2nd harmonic $\Rightarrow$ reduced voltage ripple *(tolerances!)*
- Supplies the reactive power to the main transformer



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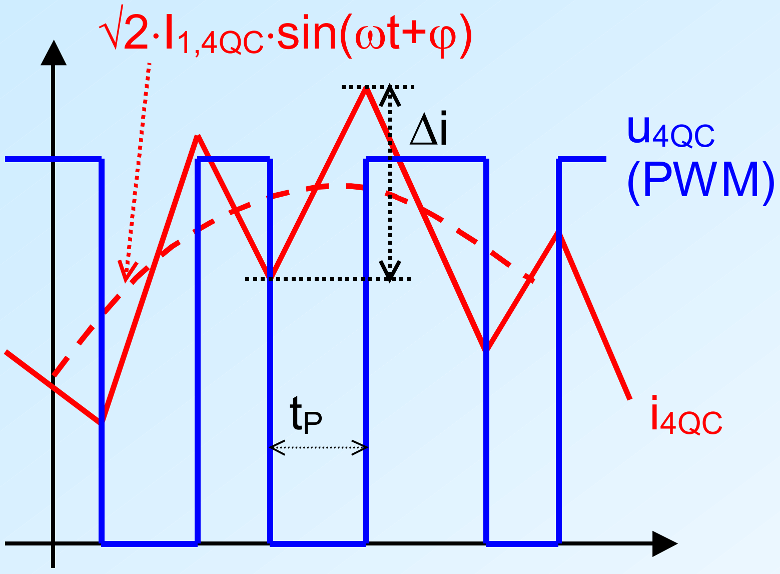
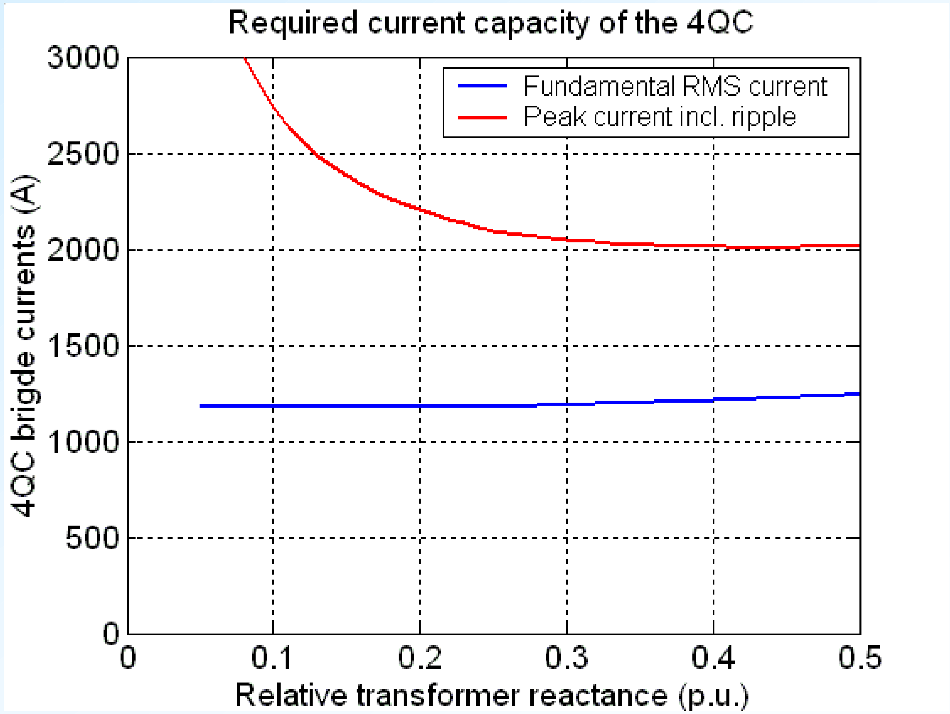
4QC currents



4QC peak current



A big transformer allows for a smaller converter!

