

Traction System Case Study

Lars Buhrkall

Electrical engineer

Electrical drives, traction
systems, and compatibility

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!

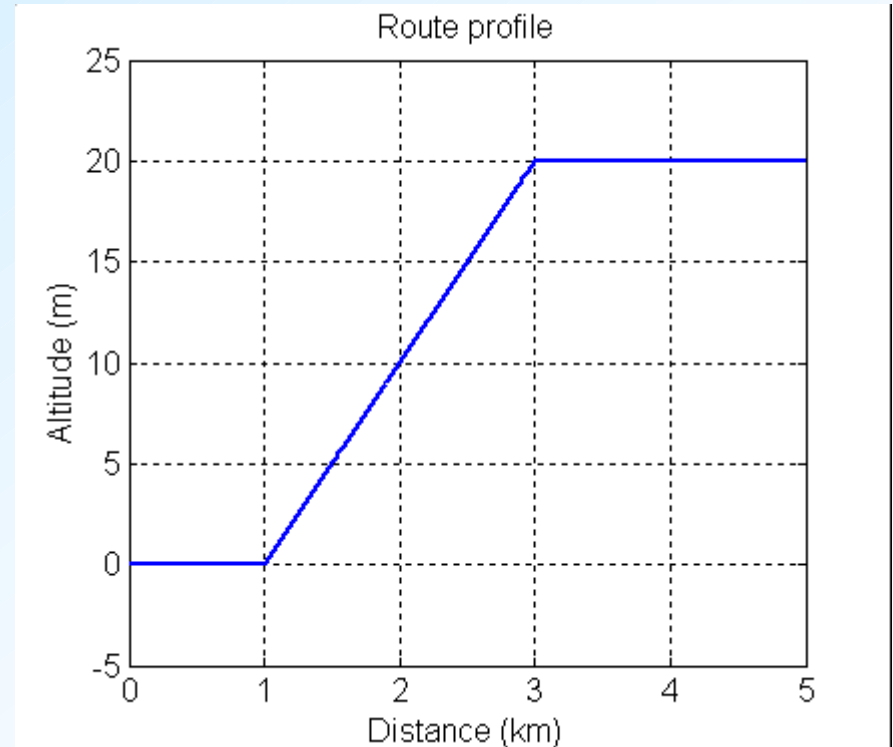
Why are trains different?



- Metro trains: All axles driven, small motors
 - High speed trains: Locomotives, high power
- Q: How many motors, and how much power?

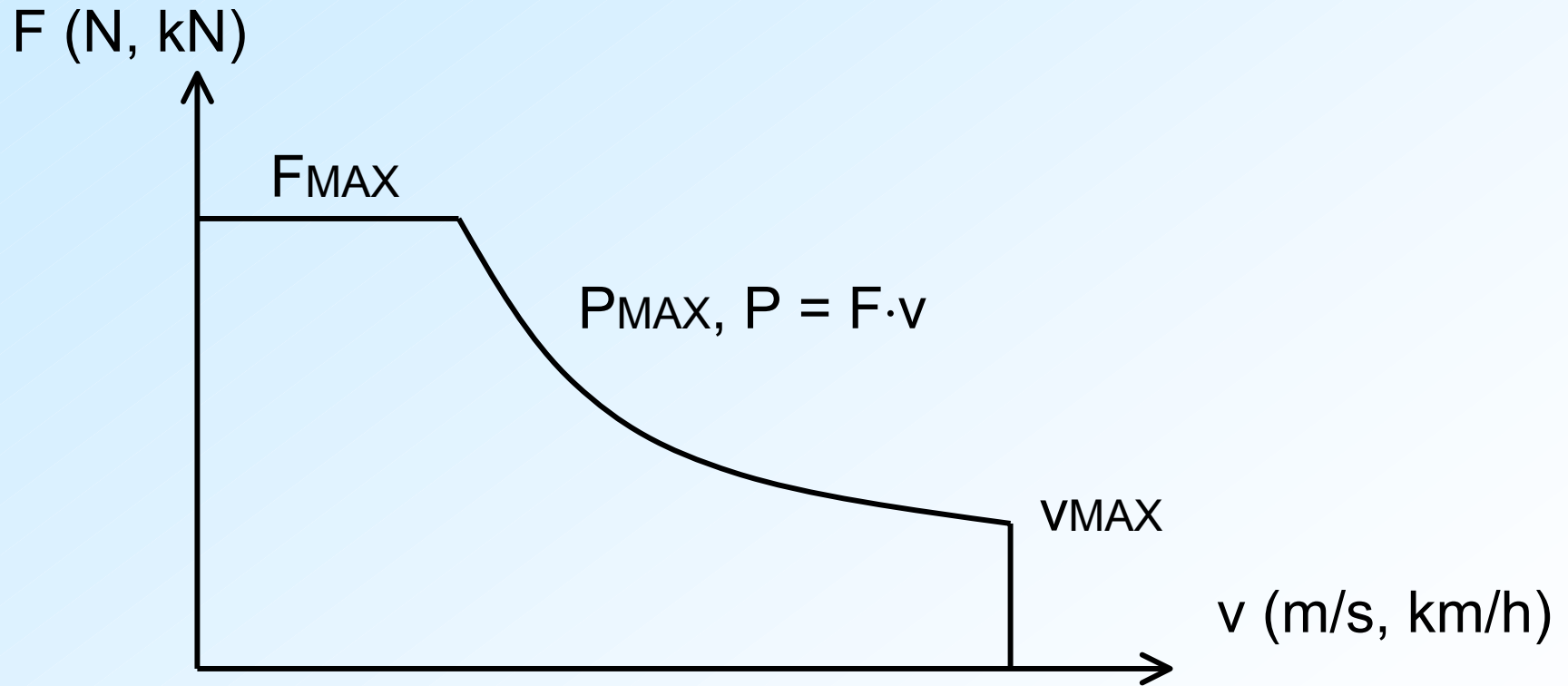
Performance Specification

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



Route profile

Generic Tractive Effort curve



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

Maximum tractive effort

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

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:

$$F_G(s) \approx m \cdot g \cdot G(s) / 1000 \quad (G \text{ in } \%, G \leq 100 \%)$$

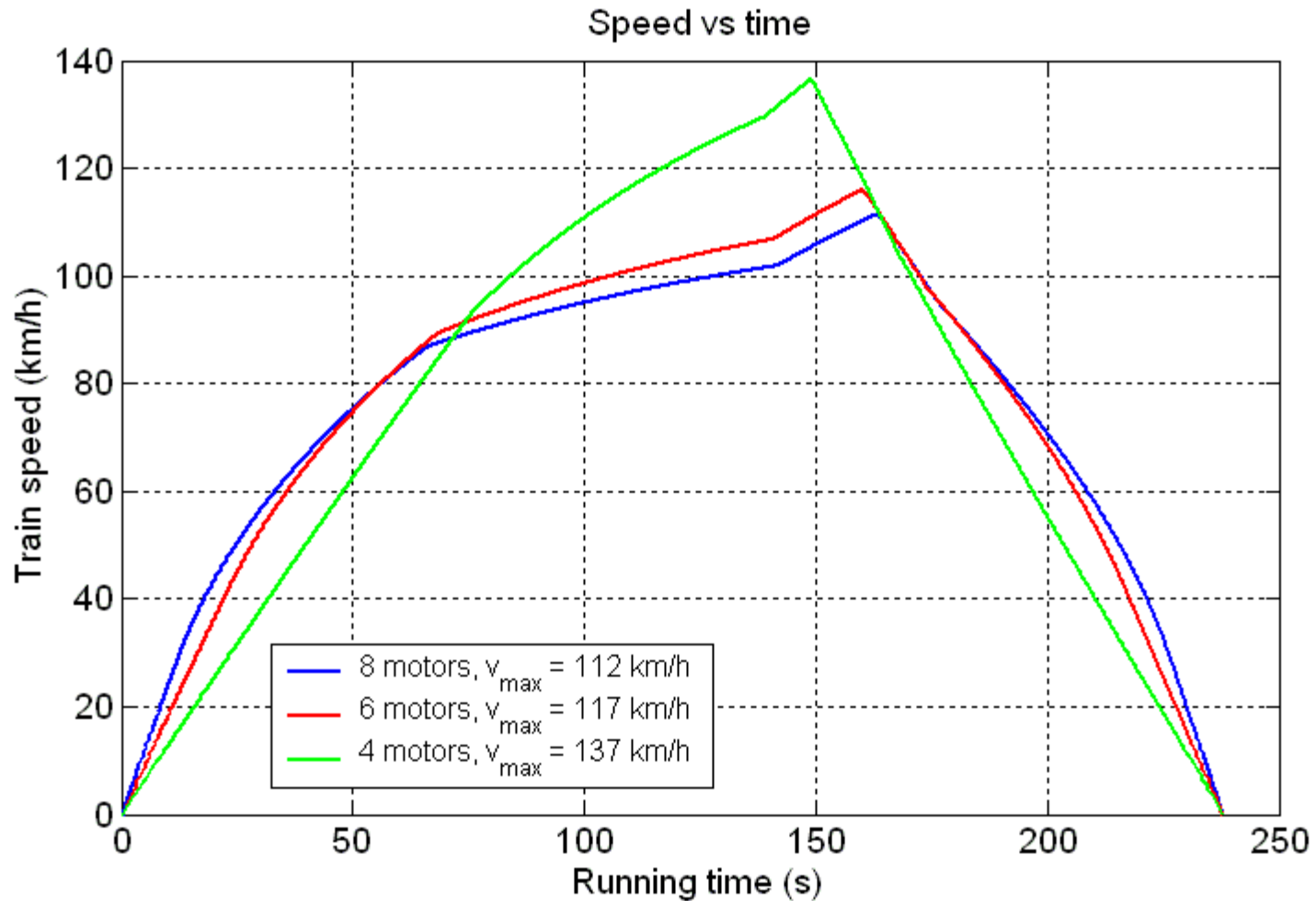
- Curve resistance: $F_C(s) = m \cdot g \cdot K / r$ ($K \approx 0.75$)

