Challenges of Modern AC Motor Traction Drives

Prof. Zdeněk PEROUTKA, Ph.D.
R&D center RICE and testing of modern traction drives

Traction drive concepts
• Low-floor trams

Design of traction power electronics converters
• New converter designs – packages / devices
• Converters for EMUs and multisystem locomotives

Traction drive control
• Drive stability
• Interaction of the drive with its environment
• Optimal control contribution
R&D center RICE

Basic Overview

- **RICE** is a trademark of the Faculty of Electrical Engineering in Pilsen, **Czech Republic** for the R&D area.
- Close to 200 researchers.
- Whole research chain from basic (theoretical) research up to development of functional samples and their complete testing.
- R&D projects with **total budget approaching 100 mil. EUR**.
- Leader / coordinator of more than 70% of the projects.
World-unique research infrastructure:

- Investment cost **over 25 mil. EUR** in last 5 years.
- A hall laboratory and testing room for medium-voltage power electronics and transportation systems for testing up to 31 kV$_{AC}$/4MW.
- **Opened on June 15, 2016**
Hall laboratory in deeper details

Testing of transportation and MV power electronics systems

- Typical DUT power up to 4 MW.
- Max. dissipated heat (power losses) of 500 kW.
- Traction catenary:
  - AC 25 kV / 50 / 60 Hz (max. 31.5 kV),
  - AC 15 kV / 16,7 Hz (max. 19 kV),
  - DC 600 V, 750 V with max. voltage up to 1 250 V,
  - DC 1.5 kV and 3 kV with max. voltage of 5.5 kV.
- 3-phase power supply systems:
  - Fixed voltage and frequency: 22 kV / 50 Hz, 10 kV / 50 Hz, 6 kV / 50 Hz, 3 kV / 50 Hz, 690 V / 50 Hz, 400 V / 50 Hz.
- Programmable power supplies:
  - AC 0 – 11.5 kV / 40 – 120 Hz, AC 0 – 690 V / 0 – 120 Hz.
  - DC 0 – 15 kV.
- 2 MV test beds, reconfigurable LV test area up to 4 test beds.
- MV and LV pits with loading motors (IM, PMSM).
- High-speed high-precision measurements (50 μs sampling rate).
- IR cameras with trigger event capability.
- Max crane load 12500 kg.
RICE – unique research infrastructure

Hall laboratory for medium-voltage power electronics and transportation systems
Hall laboratory in deeper details

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Outlines

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- **Traction drive concepts**
  - Low-floor trams
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  - New converter designs – packages / devices
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- **Traction drive control**
  - Drive stability
  - Interaction of the drive with its environment
  - Optimal control contribution
### Bogies for low-floor trams

<table>
<thead>
<tr>
<th>Grade of low-floor</th>
<th>Description and typical height of floor</th>
<th>Cross sectional view of the vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>High floor or slope or steps inside vehicle 700mm to 900mm</td>
<td><img src="#" alt="Diagram a) Floor upon traction wheel" /></td>
</tr>
<tr>
<td>1°</td>
<td>Minimized space for traction motor (i.e. high speed motor or special types of motor) 550mm</td>
<td><img src="#" alt="Diagram b) Floor upon traction motor" /></td>
</tr>
<tr>
<td>2°</td>
<td>Motor (or motors) outsized wheels – i.e. on side of vehicle or on other (height parts of vehicle upon seat etc.) 450mm</td>
<td><img src="#" alt="Diagram c) Floor upon traction axis" /></td>
</tr>
<tr>
<td>3°</td>
<td>“Independent” wheels without joint axes. Mechanical construction with subframe bellow floor 350mm</td>
<td><img src="#" alt="Diagram d) Floor upon subframe" /></td>
</tr>
<tr>
<td>4°</td>
<td>“Independent” wheels without joint axes. Mechanical construction with gantry upon passengers 197 to 205mm</td>
<td><img src="#" alt="Diagram e) Ultra low floor tram" /></td>
</tr>
</tbody>
</table>

**Existing configurations:**

- a) Classical bogie design,
- b) Old types of trams,
- c), d) Low-floor tram (with classical wheelset),
- e), f), g) Low-floor tram (independent tram wheels without classical wheelset),
- h), i), j), k) Low-floor tram (independently rotating wheels with motors for each wheel).
Low-floor tram drive concepts

- **Partially low-floor drives**
- Full low-floor drives
- Two-wheel drives
- Longitudinal drives
- Longitudinal/lateral drives
- Single-wheel drives
- Planetary gearing
- Hub traction motor / gearless drives
- Vertical drives