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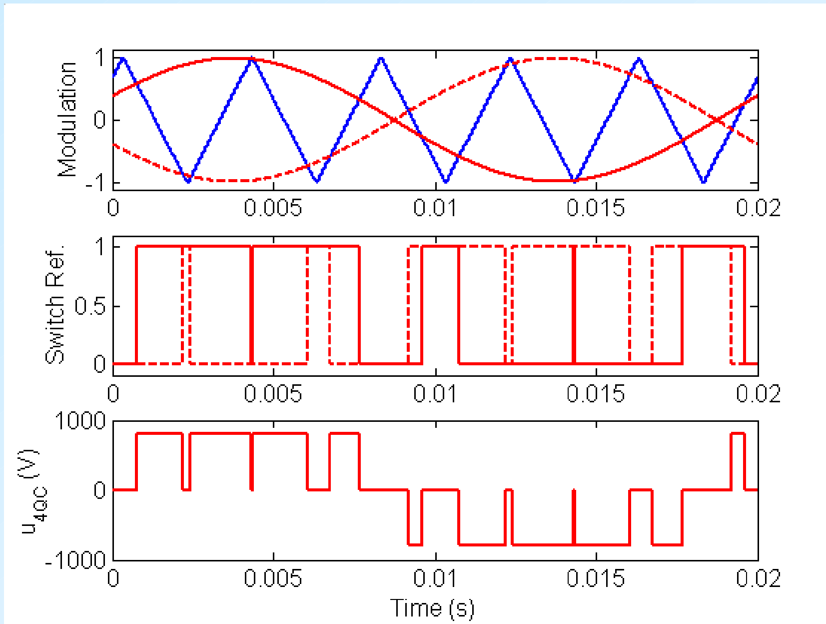
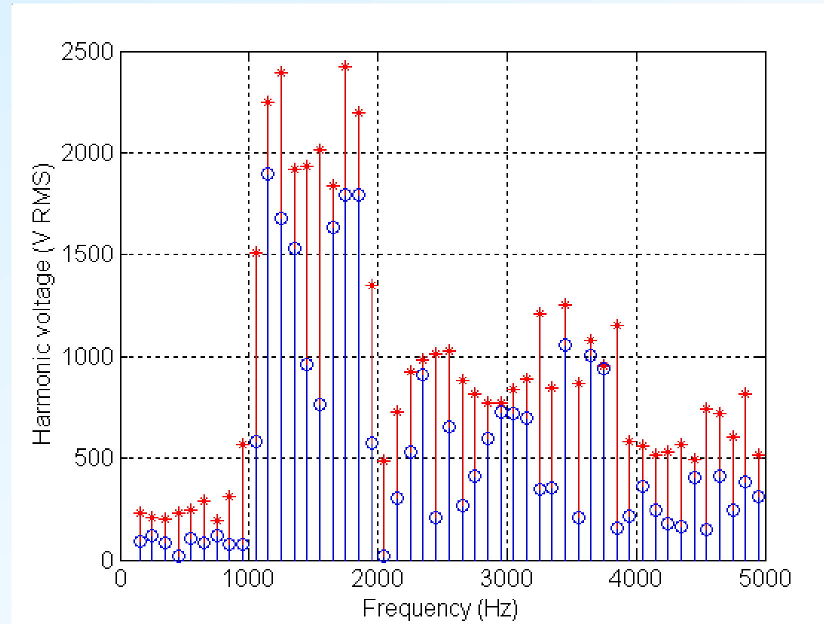
4QC voltage spectrum





4QC modulation

Voltage spectrum, primary side

(3 interlaced bridges)

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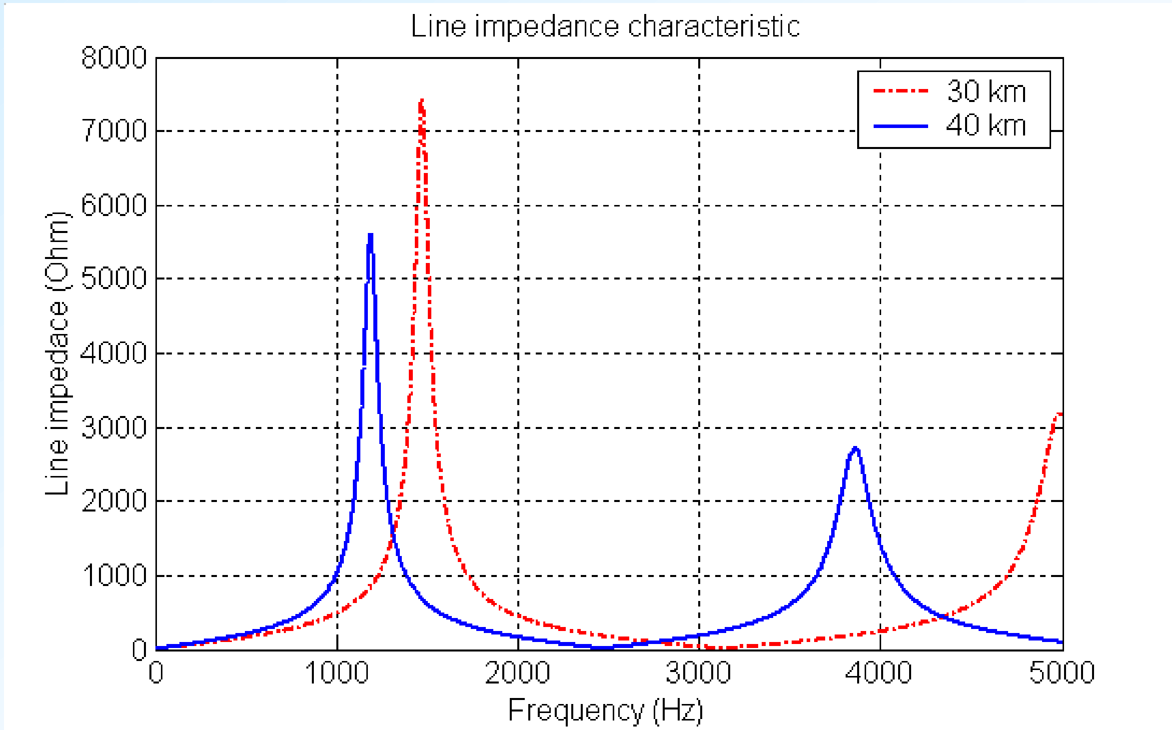
Line impedance

