Contents of Work Package 1-WP01 Electric and Hybrid Powertrains

1-WP01: Electric and Hybrid Powertrains

Coordinator of the WP

University of West Bohemia in Pilsen, Prof. Ing. Zdeněk Peroutka, Ph.D.

Participants of the WP

UWB, CTU, Škoda Auto a. s., Škoda Electric a. s., Eaton Elektrotechnika, a. s.

Main Goal of the WP

The research of new electrical equipment applicable for both electric cars and traction vehicles for public transportation, especially high efficiency and high power density traction electric drives and power converters, optimization of power consumption, drive range and battery charging, complex mathematical modeling and simulators.

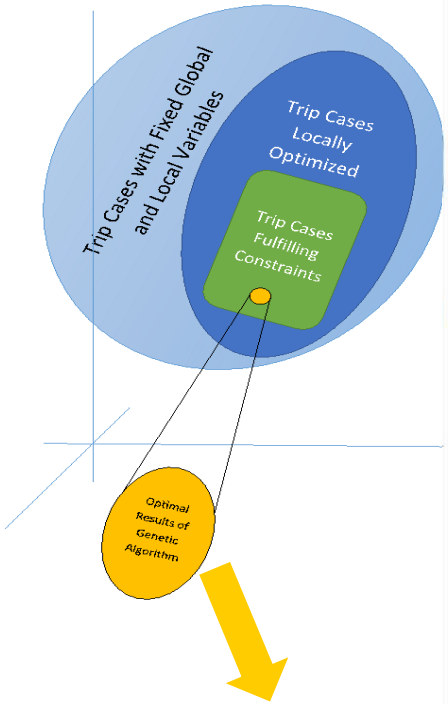
Partial Goals for the Current Period

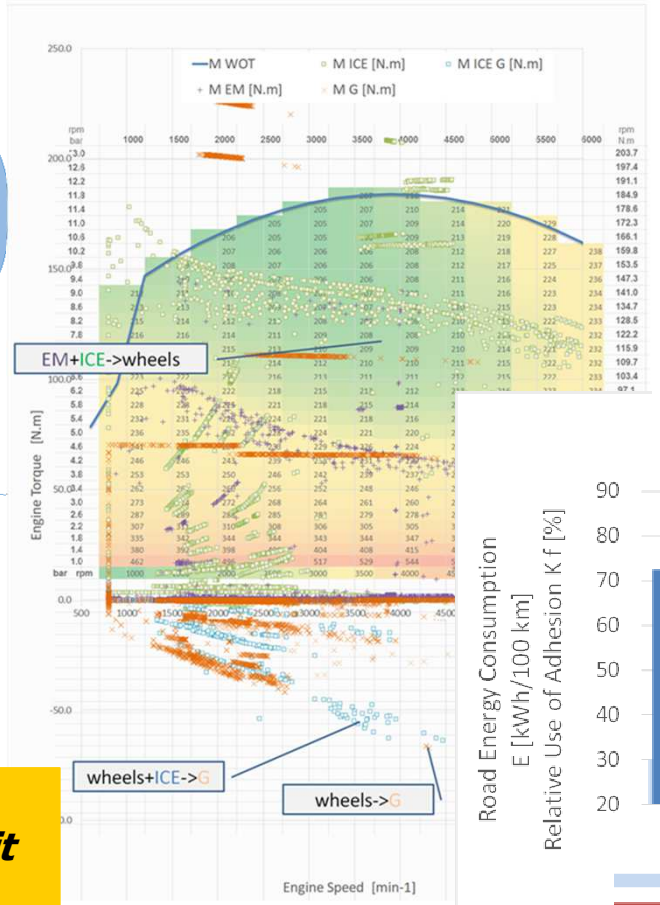
Final R&D activities, achieving project outcomes according to the project schedule, especially:

- 1-WP01-001 (ZV) – Benchmarking code for ultimate energy consumption at defined route with defined constraints,
- 1-WP01-003 (ZV) | Wide bandgap devices based main traction converter with high power density (alpha sample).