Plenty of smart solutions…
Wheel drives

RICE + Škoda – series ForCity
PMSM, 48 kW, water cooling

Alstom

Siemens - ULF 197
80 kW, water cooling
Gearless wheel drives

Design by RICE + ŠKODA – series ForCity

PMSM can operate in 5 fundamental modes. Three of them are convenient for the wheel traction drive:

MODE 1
Voltage limit of traction voltage-souce inverter

MODE 2
Voltage limit of traction voltage-souce inverter

MODE 4

Typical two-wheel/wheelset drive configurations

- Bombardier Flexx
- Siemens Avenio
- Škoda ForCity (X53)
Current drive concepts with gearbox

Low integration level!

ŠKODA X53 100 kW, water cooling

SIEMENS ULF197
80 kW, water cooling

GMEINDER 2x60 kW, air self cooling

HENSCHEL 135 kW, water cooling

New generation of compact traction drive unit

The drive unit design is protected by patent application – RICE + WIKOV

High-speed PM motor with passive cooling:
96.5% efficiency at rated point
Maximum power of 180 kW
Continuous power of 110 kW

Multistage gearbox:
Max. wheelset speed of 643 rpm
Nom. torque on the wheelset of 3854 Nm
Acceleration torque of 5625 Nm
Braking torque of 6660 Nm
Main advantages

- compact drive unit embedded into a single housing – **high integration level**, simple and fast integration to vehicle,
- applicable for both wheel and wheelset/axle drive,
- **significantly reduced dimensions/volume and weight**, optimal heat transfer,
- minimised noise,
- mechanical brake as an option.

Current commercial solution

Second generation prototype

~ 1000 kg

< 700 kg
New generation of compact traction drive unit

First time introduced by RICE + WIKOV on

INNOTRANS, Berlin
09/2016
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New converter designs

Low inductive power modules … XHP / LinPak

- low-voltage 1200V - 3300V
- medium-voltage 3300V – 6500V
- higher power density
- total stray inductance reduction
- lower dynamic losses
- easy to parallel
- separated AC/DC terminal for better busbar layout
- ready for SiC

Infineon’s XHP™ LV and HV modules

ABB’s LinPak power module

Turn-on and turn-off waveforms XHP vs. IHV-B comparison [B]
New converter designs

Optimal converter design with parallel power modules

**XHP™ traction converter demonstrator**

- 3x FF450R33TE3 (Infineon’s 3300V 450A half-bridge)
- DC bus voltage up to 2kV
- Switching frequency range up to 1kHz
- Designed for low current imbalance
XHP™ demonstrator

- Low-inductive busbar
- High-pulse, low-inductive capacitors
- Single two-channel driver
- Compact design with water cooling
- Rack type arrangements

New converter designs

Introduced on PCIM 05/2016, Norimberk
XHP™ power blocks ideas

- capacitor-less power cells
- centralized dc-link capacitor banks
- very high power density

New converter designs

Capacitor-less traction building blocks

dual phase per power block

single phase per power block
Challenges in traction converter design

All-SiC converter concepts: new phenomenon?!
Mitsubishi Electric

- Installs Railcar Traction System with All-SiC Power Modules on Shinkansen Bullet Trains for Central Japan Railway Company

Specifications of Main Circuit
- Input voltage: 2500V AC
- Main circuit system: Large-capacity all-SiC power module
- Control system: Four traction motors with 305kW, parallel control
- Cooling system: Self-cooling

Supply Railcar Traction Inverter with All-SiC Power Module to Odakyu Electric Railway

Specifications of Main Circuit
- Input voltage: 1500V DC
- Main circuit system: Two-level PWM inverter with regenerative brakes
- Control system: Four traction motors with 190kW, parallel control
- Cooling system: Self cooling
SiC MOSFETs Mitsubishi Electric vs Cree vs ABB?