OHL impedance parameters:

- R_{SERIES}
- L_{SERIES}
- C_{SHUNT}
- G_{SHUNT}

$Z_{LINE}(f)$ is subsequently inductive and capacitive, with parallel (highs) and series (lows) resonance points.



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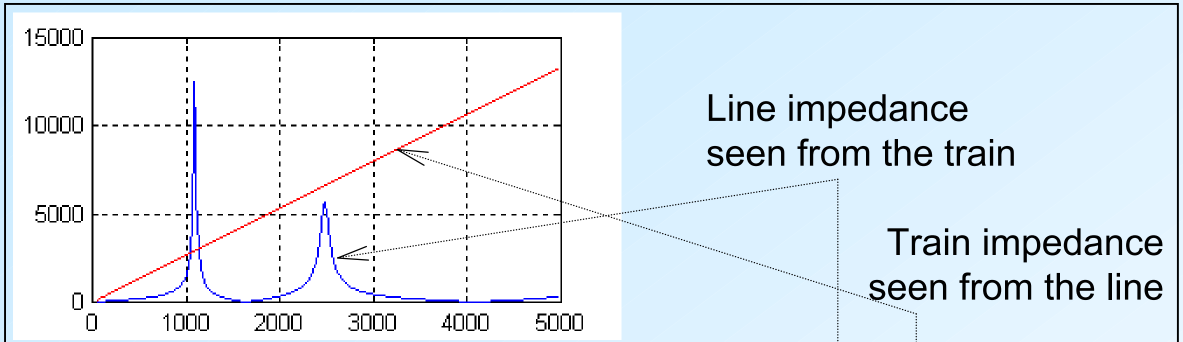
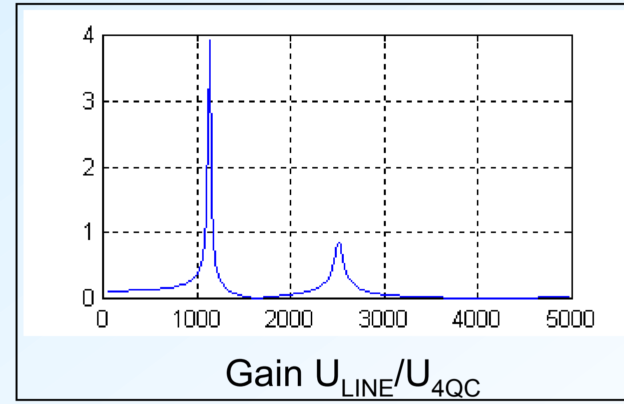
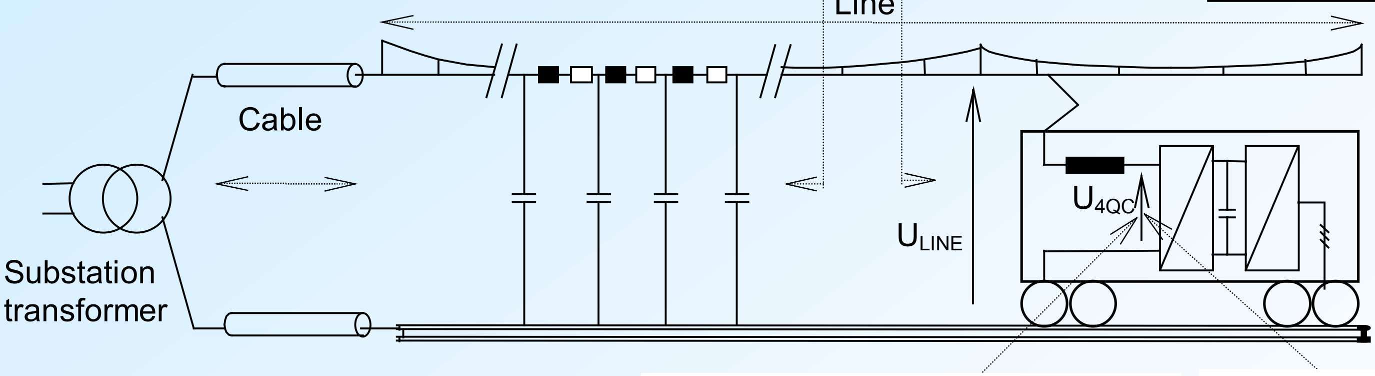
Line-vehicle resonance