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

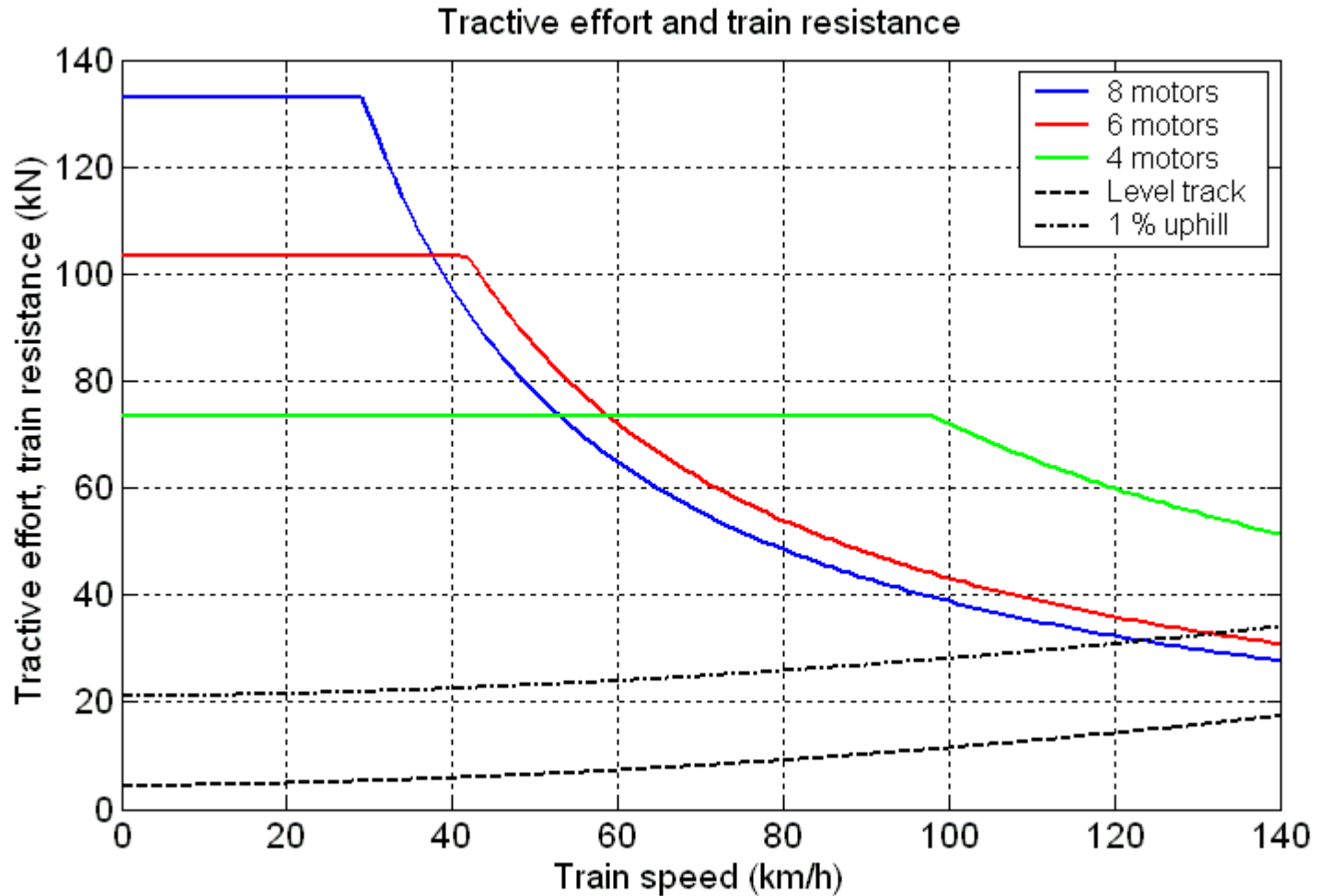
Performance Simulation

- 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
$$a = F(v(s-\Delta s))/m_{\text{dyn}}$$
 and $\Delta s \approx 1 \text{ m}$
- Time vector $t(s)$:
$$t(s) = t(s-\Delta s) + 2 \cdot \Delta s / (v(s) + v(s-\Delta s))$$

Calculated run times



TE curves



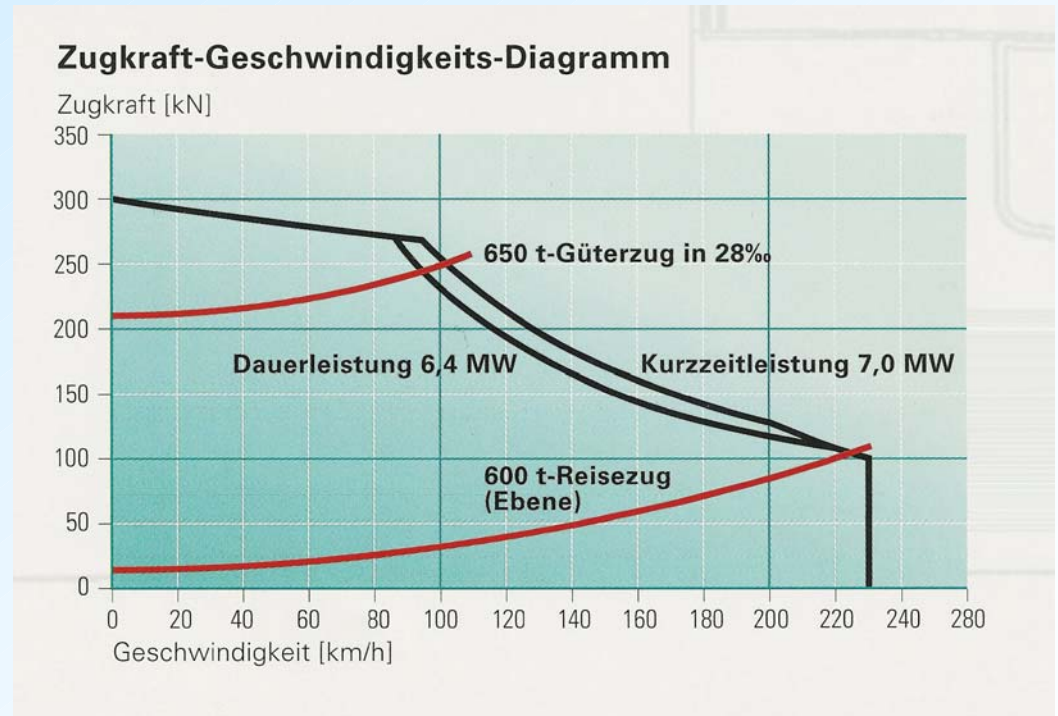
Spec compliant systems

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

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			(+)	+

Motor and inverter size

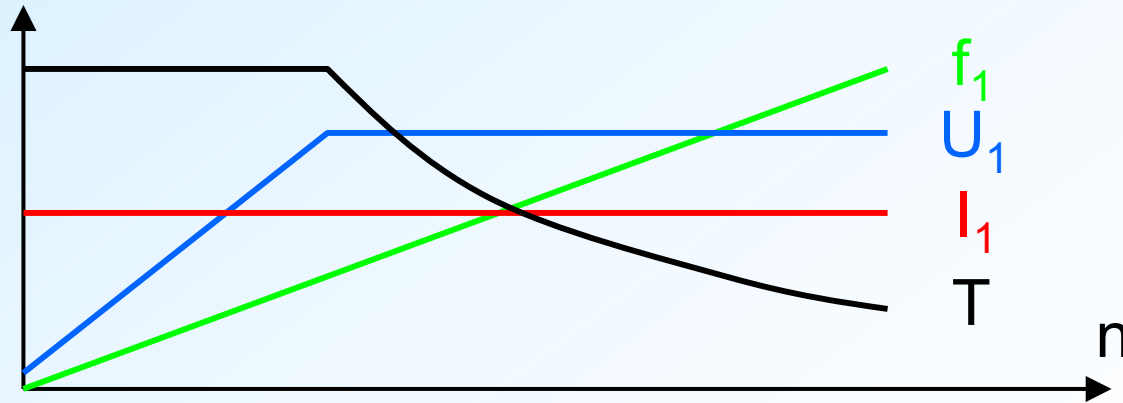


Why is the short-term power reduced at high speeds?

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)
- $P \sim U_1 \cdot I_1$, $T \sim P/n$



Motor torque

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

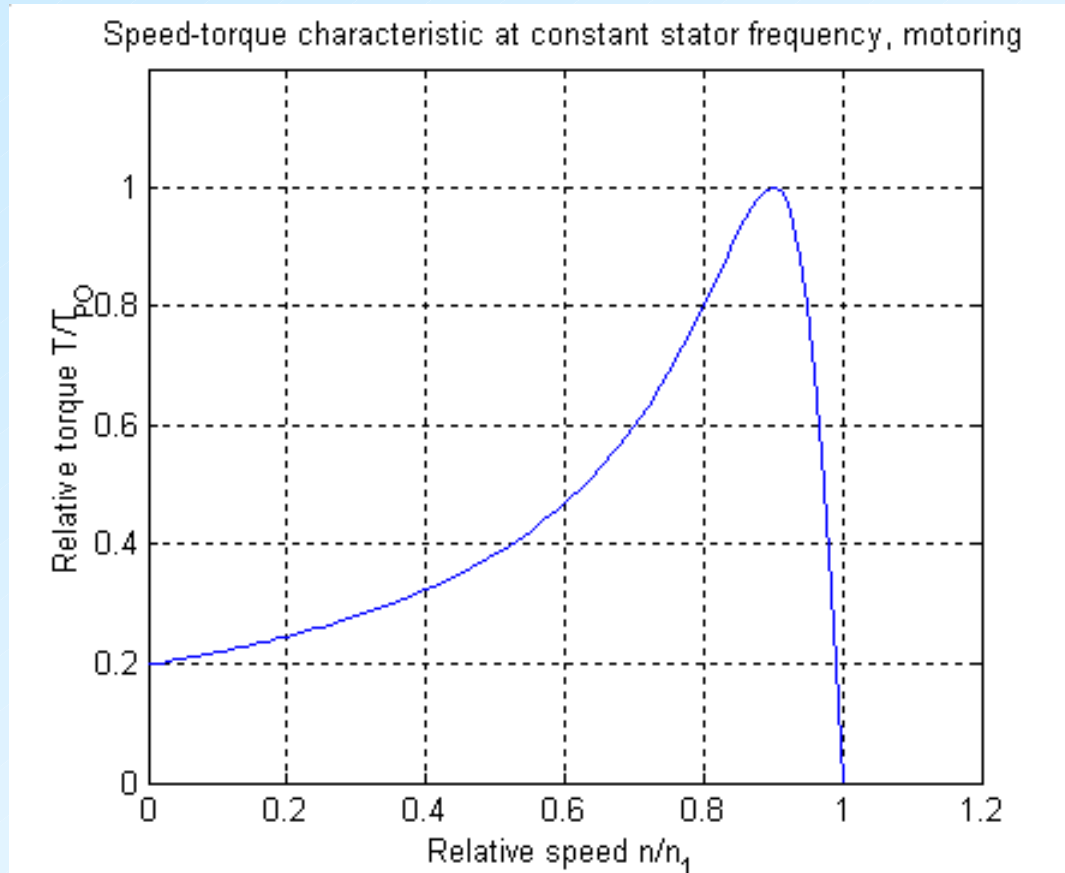
V_{ROTOR} = active rotor volume

J = stator current surface density

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

ϑ_i = angle between J and B vectors
(*increases at increasing J , \Rightarrow pullout!*)