**Mitsubishi Electric**

**SiC MOSFET**
- Drain – Source Voltage: 3300V
- Drain Current: 400A
- On – Resistance: 6mΩ
- Energy On: 193mJ
- Energy Off: 58mJ
- Package: Silicon Carbide

**Silicon Carbide**

**Ready to Run the Rails**

**Cree (Wolfspeed)**

**SiC MOSFET 3.3kV**
- Drain – Source Voltage: 3300V
- Drain Current: ??
- On – Resistance: 5.7mΩ
- Package: XHP

**SiC MOSFET 6.5kV**
- Drain – Source Voltage: 6500V
- Drain Current: ??
- On – Resistance: 100mΩ
- Package: XHP

**SiC MOSFET 10kV**
- Drain – Source Voltage: 10000V
- Drain Current: ??
- On – Resistance: 100mΩ
- Package: XHV
Auxiliary power supplies

SiC based converter is going to be the state of the art

Bi-directional DC/DC converter

- Input voltage 400 VDC - 950 VDC
- Output voltage 950 VDC - 1050 VDC
- Nominal power 25 kW (30 kW / 5 min)
- Switching frequency over 30 kHz
- Infineon FF45R12W1J1 SiC JFETs (1200V/45A)
- Compact size / weight
- Switching frequency far above the audible range
- Enhanced APS functionality due to bi-directional operation

In production as of 2014/2015 (26Tr, 27Tr, 30Tr and 31Tr by SKODA ELECTRIC)
**GaN devices**
- discrete devices 650V/100A+/ <10mΩ devices available
- consumer electronics, IT, telecom targeted markets
- 1200V/20A/140mΩ device reported [1]
- 1200V vertical GaN trench MOSFET described [2]
- high power density converters demonstrated
  Google Little Box Challenge - 147W/in³ inverter using GaN devices

**Auxiliary drives 20 kW+**
- high devices count in parallel or modular approach
- lack of power modules
- long-term reliability required by industry is a concern
- EMC

**Diamond next?**
- 1700V diamond substrate MOSFET [3]

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[1] P. Moens et al, "AlGaN/GaN power device technology for high current (100+ A) and high voltage (1.2 kV)," 28th International Symposium on Power Semiconductor Devices and ICs (ISPSD), Prague, 2016.


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Main converter design with MF transformer

- New generation of multi-system locomotives, train sets and particularly suburban unit supplied from ac electrification system of 25kV/50Hz and/or 15kV/16.7Hz.
- Main goals – **reduction of weight and dimensions** of vehicle electrical equipment.
- The investigated traction converter configurations are often inspired by known topologies from switching power supplies.

Main Traction Converter with Medium-Frequency Transformer

[Diagram showing the connection between AC Catenary and the components of the traction converter system.]
Main converter design with MF transformer

CONCEPT I, ABB

- 1.2 MVA PETT prototype for 15kV/16.7Hz
- Indirect frequency converters
- Separate MFTs
- Rated/peak power of each cell of 150 kVA/225 kVA
Main converter design with MF transformer

CONCEPT II, ABB

- 1.2 MVA PETT prototype for 15kV/16.7Hz
- Direct frequency converters
- Separate MFTs, module power 75kVA, frequency of 400 Hz
Main converter design with MF transformer

CONCEPT Bombardier

- Indirect frequency converters
- Separate MFTs, module power 450kVA, frequency of 5.6 kHz
Main converter design with MF transformer

Alstom - LIREX

- Indirect frequency converters
- Multi-winding MFT, module power 180kVA, frequency of 5 kHz
Main converter design with MF transformer

CONCEPT Siemens

- **M2LC converters**
- **Simple MFT**, module power 270kVA, frequency of 350 Hz
Main converter design with MF transformer

CONCEPT I, RICE + SKODA

- Indirect frequency converters
- Multi-winding MFT, rated power 100kVA, frequency of 400 Hz
Main converter design with MF transformer

RICE Concept II (direct frequency converters)

- Direct frequency converters
- Multi-winding MFT, frequency of 400 Hz

Main converter design with MF transformer

RICE Concept III – ready for application (indirect frequency converters)

- Indirect soft-switching frequency converters
- Separate MFTs, cell power of 200kVA, frequency of 6-8 kHz

**AC Catenary**
- 25kVAC/50Hz, 15kVAC/16.7Hz

**DC Catenary**
- 1.5kVdc, 3kVoc

**Diagram**
- TCC: Traction converter cell
- PAR: Primary active rectifier
- PI: Primary inverter
- SAR: Secondary active rectifier
- MTI: Main traction inverter
- TM: Traction motor
- HFT(MFT): High/medium frequency transformer
- RSC: Resonant cell

**Typical Appearance**
- Images of components and circuits
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Stability of dc catenary fed traction drives

Traction drive stability – physical background

DC catenary

Input (trolley-wire) filter

Traction voltage-source converter (DC/AC)