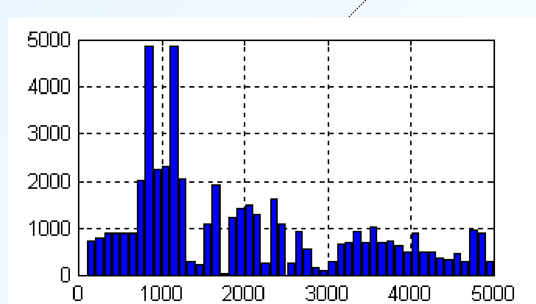


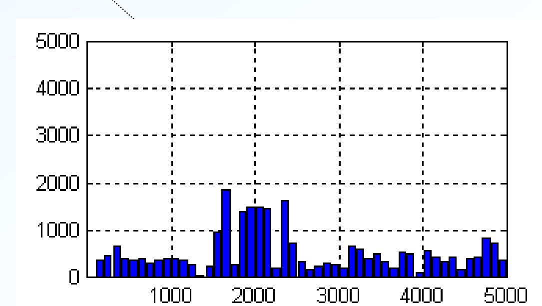


Resonance between the capacitive line and the inductive train (transformer) causes amplifications of harmonics

Examples, 4QC voltage spectra.
50 Hz line frequency,
250 Hz switching frequency.

Left: 2 interlaced bridges
Right: 4 interlaced bridges





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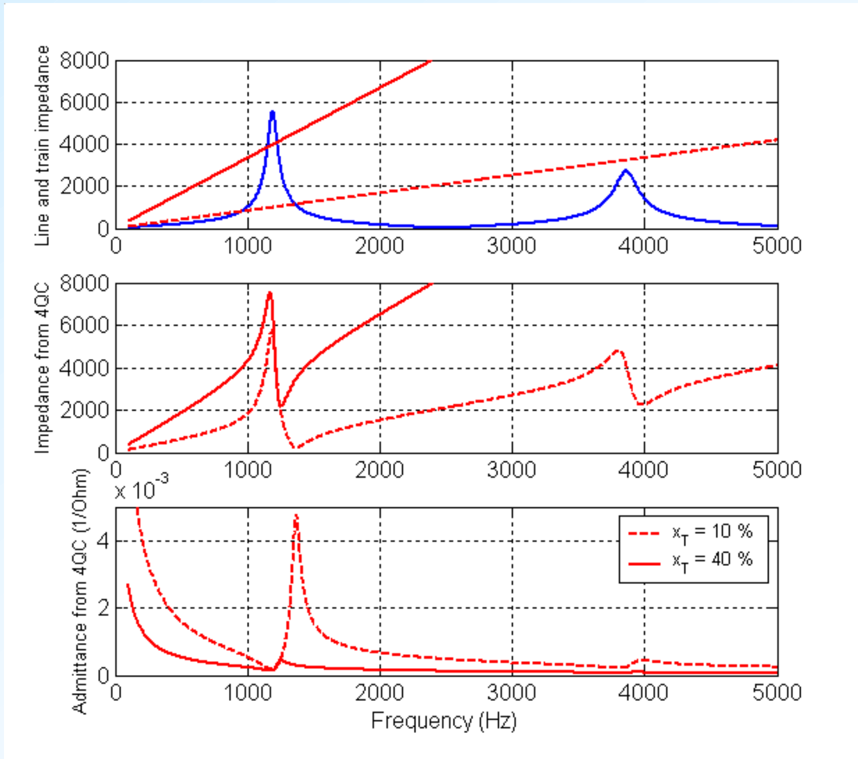
Line-vehicle resonance

- Seen from the 4QC, the transformer and the line are in series
- The impedance of the series connection of an inductive transformer and a capacitive line is lower than the impedance of the transformer alone
- A high admittance is seen at the resonance point where $|X_L| = |X_C|$



From top:

- Line and train impedance
- Impedance seen from 4QC
- Admittance seen from 4QC

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Relative admittance seen from the 4QC

Relative transformer reactance e_X	10 %	40 %
Z_{LINE} is assumed to be 0	*4*	*1*
The real line impedance is considered	*22*	*2.1*

- A high e_X is advantageous
- The ”conservative” estimate Z_{LINE} = 0 is wrong!