Contents of Work Package 1-WP01 Electric and Hybrid Powertrains

1-WP01-001 (ZV) Benchmarking code for ultimate energy consumption at defined route with defined constraints

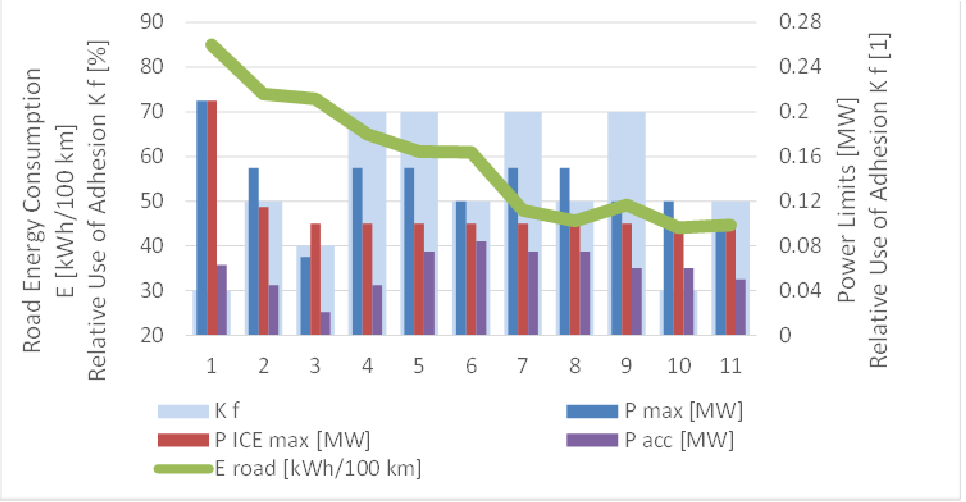




Optimum Vehicle Speed Definition of Power Limit Power Split

Results for 2 000 kg hybrid SUV in WLTC from 80 to 45 kWh/100 km:

- optimum ICE power
- optimum gearbox and shifting
- optimum speed-distance schedule
- optimum e-horizon for prediction of charging/discharging

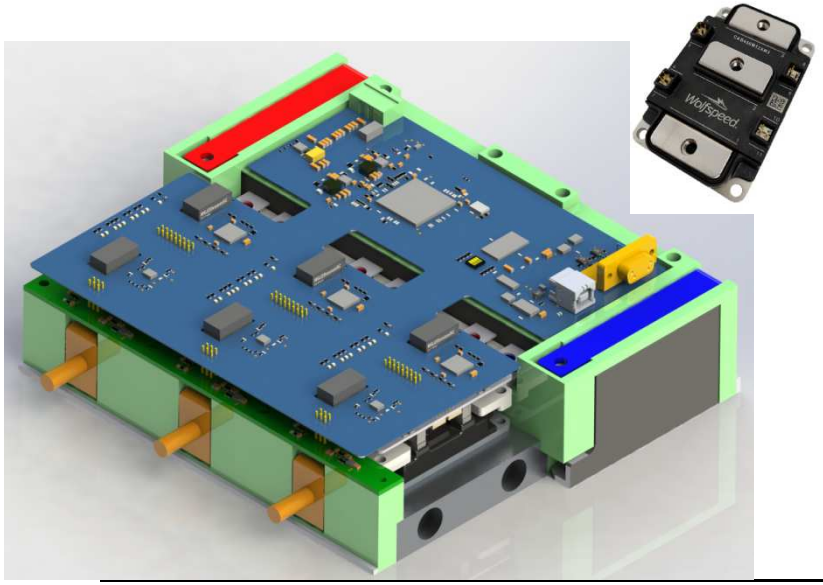


Contents of Work Package 1-WP01 Electric and Hybrid Powertrains

1-WP01-003 Wide bandgap devices based main traction converter with high power density (alpha sample)

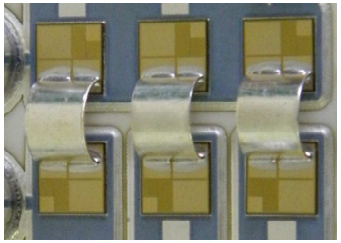
Traction converter based on CREE module

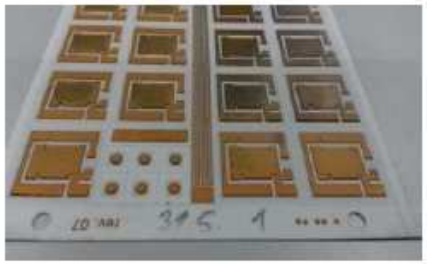
- CREE module CAB450M12XM3
- Estimated converter power 250kW
- Power density ~ 87 kW / liter (incl. DC capacitor, current sensors, CPU)