Pullout torque



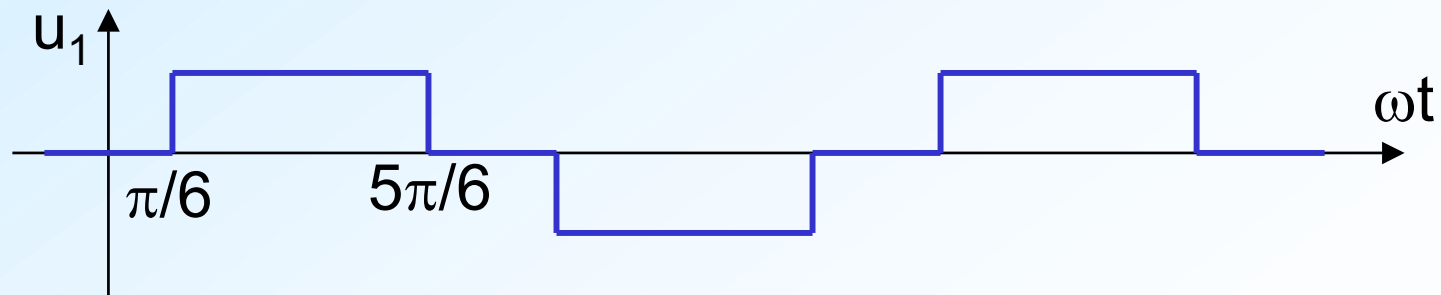
Speed-torque characteristic at constant stator frequency

Pullout torque limit at high speed

Pullout torque vs. voltage and frequency:

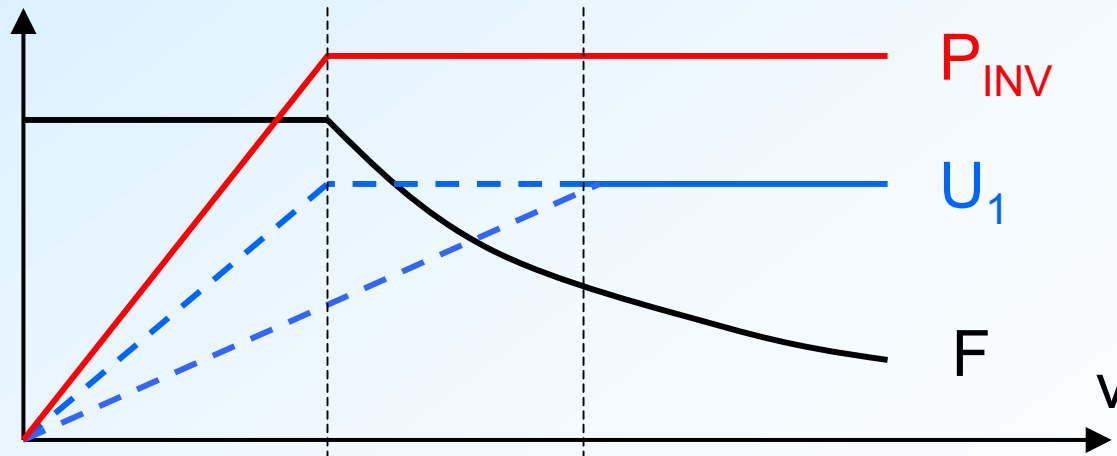
$$T_{PO} = (k_2/L_\sigma) \cdot (U_1/f_1)^2,$$

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



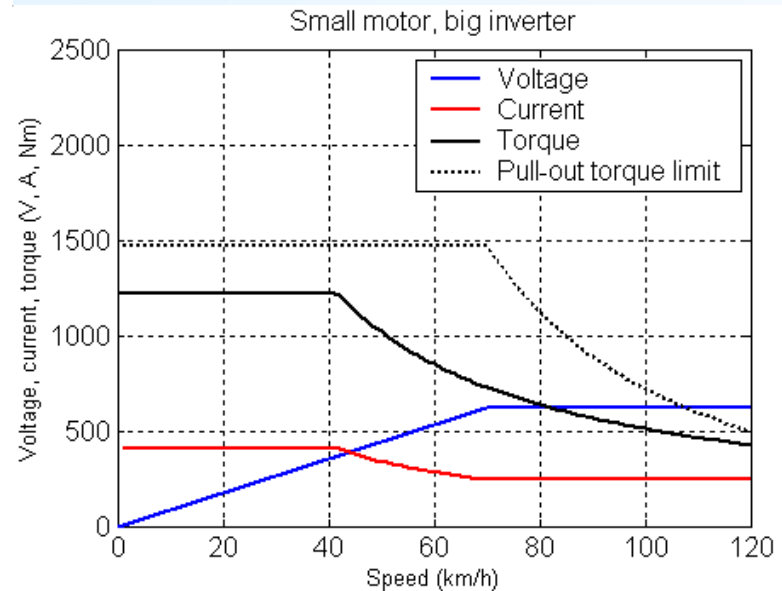
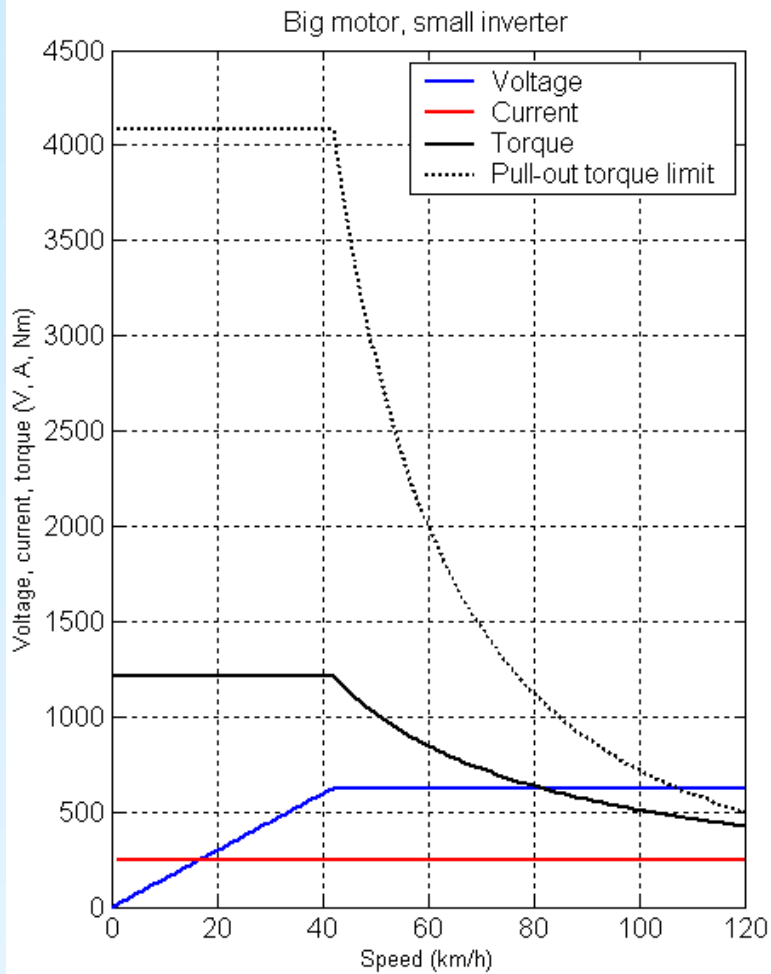
Inverter power and current

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



Two different designs, equal performance

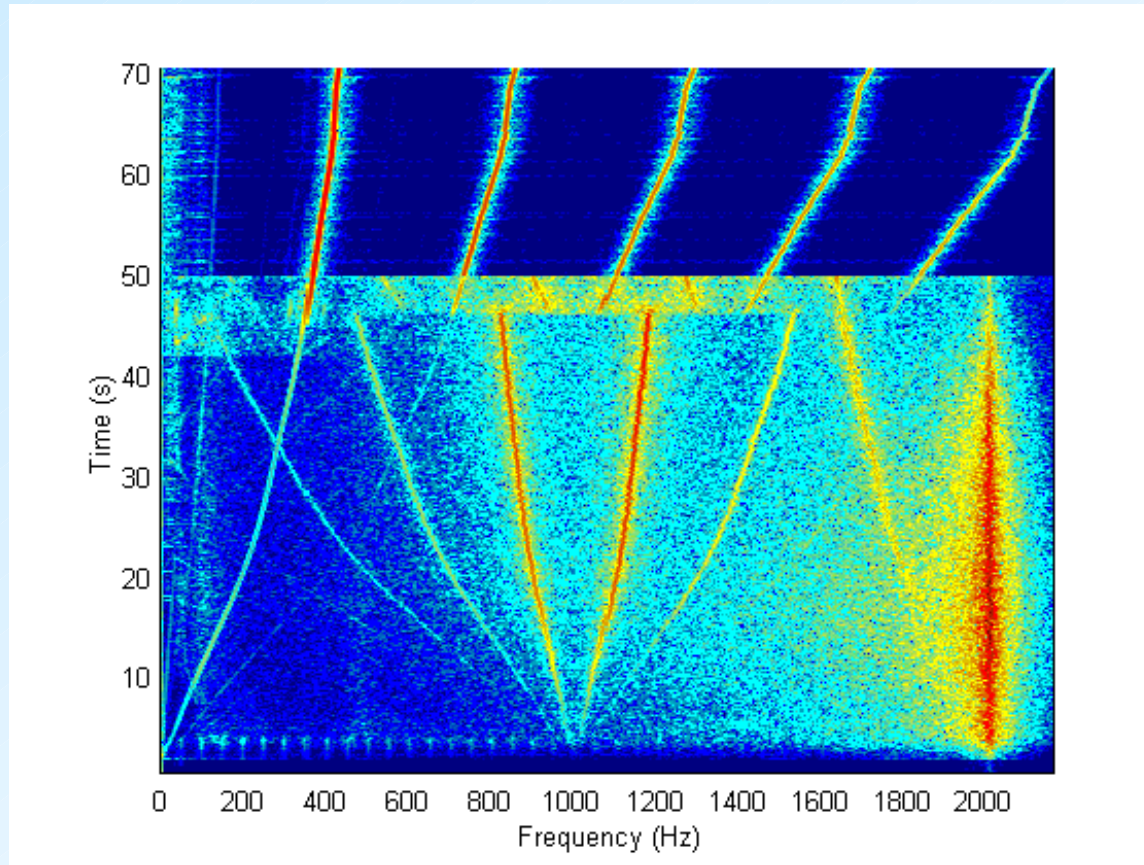
- Motor size \sim max. torque
- Inverter size $\sim U_{MAX} \cdot I_{MAX}$