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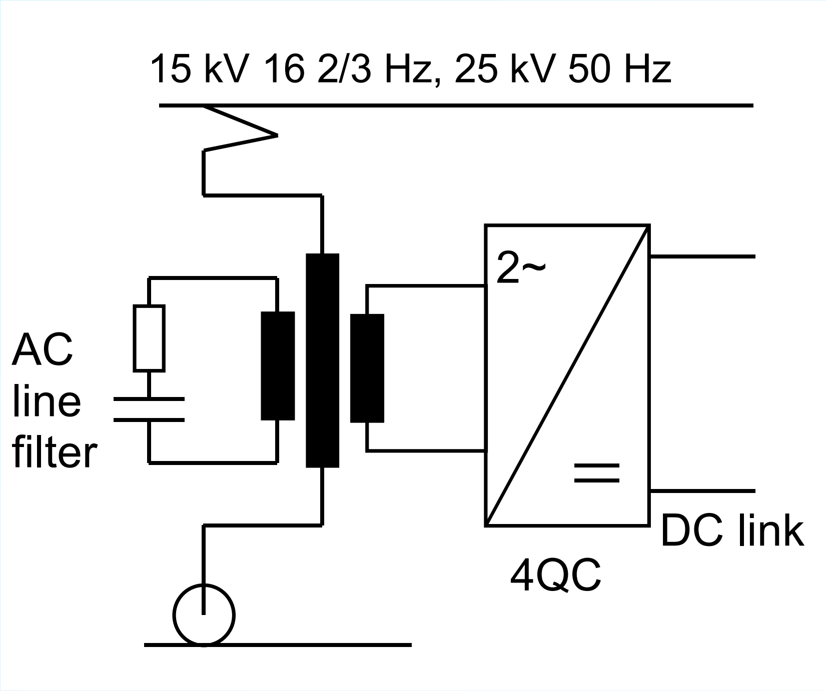
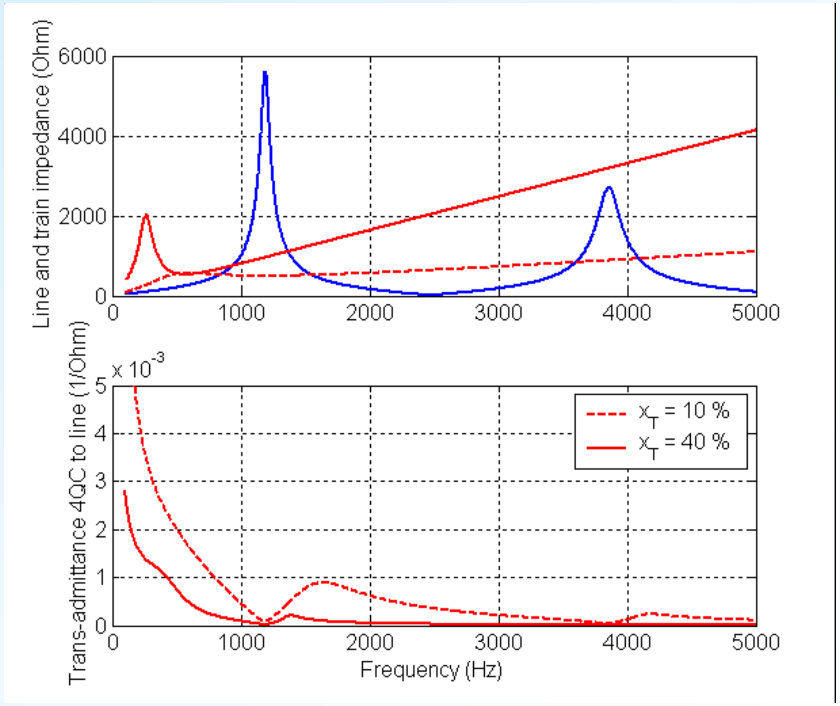
AC line filter





- R damps the resonance
- C reduces power losses
- Option: L parallel to R

- Upper: Line and train impedance
- Lower: Trans-admittance from 4QC to line

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Relative (trans-) admittance 4QC to line

Relative transformer reactance e_X	10 %	40 %
Z_{LINE} is assumed to be 0 or real line and filter	*4*	*1*
The real line impedance is considered, no filter	*22*	*2.1*

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Dual voltage operation (AC and DC)

Step-up chopper or direct-on-line?