Control with excellent dynamic properties

\[ P_{dc} = U_c I_z \sim P_m = \text{const.} \]

\[ P_m = T \omega_m = \text{const.} \]

\[ J \rightarrow \infty \Rightarrow \omega_m = \text{const.} \]

\[ T_w = \text{const.} \Rightarrow T = \text{const.} \]
Stability of dc catenary fed traction drives

Decrease of the catenary voltage:

$\downarrow U_c \Rightarrow \uparrow I_z \Rightarrow \downarrow U_c$

Positive feedback (negative resistance effect)

LC filter oscillations

$P_{dc} = U_c I_z \sim P_m = \text{const.}$
Stability of dc catenary fed traction drives

**Passive**
- Adding the damping component
  - Simple
  - Additional power losses
  - Increase of vehicle weight

**Active**
- Control of equivalent drive impedance
  - Brings torque oscillations
  - Classical or advanced methods
- Decoupling control from the dc-link voltage and adjusting control gains

Traction drive stability – damping

\[ T_W (I_{QW}) \]

Setpoint corrections → Drive control
Stability of dc catenary fed traction drives

Traction drive stability – classical damping methods

\[ T'_{w} = \left( \frac{U_{C}}{U_{CF}} \right)^{n} \cdot T_{w} \]


- \( U_{CF} \) – lowpass filtered \( U_{C} \)
- \( K_{STAB} \) - gain

\[ T'_{w} = K_{STAB} \cdot U_{CF} + T_{w} \]


- \( U_{CF} \) – bandpass filtered \( U_{C} \)
- \( K_{STAB} \) - gain

\[ T'_{w} = \left( \frac{U_{C}}{U_{CF}} \right) \cdot T_{w} + K \cdot (U_{C} - U_{CF}) \]


- \( U_{CF} \) – lowpass filtered \( U_{C} \)
- \( K \) - gain
Stability of dc catenary fed traction drives

Problem statement

DC Catenary

Application of predictive control theory

- Overall system is non-linear:

\[
\begin{align*}
\frac{di_d}{dt} &= -\frac{R_s}{L_{sd}} i_d + \frac{L_{sq}}{L_{sd}} i_q \omega + \frac{1}{L_{sd}} U_c u_d, \\
\frac{di_q}{dt} &= -\frac{R_s}{L_{sq}} i_q - \frac{\Psi_{pm}}{L_{sq}} \omega - \frac{L_{sd}}{L_{sq}} i_d \omega + \frac{1}{L_{sq}} U_c u_q, \\
\frac{dU_c}{dt} &= \frac{1}{C_f} (i_l - i_z),
\end{align*}
\]
Predictive Control

- Natural handling of non-linear system
- Based on numerical minimization of cost function
- Control is designed to minimize cost:

\[
\text{cost} = g_{PMSM}(x_t, u_t) + \lambda g_{LC}(x_t, u_t)
\]

- FCS-MPC for one-step ahead prediction

Improvement using horizon extension for the LC filter via LQ approximation [1]:

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Interaction of a drive with its environment

Interaction of traction drive and interlocking plant

- Free AC parallel track circuit (simplified)

- Occupied track circuit

- Malfunction of track circuit
Interaction of a drive with its environment

Interaction of traction drive and railway safety system

- Catenary current spectra of VSI fed induction motor
- Switching frequency 833Hz
- Monitored frequencies: 25, 50, 75, 275Hz
Interaction of a drive with its environment

Noise of modern traction drives

- High content of harmonics in modern drives causes unwanted noise.
- Unsuitable environment for the driver and passengers.
- Harder and harder standards and customer requirements.

http://www.skoda.cz
Interaction of a drive with its environment

Noise of modern traction drives

- Noise spectra of VSI fed induction motor.
- Motor accelerated to 1500rpm, then power supply turned off to split electromagnetic and other sources of noise.
- Switching frequency of 1kHz.
Spectrum shaping

**Predictive control**

- **Classical approach based on linear system**
  - Can be solved using by minimizing response on a designed filter(s)
  - Control is designed to minimize cost:
    \[
    \text{cost} = g_{PM} (x_t, u_t) + \lambda g_{filter} (x_t, u_t)
    \]
  - using predicted response of a filter (green)
  - FCS-MPC for one-step ahead + LQ [2]
  - Performance not guaranteed

**Challenging approach guaranteeing hard constraint**

- Control is designed to minimize cost:
  \[
  \text{cost} = g_{PM} (x_t, u_t)
  \]
  \[
  \text{subject to: } g_{filter} (x_t, u_t) < \alpha
  \]
  - Filter on local window
  - Computationally heavy

RICE on the web

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