Electrification Infrastructure Whole Life Cost Reduction Congress 2014

Design Best Practices for New HS Routes

Jan Hauben, Paul Tobback, Sam Breugelmans, David Van de Sype
Introduction
Introduction

314 km of high speed network integrated in the existing railway infrastructure (1992 – 2009)

200km newly built high-speed railway lines with design speed of 320 km/h electrified in 2 x 25 kV AC (50Hz).

114km modernised railway lines with design speed up to 200 km/h electrified in 3 kV DC.
What is the difference between HS and CR?

- Nothing?

- Power and energy:
  - $F_{\downarrow D} = \frac{1}{2} \rho v_{\uparrow D}^2 C_{\downarrow D} A = E_{\downarrow D}$
  - $P_{\downarrow D} = \frac{1}{2} \rho v_{\uparrow D}^3 C_{\downarrow D} A$

- Speed 30 m/s
  - $E_D = 1.6 \text{ kWh / km}$
  - $P_D = 175 \text{ kW}$

- Speed 90 m/s
  - $E_D = 14.6 \text{ kWh / km}$
  - $P_D = 4.7 \text{ MW}$
Introduction

What is the difference between HS and CR?

- Maximum operating speed < 70% of wave propagation speed

\[ v_{\downarrow c} = \sqrt{T_{\downarrow CW} / m_{\downarrow CW}} = \sqrt{\sigma_{\downarrow CW} / \rho_{\downarrow CW}} \]

=> Interaction between contact wire and pantograph becomes important

<table>
<thead>
<tr>
<th>Material</th>
<th>( V_{\text{max}} ) [kmph]</th>
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Electrical design – supply voltage

- DC
- Quasi-DC
- AC
Electrical design – supply voltage

- TSI ENE CR: 25 kV 50Hz = standard supply voltage
- TSI ENE HS is less explicit
- Why was 3 kV the limit for DC?
  - Series motors of 1500 VDC
  - Diode reverse breakdown voltage
  - Circuit breakers
Electrical design – supply voltage

- Current state of the art for traction:

⇒ DC voltages larger than 10kV are feasible
⇒ Need for traction transformer?

6.5 kV
750 A
Electrical design – supply voltage

- State of the art for circuit breakers

ABB: Single cell of HVDC breaker
9 kA @ 80 kV
Electrical design – supply voltage

- **Advantages DC**
  - DC transmission = more efficient
  - No zero crossings of power
  - No inverse current in 3-phase network
  - No inductance e.g. $Z = 0.139 + j0.366 \ \Omega/km$
  - No skin effect in rails $Z_{AC} \approx 0.2 + j0.2 \ \Omega/km, R_{DC} \approx 0.03 \ \Omega/km$

- **Disadvantages DC**
  - Regenerative breaking
  - Electrochemical corrosion due to stray currents
Electrical design – supply voltage

- Antenna supply of 30 km at 25 kV AC

\[ \Delta V \approx 1700 \text{ V} \]

- Voltage drop AC: \((1590 + j 2540) \text{ V} \Rightarrow \Delta V \approx 1700 \text{ V} \]
Electrical design – supply voltage

- Antenna supply of 30 km at 25 kV DC

  \[ \Delta V = 940 \text{ V} \Rightarrow \text{double-end feed: } \Delta V = 470 \text{ V} \]

- 10 kV-15kV DC similar performance as 25 kV AC
Electrical design – load flow

- Load flow inputs
  - Track characteristics (slopes, curves, …)
  - Train characteristics
  - Timetables
  - Possible locations for substations
  - Circuit impedances
  - Catenary geometry
Electrical design – load flow

- Load flow outputs (TraXim):
Usage of results:

- **Currents:**
  - current ratings of transformers, busbars, OCL, etc.

- **Voltages:**
  - Compared to EN 50163 and EN 50388
Electrical design – load flow

- What is the load flow based upon?