Comparison of the two designs

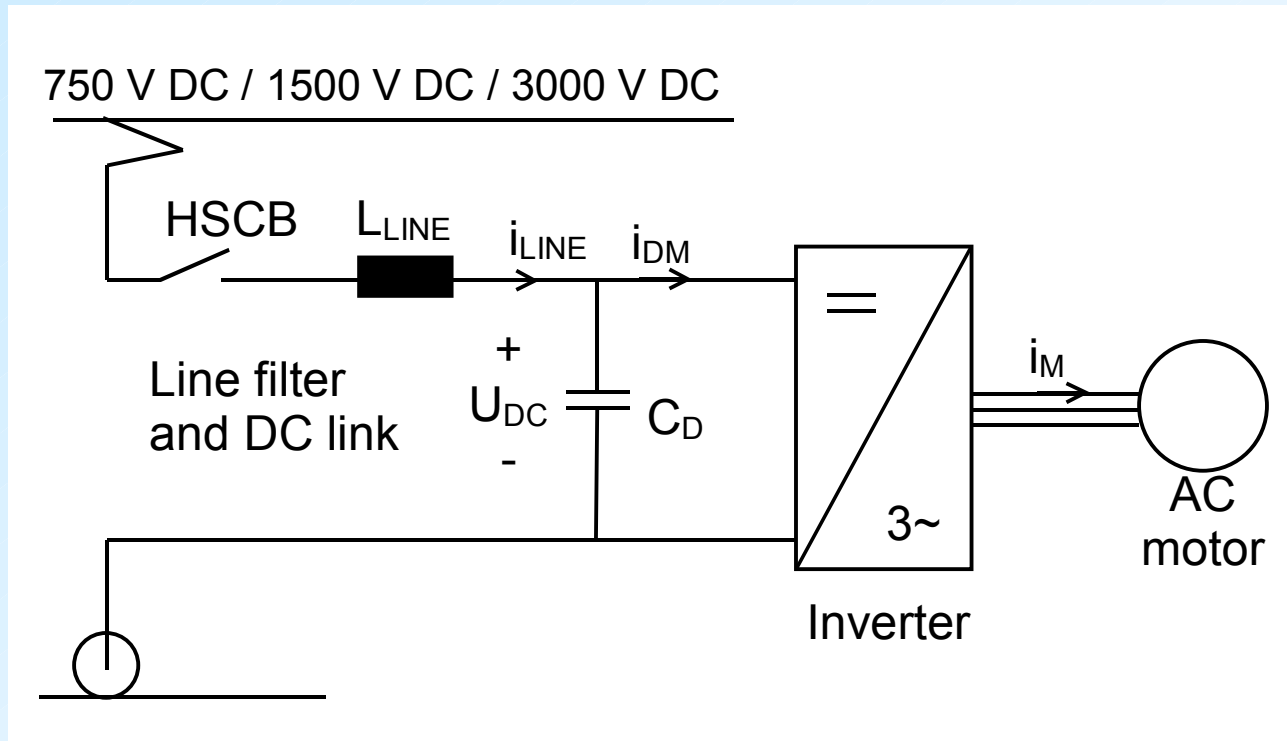
	Big motor, small inverter	Small motor, big inverter
Relative motor size (V_{ROTOR})	2.8	1
Relative inverter size ($U_{\text{MAX}} \cdot I_{\text{MAX}}$)	1	1.7
Requirements on motor cooling	<i>Low</i>	<i>High</i>

DC Traction and Line Filters



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

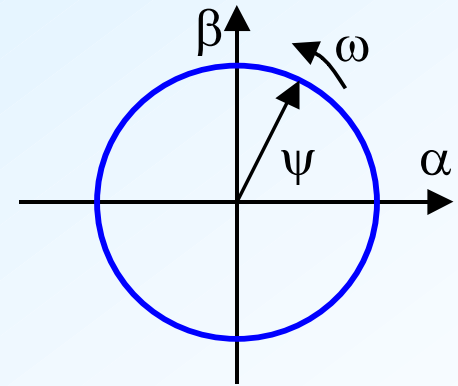
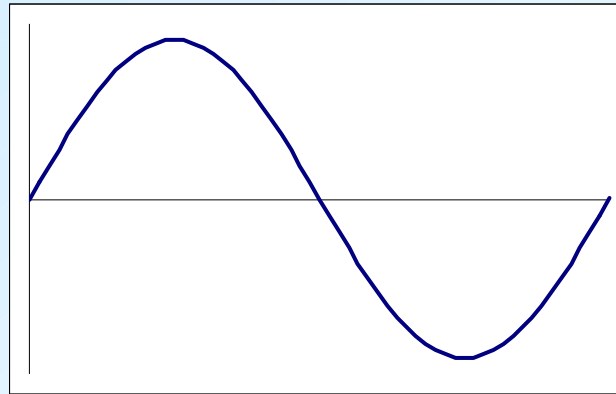
DC Traction Systems



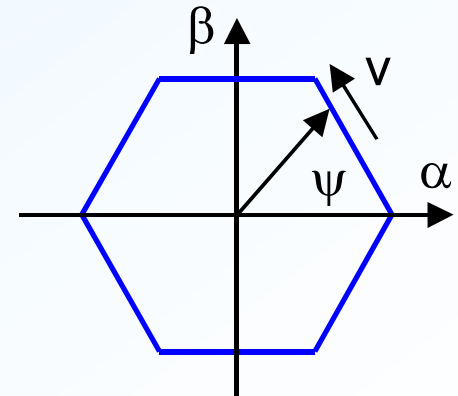
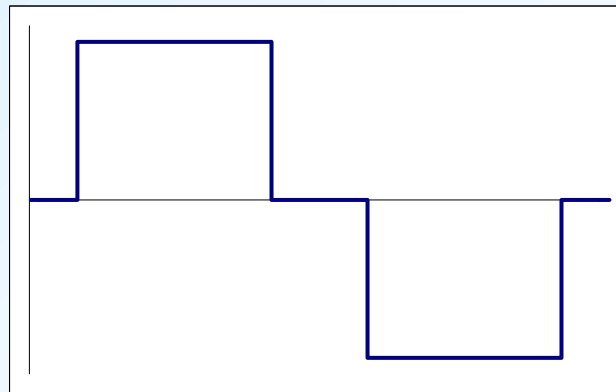
Interference current generation mechanisms,
motor/inverter combination, and line filter design

Trajectory of the stator flux vector

- Sinusoidal voltage \Rightarrow Circular flux trajectory



- Squarewave voltage \Rightarrow Hexagon flux trajectory

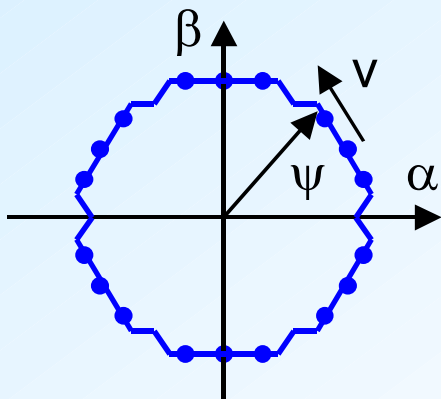


Base frequency and Reed track circuit interference

- 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!

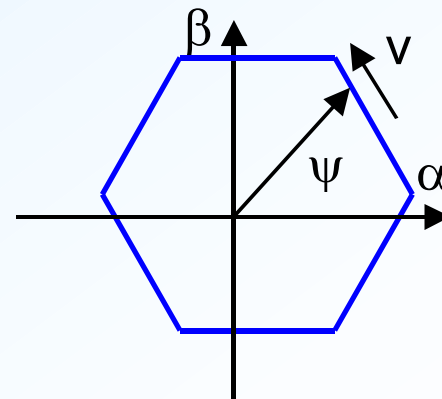
Low speeds

- 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} !



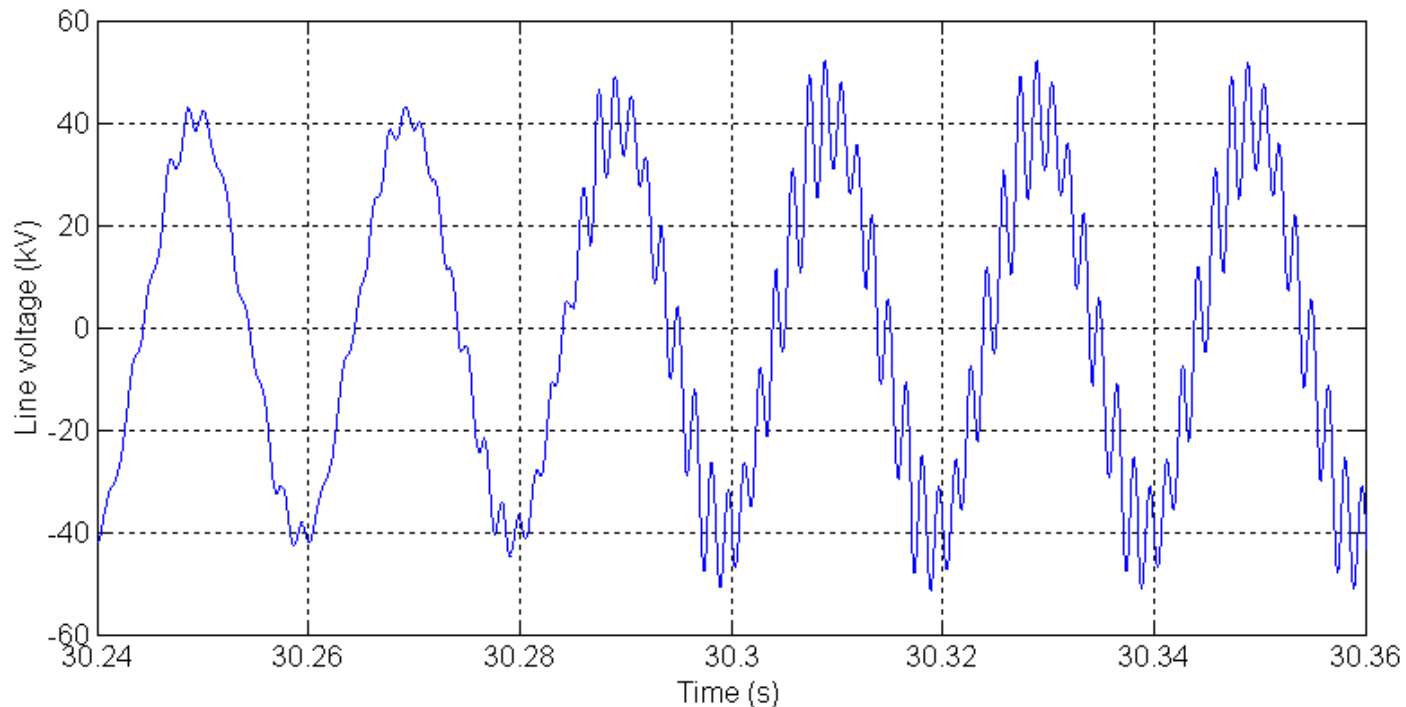
DC line filter

- Gain of 2nd order L-C filter:

$$i_{\text{LINE}} = i_{\text{DM}} / (1 - \omega^2 LC)$$

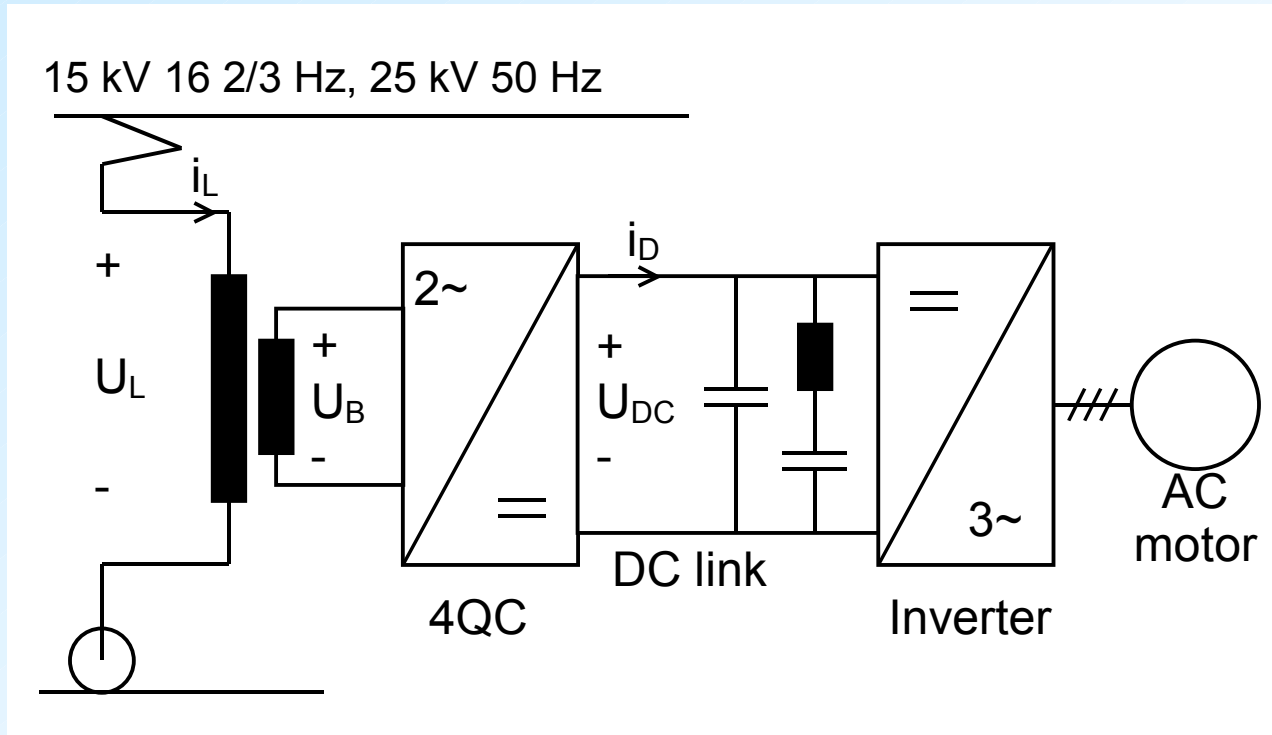
- Typical values:
 - Reed limit = 10 mA at 363 Hz
 - 6th harmonic = 200 A (*big motor, small inverter*)
- If C = 15 mF, then L ≥ 260 mH !!!
- Use small motor / big inverter combo, or 4th order filter, and/or cornerfolding

Line side circuits for AC-AC traction systems



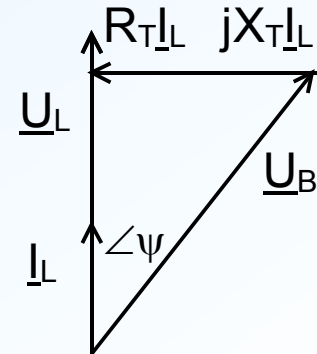
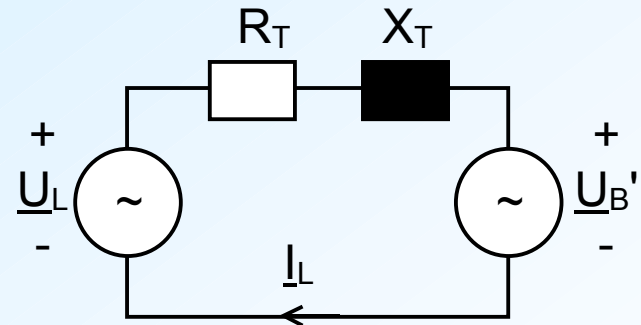
How do we avoid this line voltage wave shape?

AC-AC Traction



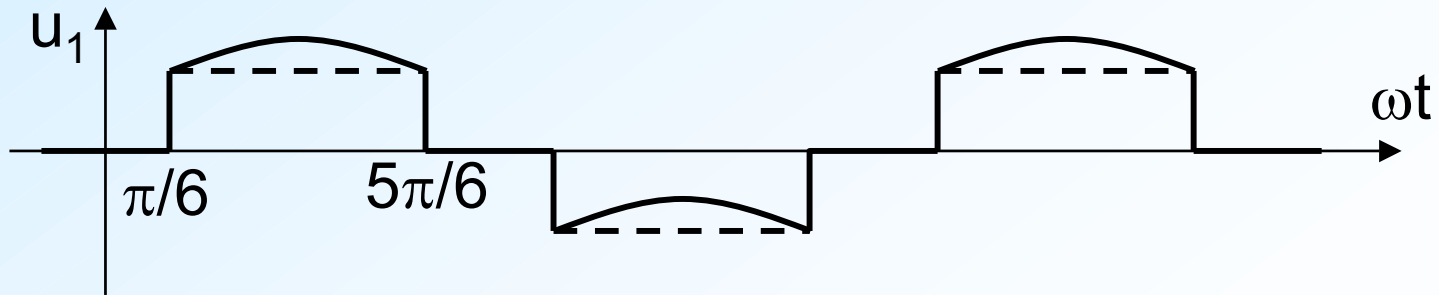
The short circuit impedance of the main transformer – a key parameter