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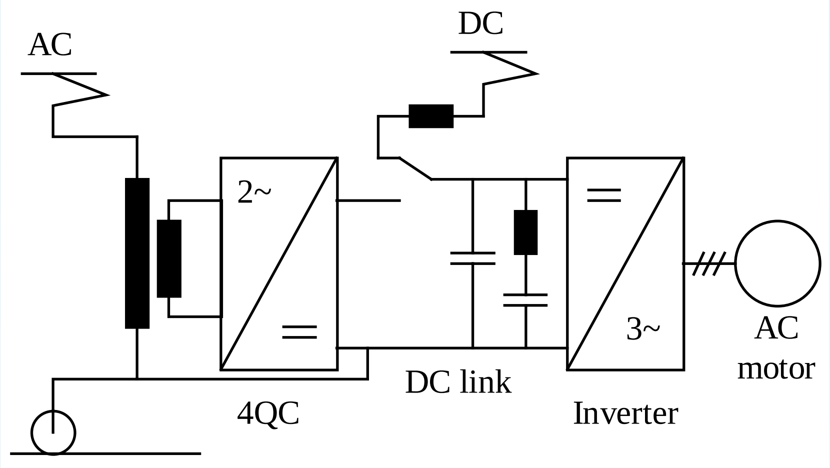
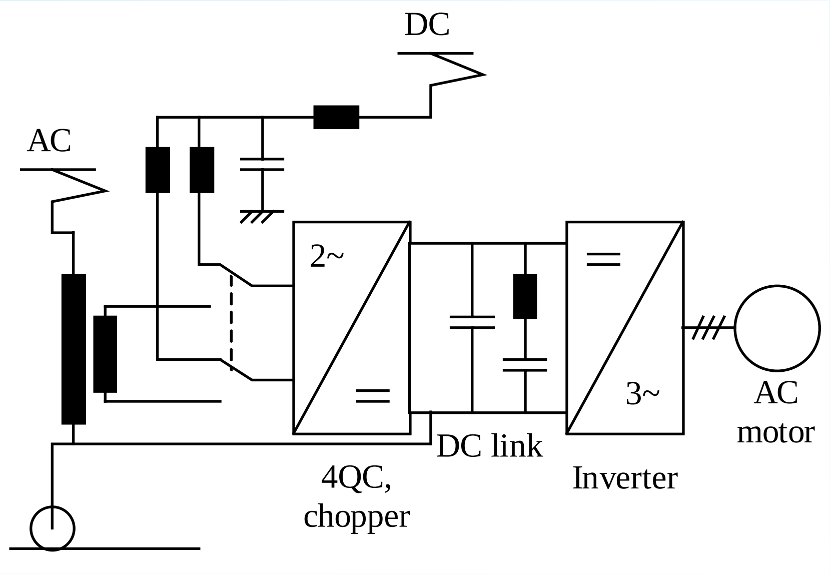
Dual voltage systems (DC and AC)





- Direct-on-line DC
- ≈ 750 V DC link

- Step-up choppers
- > 1000 V DC link

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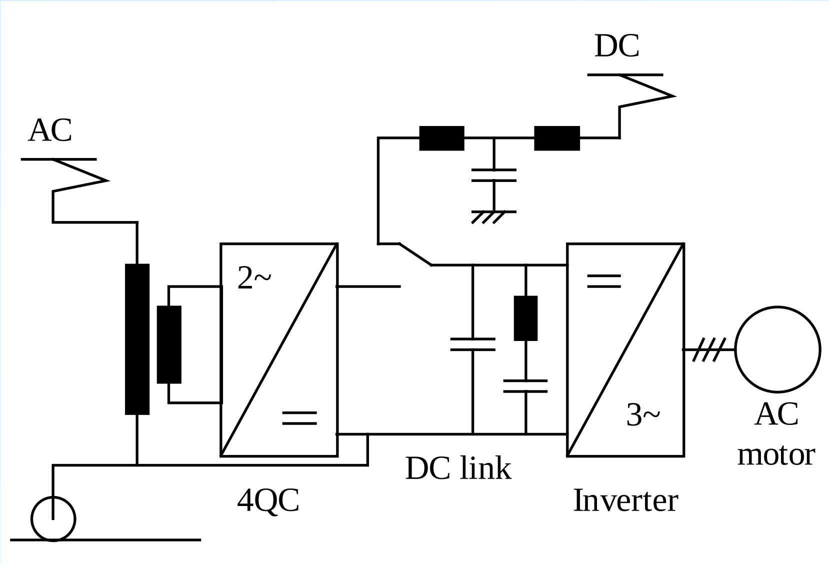
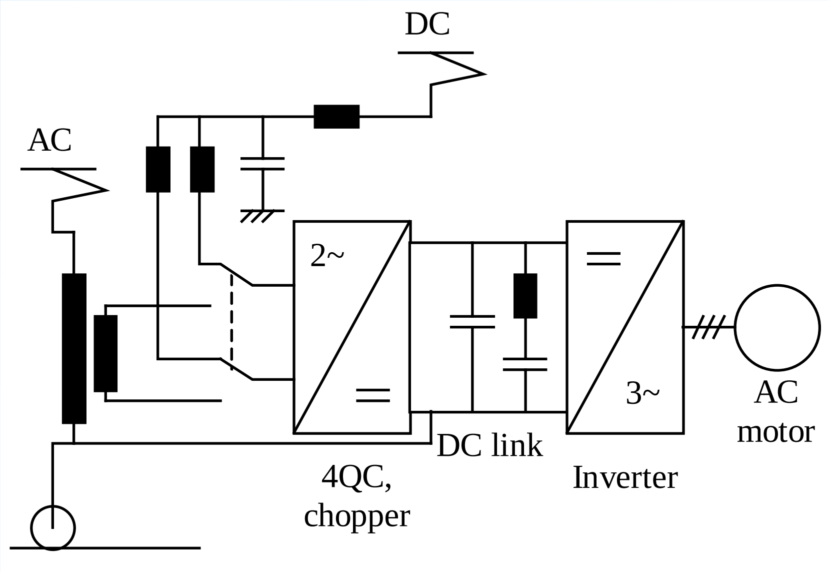
Comparable 4th order filter configurations