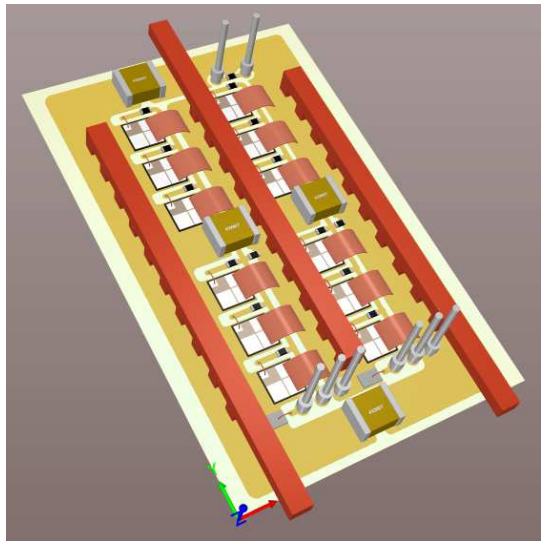


Customize development - TPC technology

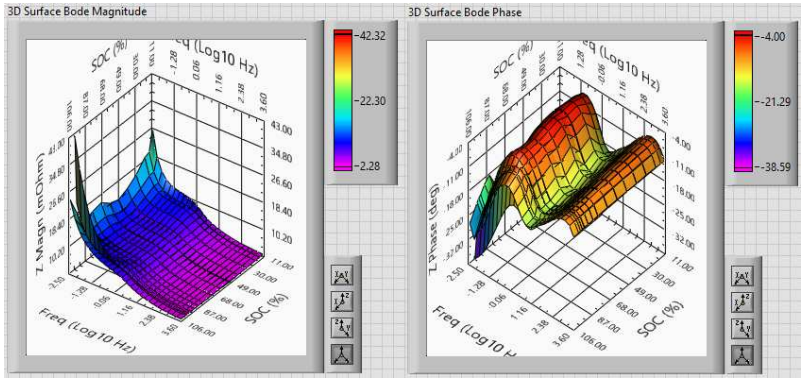
- Half-bridge 2x6 dies
- Power & signal electronic on one substrate
- Snubber capacitors, gate resistors, desaturation diode dies and NTC temperature sensors embedded
- Current sensors ?



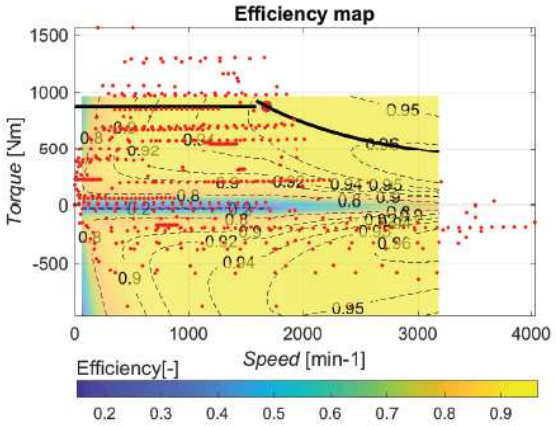




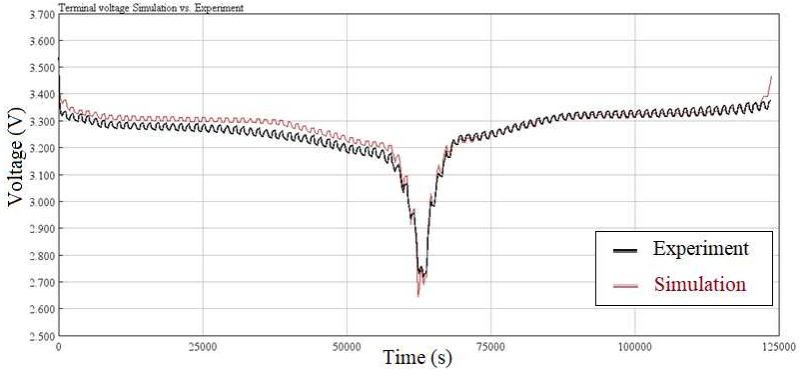
Contents of Work Package 1-WP01 Electric and Hybrid Powertrains