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



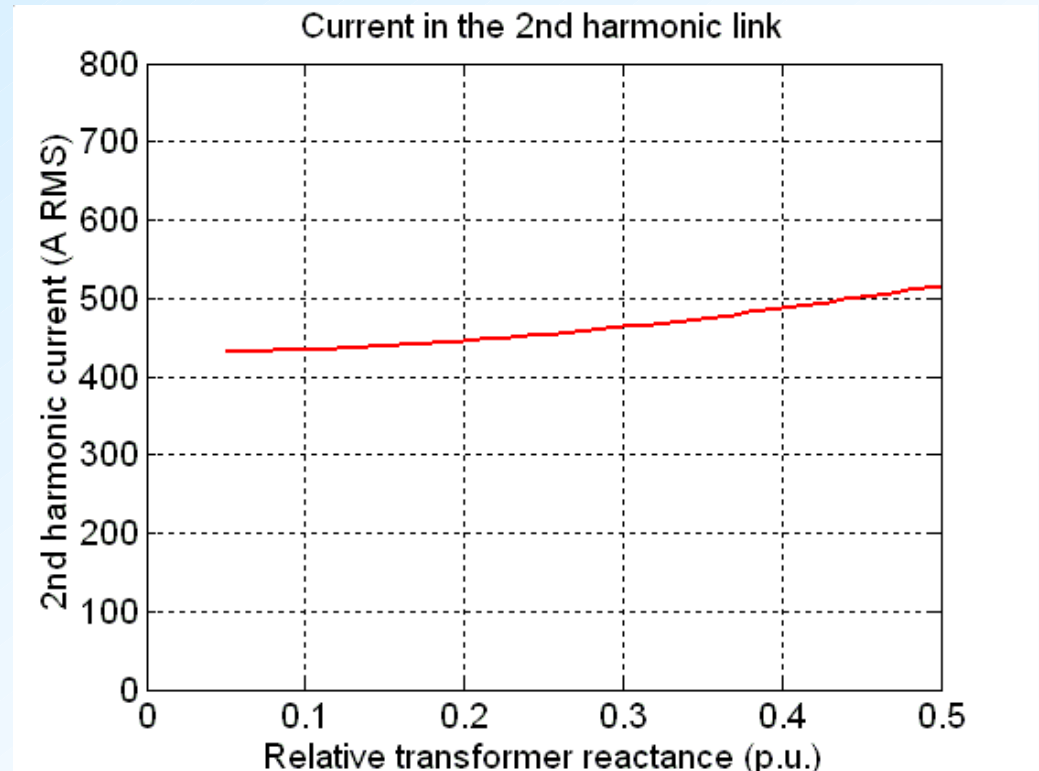
2nd harmonic current

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

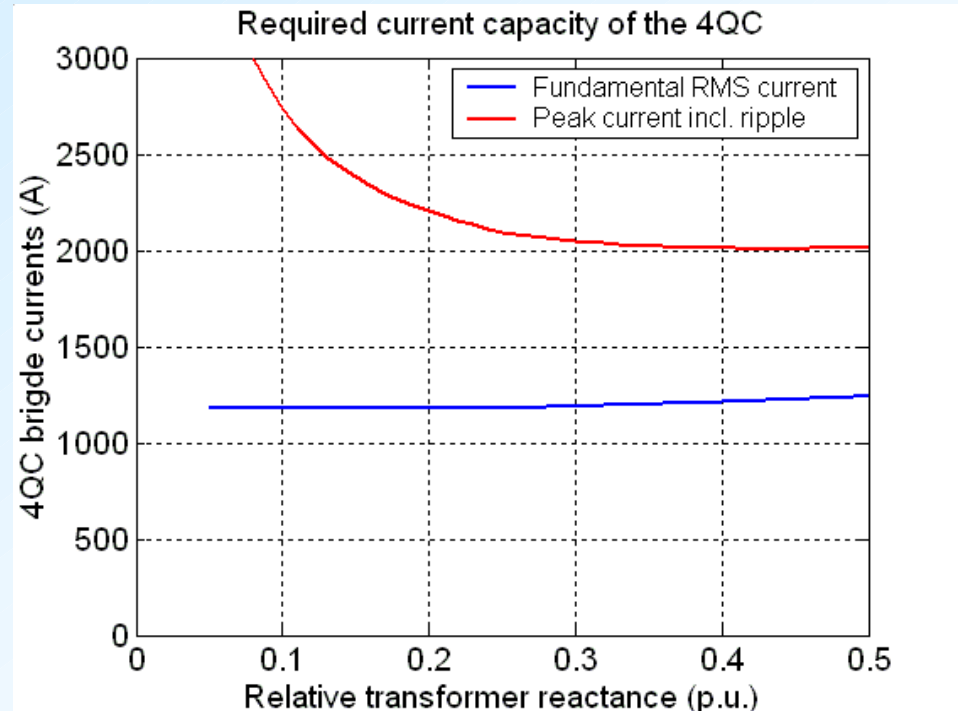
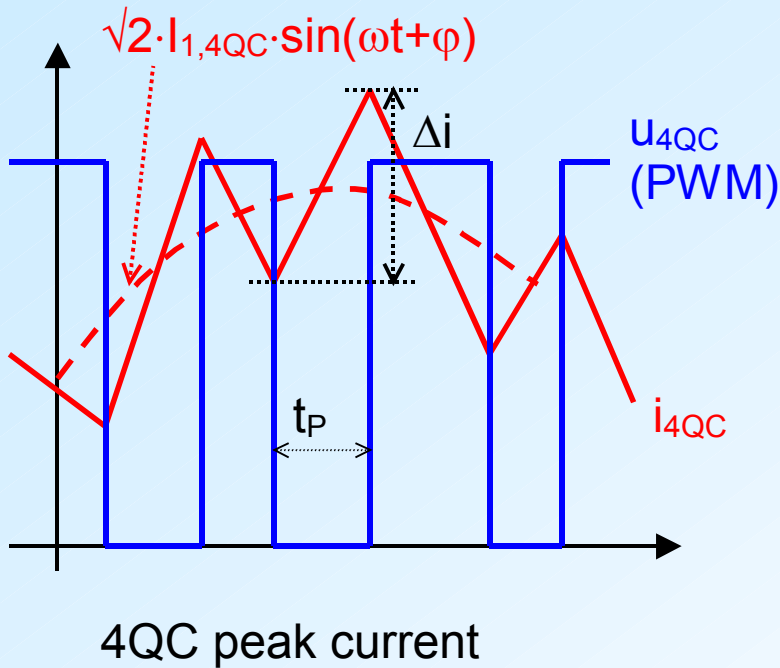


2nd harmonic link

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

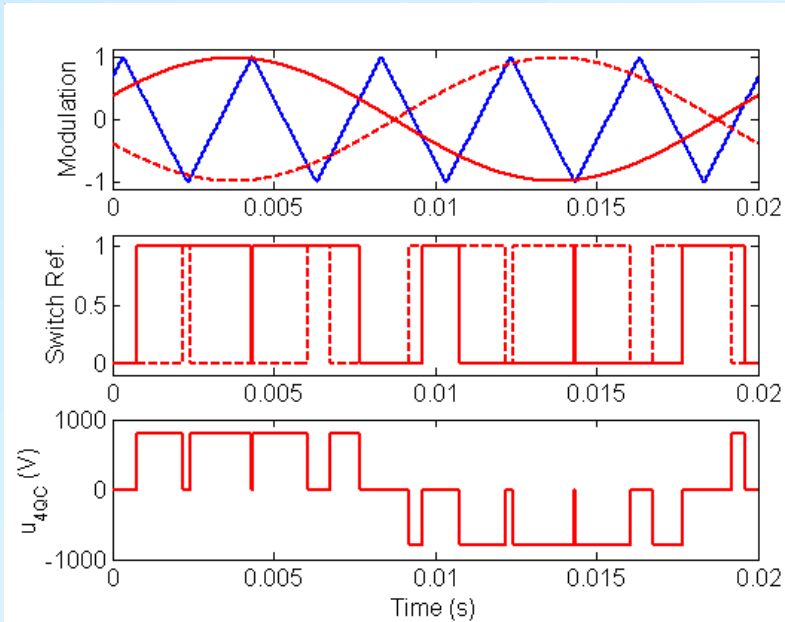


4QC currents

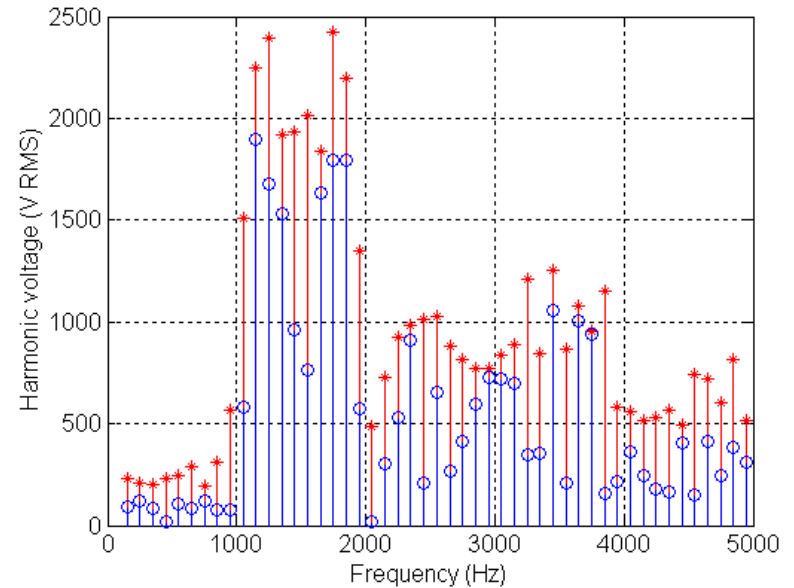


A big transformer allows for a smaller converter!

4QC voltage spectrum



4QC modulation



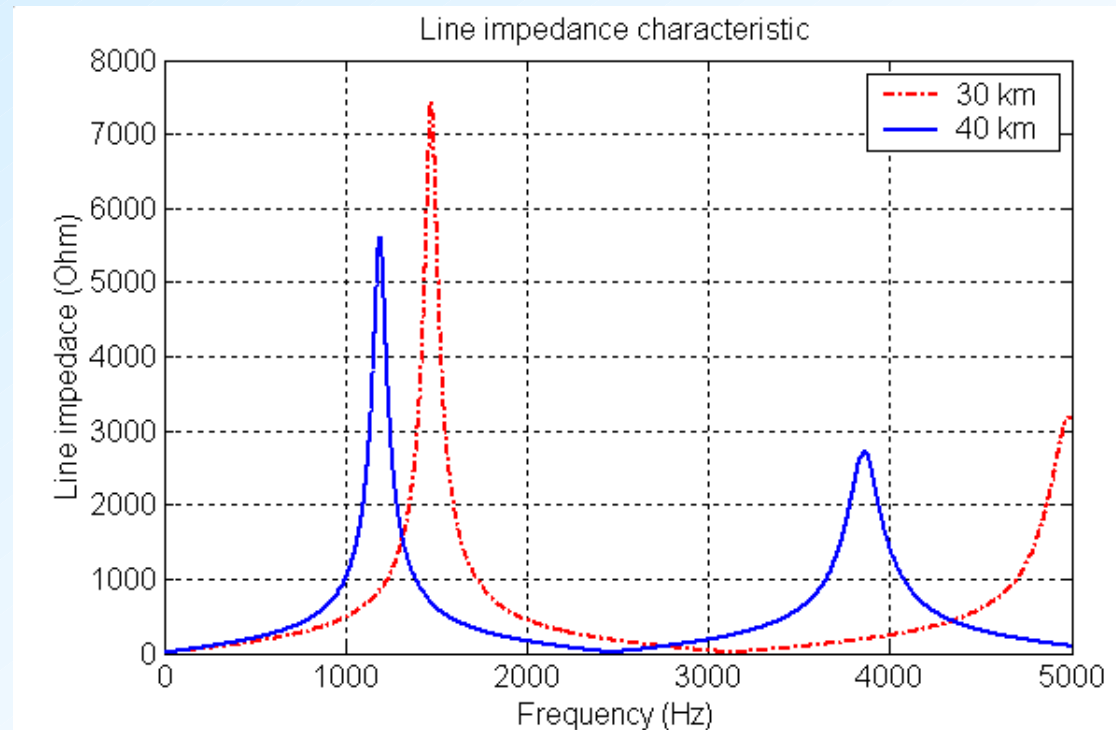
Voltage spectrum,
primary side
(3 interlaced bridges)