Equal power rating of components in equal positions gives basically equal performance

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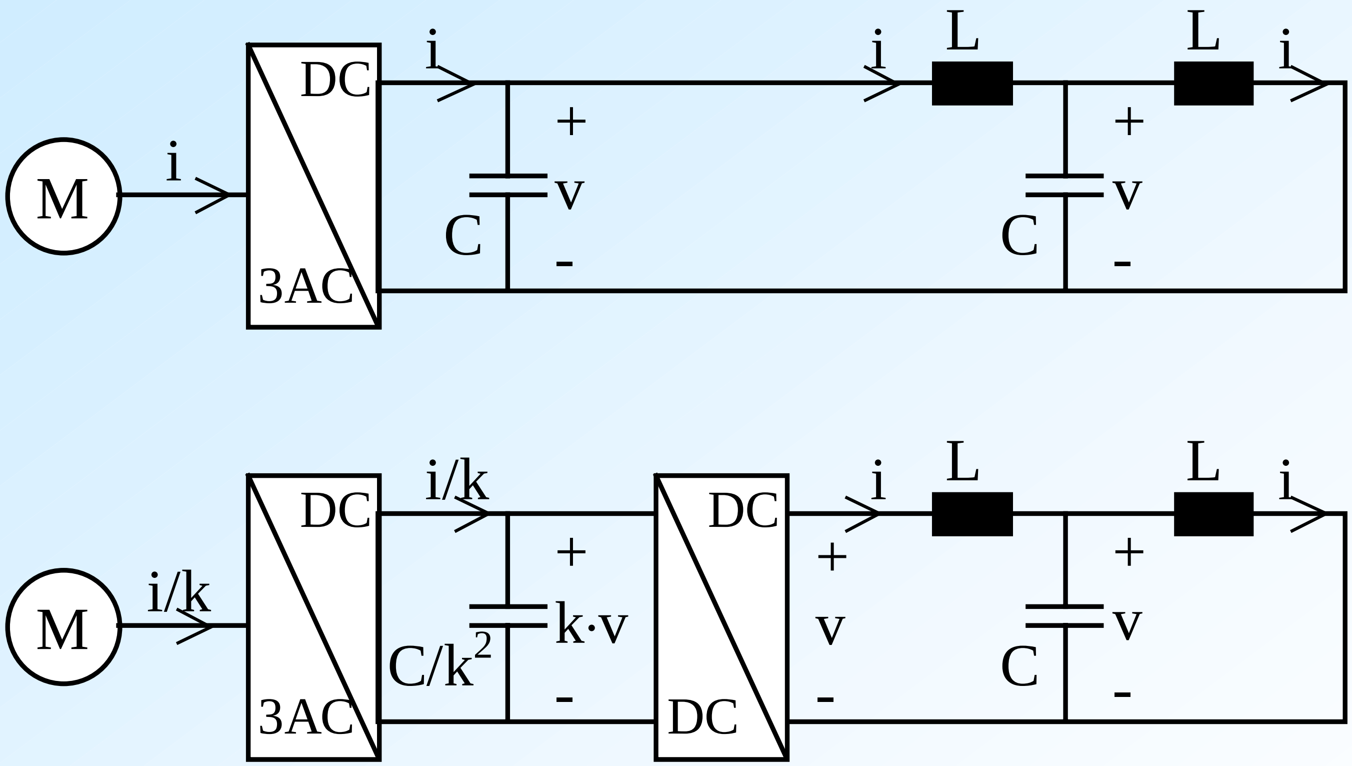
Relative currents and voltages