I see a lot of diesel trains

- What about the human factor?
Electrical design – train voltages

- Catenary impedance is mainly inductive: $Z = 0.139 + j0.366 \, \Omega/km$

- Line converter may deliver reactive power (capacitive behaviour)
Electrical design – train voltages

- Allowable see EN 50388 Annex E
- Voltage drop due to train with capacitive current ($\cos \varphi = 0.98$)

- Voltage drop AC: $(490 + j 2950) \text{ V} \Rightarrow \Delta V \approx 660 \text{ V} \text{ (versus 1700V inductive)}$
Future trains may be designed to deliver capacitive power

Capacitive power may be determined by measured voltage at pantograph

Voltage drop becomes less of an issue

Currents are most important

⇒ Calculate voltages with actual traffic and unfavourable cos \( \phi \)?

⇒ Demand capacitive behaviour of future trains?
Electrical design – currents

- Transformers and autotransformers
  - Design as ONAN for actual worst case load
  - If needed conversion to ONAF in the future
  - Increase of power of approx. 25%
Electrical design – currents

- Current carrying capacity (ampacity) of OCL is determined by:
  - Resistance characteristics of conductors (for DC)
  - Geometry of conductors due to skin-and proximity effects (for 50 Hz AC)

- Influence of environmental conditions (EN 50125-2:2003)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BE</th>
<th>DK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrastructure Manager</td>
<td>Infrabel</td>
<td>Banedanmark</td>
</tr>
<tr>
<td>mean ( T_{\text{ambient}} )</td>
<td>15 °C</td>
<td>10 °C</td>
</tr>
<tr>
<td>max ( T_{\text{ambient}} )</td>
<td>40 °C</td>
<td>50 °C</td>
</tr>
<tr>
<td>Surrounding air velocity</td>
<td>1 m/s</td>
<td>0.6 m/s</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>700 W/m²</td>
<td>1120 W/m²</td>
</tr>
<tr>
<td>Ampacity OCL 1</td>
<td>745 A</td>
<td>616 A</td>
</tr>
<tr>
<td>Ampacity OCL 2</td>
<td>883 A</td>
<td>731 A</td>
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OCL 1: Bz II 70 MW CuAg 120 CW  
OCL 2: BzCd 94 MW CuAg 150 CW
## Electrical design – currents

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<tr>
<th>MW</th>
<th>AW</th>
<th>CW</th>
<th>RF</th>
<th>Ampacity</th>
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<tbody>
<tr>
<td>Bz II 50</td>
<td>-</td>
<td>CuAg 100</td>
<td>-</td>
<td>650 DC</td>
</tr>
<tr>
<td>CuCd 94</td>
<td>CuCd 104</td>
<td>CuAg 2 x 107</td>
<td>-</td>
<td>1504 DC</td>
</tr>
<tr>
<td>CuCd 94</td>
<td>-</td>
<td>CuAg 2 x 120</td>
<td>AMS 366</td>
<td>2314 DC</td>
</tr>
<tr>
<td>Bz II 70</td>
<td>-</td>
<td>CuAg 120</td>
<td>-</td>
<td>770 AC 16¾Hz</td>
</tr>
<tr>
<td>Bz II 120</td>
<td>-</td>
<td>CuMg 120</td>
<td>-</td>
<td>1040 AC 50Hz</td>
</tr>
<tr>
<td>BzCd 94</td>
<td>-</td>
<td>CuMg 150</td>
<td>-</td>
<td>1140 AC 50Hz</td>
</tr>
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</table>
Mechanical design – components

Contact wire:

- **Maximum operation speed** < 70% of wave propagation speed (TSI ENE)

\[ v \downarrow c = \sqrt{T \downarrow CW / \rho \downarrow CW} = \sqrt{\sigma \downarrow CW / \rho \downarrow CW} \]

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**Safety class and remark**

- **EN 50119:2009**
- **EN 50149:2012**

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<td>450</td>
<td>non EN 50149</td>
</tr>
<tr>
<td>CSD-170</td>
<td>540</td>
<td>Ø 6.9 steel core 80% IACS</td>
</tr>
<tr>
<td>Japan</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACSR</td>
<td>586</td>
<td>non EN 50149 wear sensitive (Al-oxide)</td>
</tr>
<tr>
<td>CS-110</td>
<td>665</td>
<td>Ø 8 steel core 60% IACS</td>
</tr>
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Mechanical design – components

Contact wire:

- Average wear CW 150:

<table>
<thead>
<tr>
<th>Line</th>
<th>Material</th>
<th>Measured wear</th>
<th>Period</th>
<th>Traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Cu Ag 0.1</td>
<td>0.5 mm</td>
<td>18 years</td>
<td>50 trains/day</td>
</tr>
<tr>
<td>L2</td>
<td>Cu Mg 0.5</td>
<td>0.12 mm</td>
<td>7 years</td>
<td>23 trains/day</td>
</tr>
</tbody>
</table>

- Local wear (hard points)
  - +/-20 points on L1
  - Measured wear: 1 mm

=> Expected EOL for CuAg after +/- 40 years
Mechanical design – components

Droppers:

- 15 defective droppers per year on L1
Mechanical design – components

Droppers: (Jürgen Sogier, I-AM)

EN 50119
Mechanical design – components

Droppers:

- Cu-ETP: failure after 70,000 to 300,000 cycles

- CuMg or CuCd: no failure after 4,000,000 cycles

- Thermal problems in 3 kV
  - Contact resistance variation in clamps
Mechanical design – components

Messenger wire:

- Possible reasons
  - Bridge with metallic substructure
  - Contact wire wear
  - Renewal of droppers (pre-sag after renewal?)
  - 2 raised pantographs on loco?

Uplift simulation with Kairos
Contact Force

- Simulation (Kairos)
  - Non-Gaussian distribution, yet standard deviation $\sigma$ is widely used (TSI ENE, EN 50318, EN 50367 …)
  - Skew
    - $F_m - 3\sigma < F_{\text{min}}$ too restrictive
    - $F_m + 3\sigma < F_{\text{max}}$ possibly dangerous local CW wear
  - Kurtosis
    - $F_m \pm 3\sigma$ too restrictive

- EN 50119:2009 AC
  - $F_{\text{max}} < 300$ N, $v \leq 200$ kmph
  - $F_{\text{max}} < 350$ N, $v > 200$ kmph
Contact Force

- Simulation results
  - Standard deviation $\sigma$ is no good parameter
  - Criterium1: Minimum contact force $\Rightarrow$ loss of contact
  - Criterium2: Maximum contact force $\Rightarrow$ local wear of CW
# Pantographs

- Pantograph spacing
  - TSI ENE HS:
    - 2 pantographs,
    - 200m spacing
  - TSI ENE CR:
    - up to 6,
    - spacing minimum 35m (160kmph < v < 200kmph)
  - EN 50367:
    - up to 5 AC (DK, NO, SE) and 6 DC (FR),
    - spacing minimum 35m (160kmph < v < 250kmph)
# Pantographs

- **Simulation conclusions**
  - # pantographs is not limiting (! Uplift)
  - Important:
    - Uplift mode frequency (span length)
    - train speed (! Tunnels)
    - pantograph spacing sequence

Kairos: 4 pantographs@250km/h
Mechanical design – sensitivities

Wind

- R3 mixed on L162
  - Resonance of leeward OCL
  - Wake Induced Vibration?

- DB OCL Re200
  - Ice galloping
  - Aeroelastic instability: lift and drag coefficient instability
  - Den Hartog Criterion: \( \frac{d C_L}{d \alpha} + C_D < 0 \)

\[ \Rightarrow \text{sensitivity due to dynamically flexible registration arms} \]
Mechanical design – sensitivities

- R3 mixed
  - 2 contact wires BF-107 CuAg0.1
  - Messenger wire 94mm² CuCd0.7
  - Similar wire tension, mass
    ➔ Identical eigenfrequencies
  - Similar dimensions
    ➔ Similar wind forces

- Experiments
  - CW midpoint
  - change in CW/MW tension (tensioning equipment)
  + S2 contact wire clamp eliminating eigenmodes CW
Mechanical design – sensitivities

Wind

- R3 mixed on L162
  - EM 130 measurements

- Phenomenon
  - Aeolian vibrations (~ transmission lines)
  - Possible fractures in multistranded MW
Conclusions

- Don’t forget about DC
- Perform load flow calculations with known (reasonable) traffic and unfavourable cosφ
  - Demand capacitive behaviour of future trains
  - Account for future conversion of ONAN to ONAF

- Small modifications => impact reliability (infant mortality)
- Simulations of contact pantograph-OCL are important
  - Uplift
  - Hard points
  - Loss of contact
  - Forget about σ

- Reasonable demands (all designs are conservatif)