Line impedance

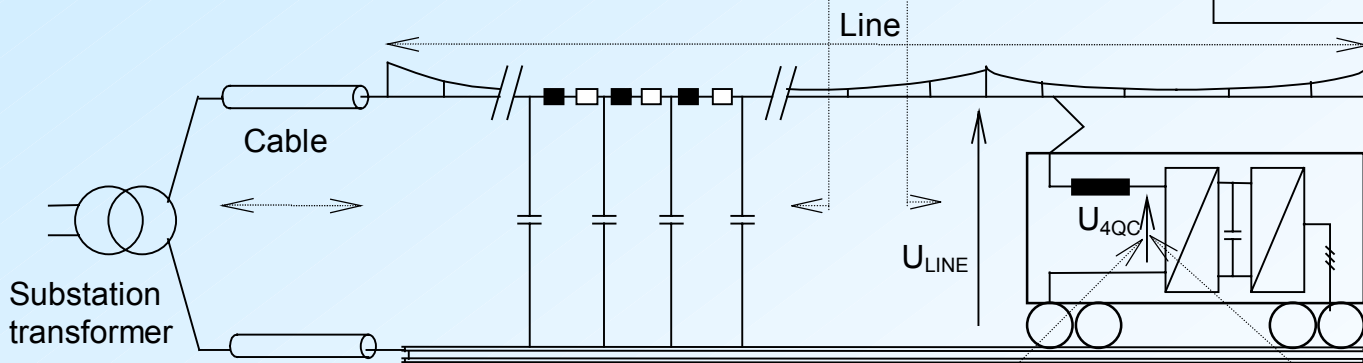
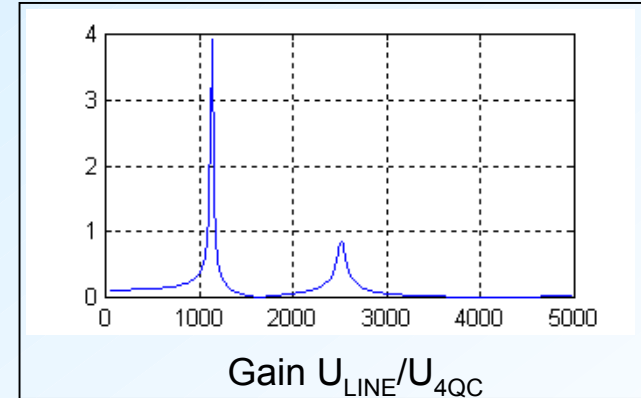
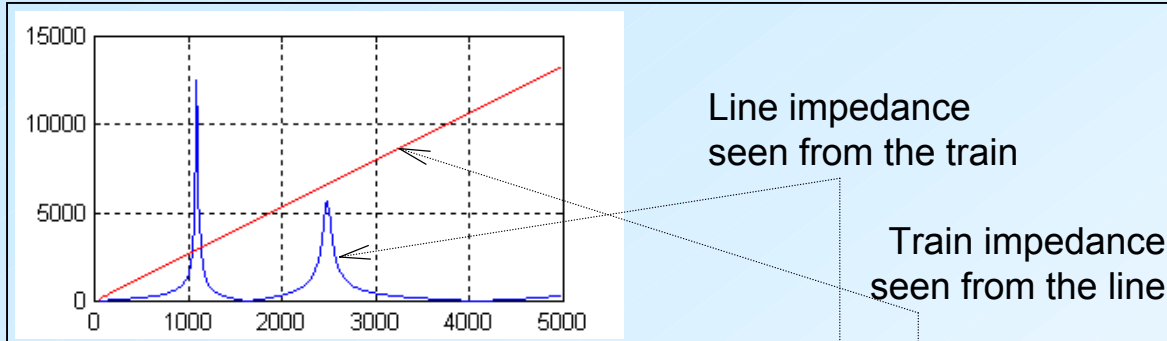
OHL impedance parameters:

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

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



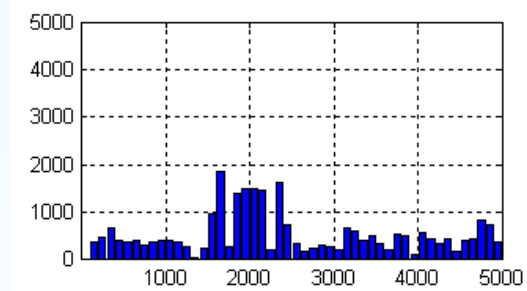
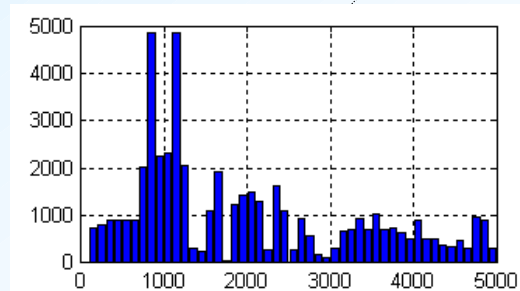
Line-vehicle resonance



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

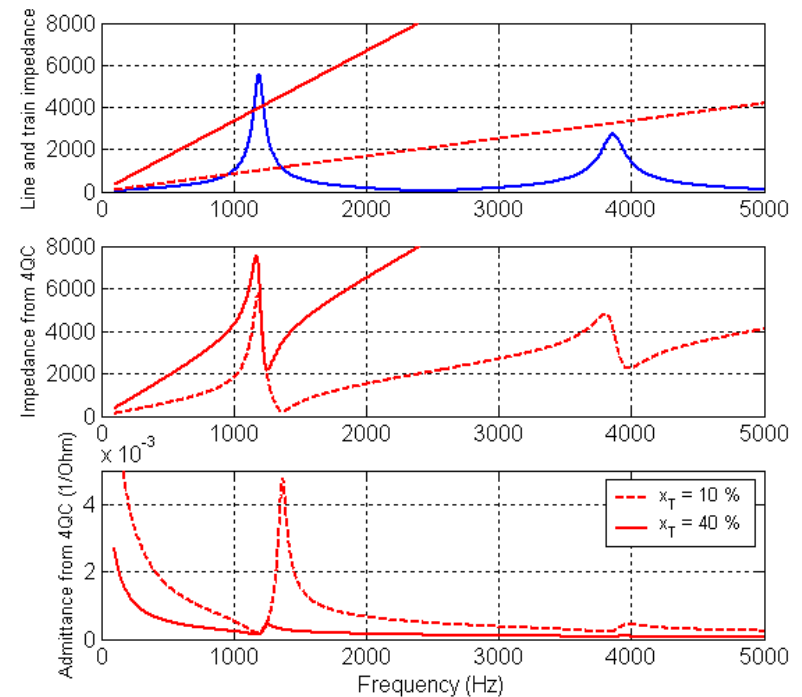
Examples, 4QC voltage spectra.
50 Hz line frequency,
250 Hz switching frequency.

Left: 2 interlaced bridges
Right: 4 interlaced bridges



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:

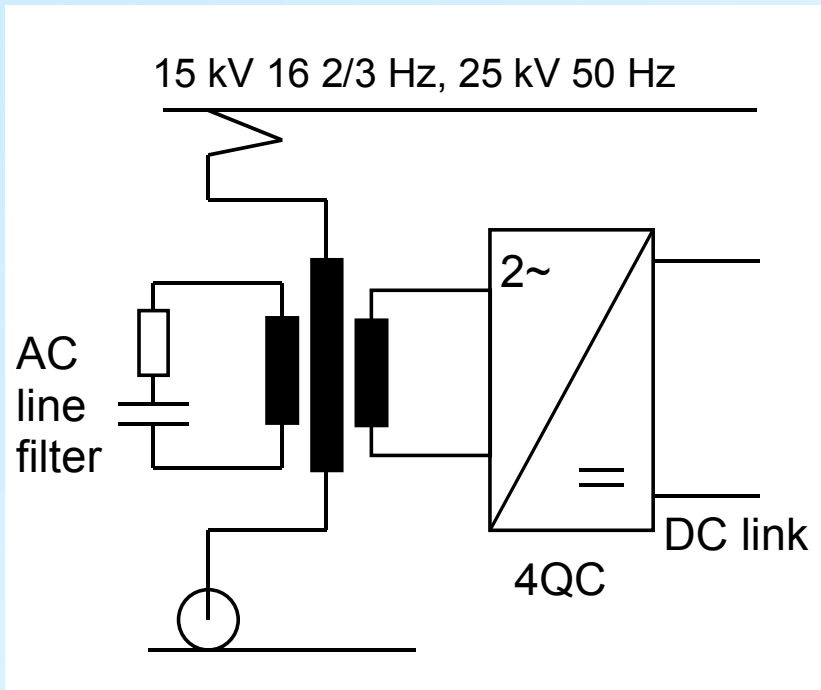
- Line and train impedance
- Impedance seen from 4QC
- Admittance seen from 4QC

Relative admittance seen from the 4QC

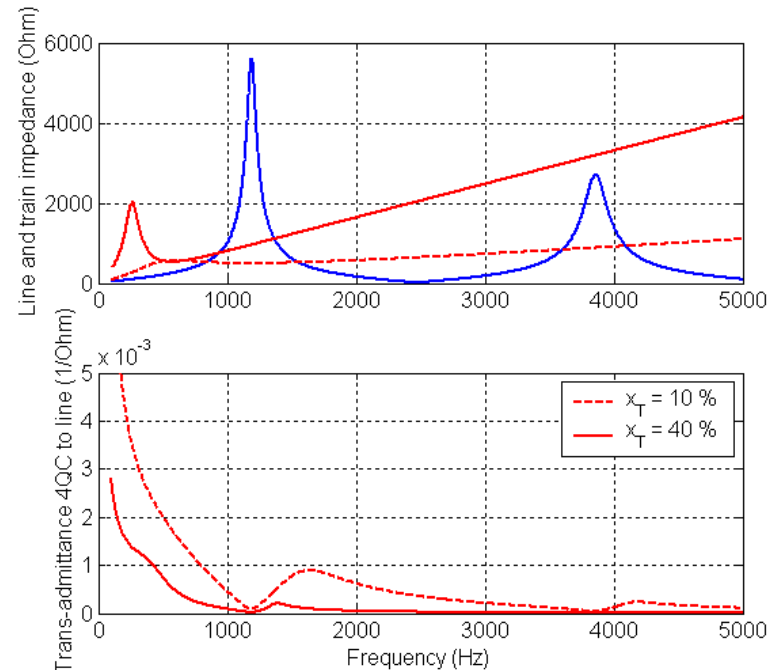
Relative transformer reactance e_x	10 %	40 %
Z_{LINE} is assumed to be 0	4	1
The real line impedance is considered	22	2.1

- A high e_x is advantageous
- The "conservative" estimate $Z_{\text{LINE}} = 0$ is wrong!

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

Relative (trans-) admittance 4QC to line

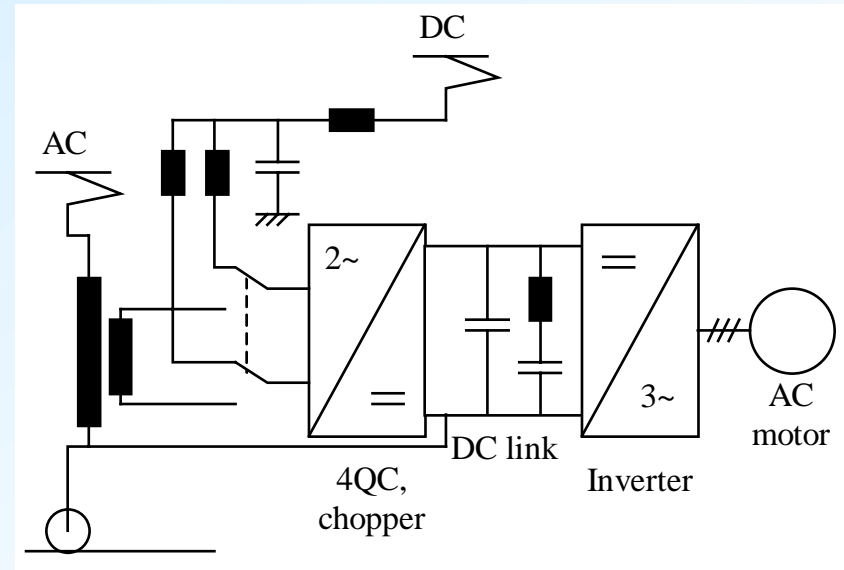
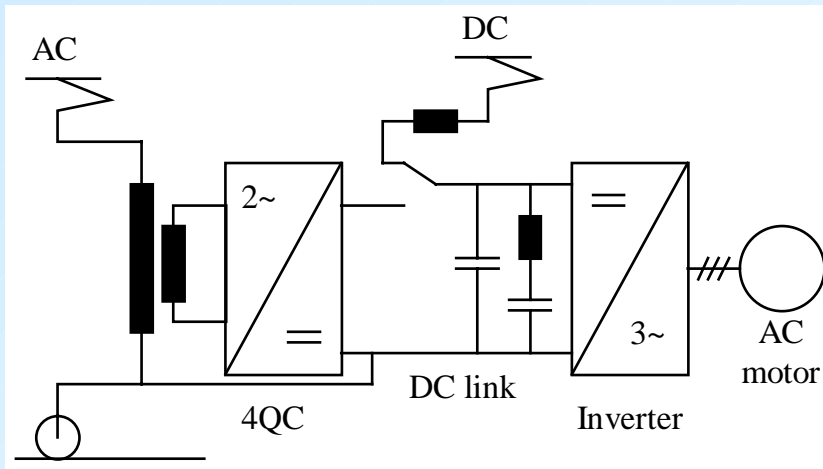
Relative transformer reactance e_x	10 %	40 %
Z_{LINE} is assumed to be 0 or real line and filter	4	1
The real line impedance is considered, no filter	22	2.1

Dual voltage operation (AC and DC)



Step-up chopper or direct-on-line?