Equal power lead to basically equal interference levels

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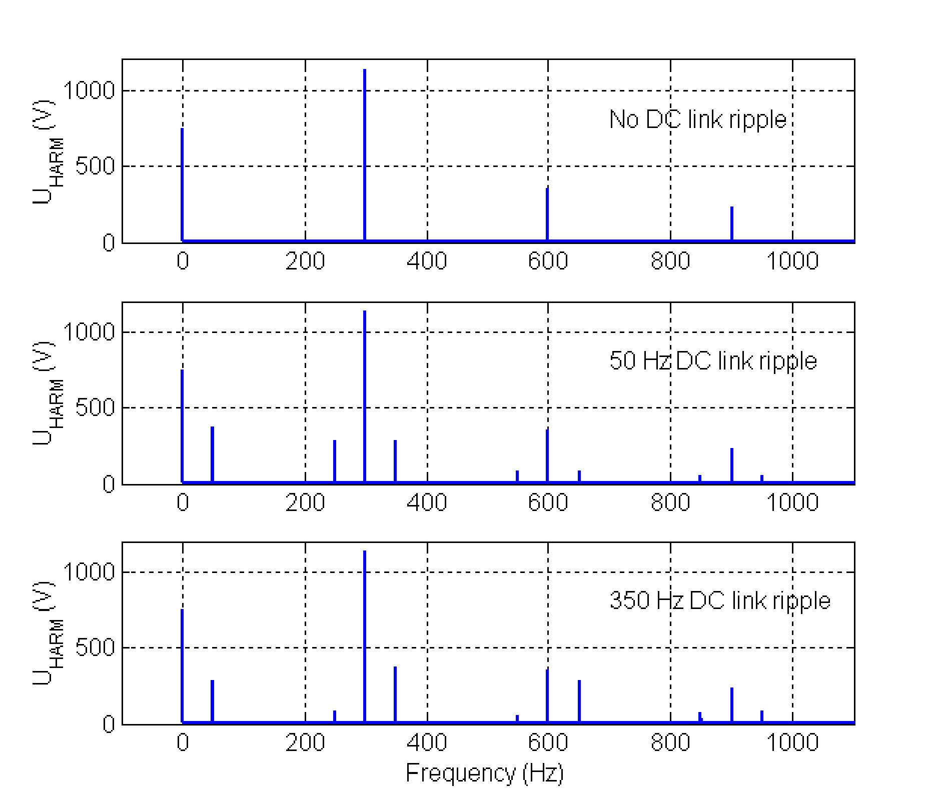
Harmonic intermodulation

- If the DC link voltage (the high voltage side of the chopper) is ideally smooth, only the chopper frequencies (here n·300 Hz) are seen at the low voltage side.
- Any DC link ripple, e. g., at 50 Hz, is also seen at the LV side. The chopper acts as a transformer.
- But also a 350 Hz ripple causes a 50 Hz component, due to intermodulation with the 300 Hz chopper frequency.



Harmonic components at the LV side

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Dual system - conclusion

- Step-up choppers should only be used if the traction power is so high that the current rating of the 3-phase inverter becomes impractical at direct-on-line supply.

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Testing and approval

Interference tests

Tractive effort tests

Compatibility tests

Winter tests

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The purpose of testing

- Convince yourself
- Convince your customers
- Convince the responsible authorities

Convince yourself

- Component tests
- Subsystem and prototype tests
- Control systems tests using real time simulators
- Combined system tests and type test
- Commissioning and testing of 1st vehicle

” - I’m convinced. I have shown that my calculations are right”.

” - But I could easily make your equipment fail!”

Convince your customer

- Run time tests
- Endurance tests
- Tractive effort tests
- Climatic tests

Convince the authorities

- Deregulations $\Rightarrow$ undefined situations in most European countries
- Every country is different
- Address this problem from day 1:
  - Technical requirements
  - Acceptance process

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Subjects for approval

- EU directives (e. g., EMC)
- International standards (EN, IEC, UIC)
- National legislation
- Local specifications (e. g., interference limits, climatic conditions, etc.)
- What has <u>not</u> been specified?
  - Local traditions
  - The already existing systems (vehicles, power supply)

Act responsible!