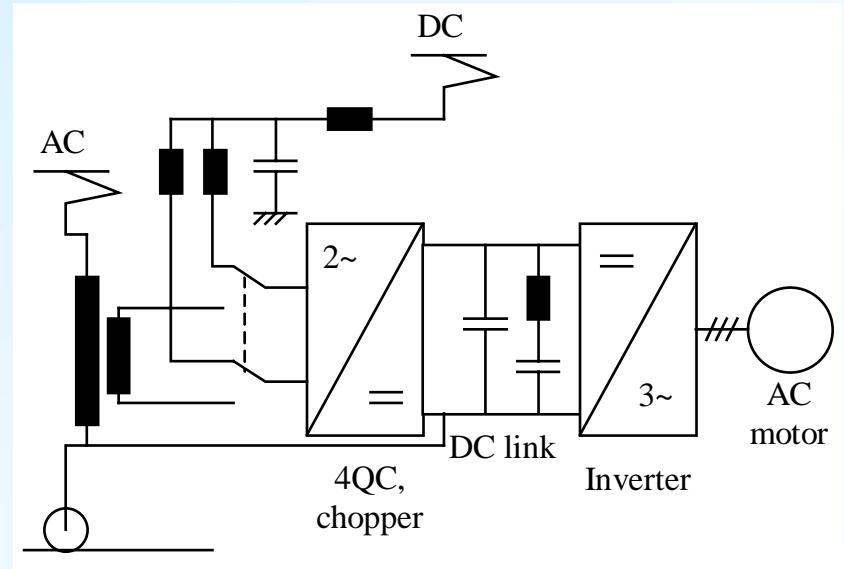
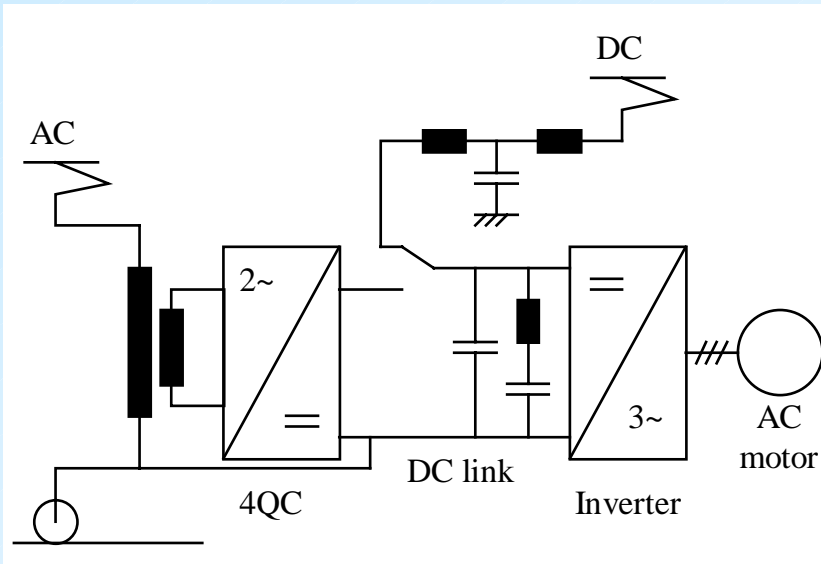
Dual voltage systems (DC and AC)



- Direct-on-line DC
- ≈ 750 V DC link

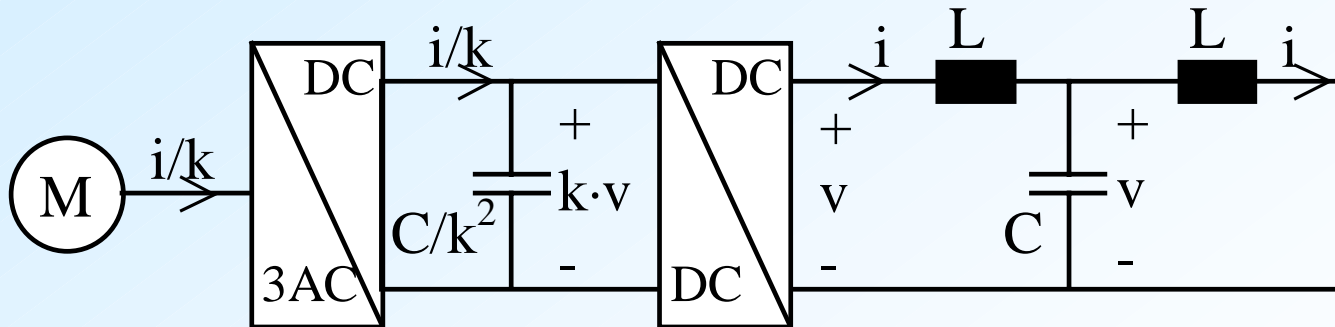
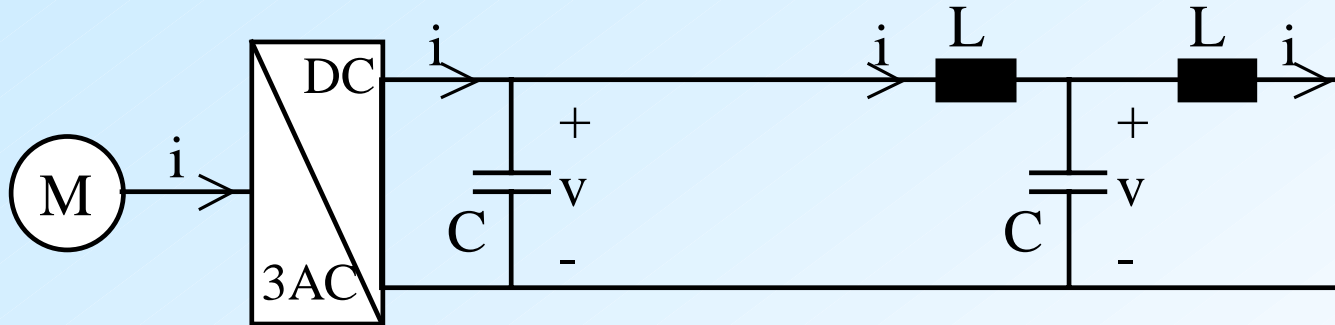
- Step-up choppers
- > 1000 V DC link

Comparable 4th order filter configurations



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

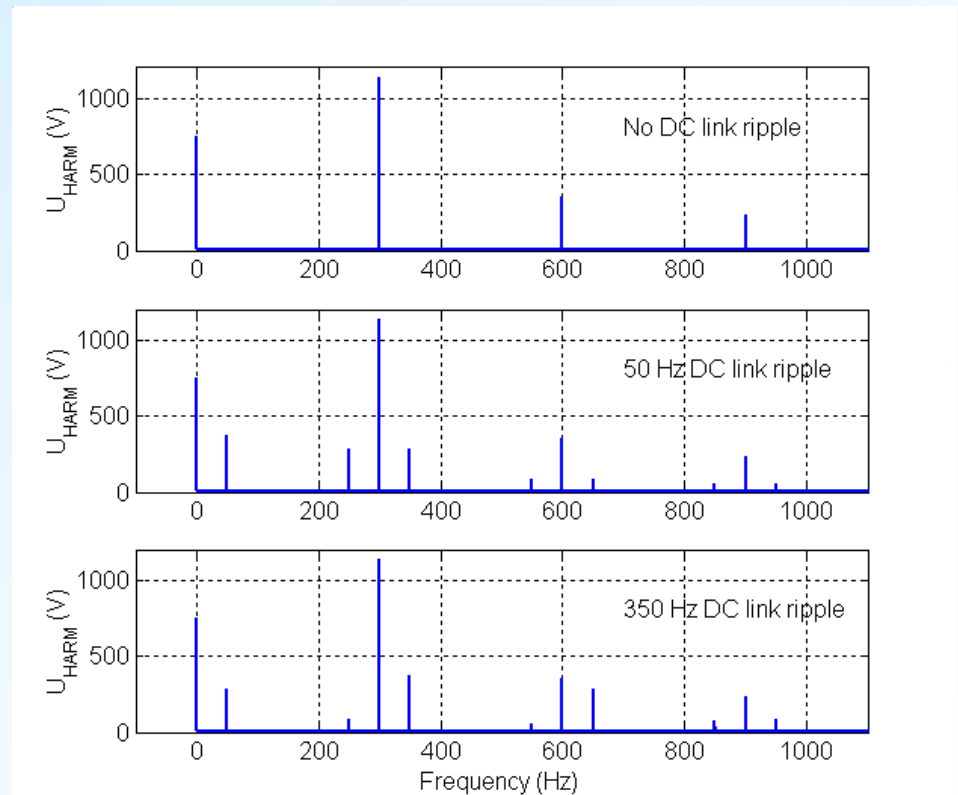
Relative currents and voltages



Equal power lead to basically equal interference levels

Harmonic intermodulation

- If the DC link voltage (the high voltage side of the chopper) is ideally smooth, only the chopper frequencies (here $n \cdot 300$ 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

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.

Testing and approval



Interference tests

Tractive effort tests



Compatibility tests

Winter tests



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

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 not been specified?
 - Local traditions
 - The already existing systems (vehicles, power supply)

Act responsible!