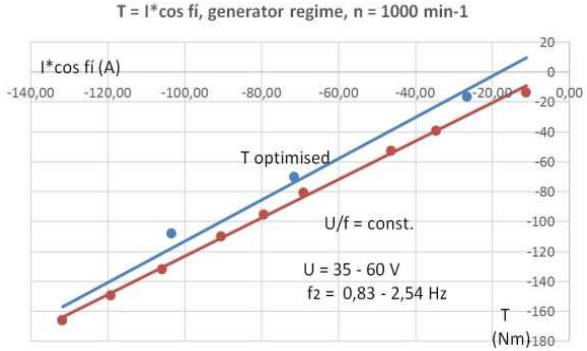
Impedance measurements of accumulators for various SOC, example LTO 2.4V/10.4Ah.



Efficiency map of requested operating points



Model calibration of batteries for various waveforms in time, example LFP 3.2V/40Ah.

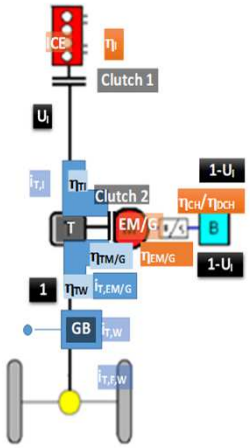


Relations between breaking torque and active current generated at recuperation regimes for U/f = constant (red line) and optimised rotor current frequency f_2 (blue line) at 1000 rev. per min

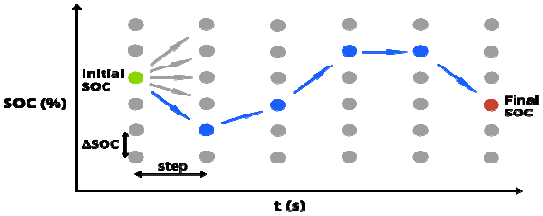
Activities in 1-WP01 Electric and Hybrid Powertrains

Benchmarking code for ultimate energy consumption at defined route with defined constraints

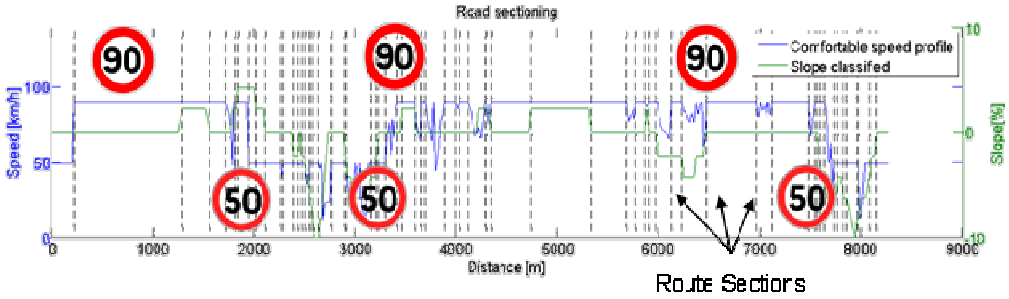
CTU-FS, CVSM Jan Macek, Rastislav Toman

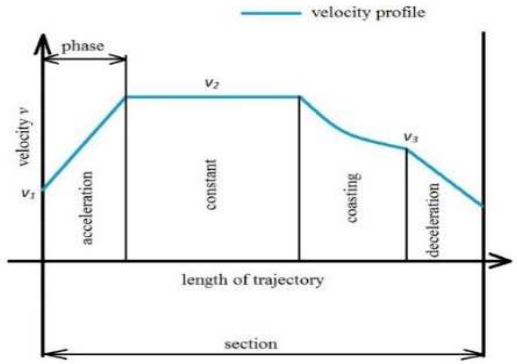


Finding compromise between computational requirements of brute force energy-consumption optimization by dynamic programming or genetic algorithm (tens of variables, hundreds-thousands of route sections) and rule-based local optimization without predictive features



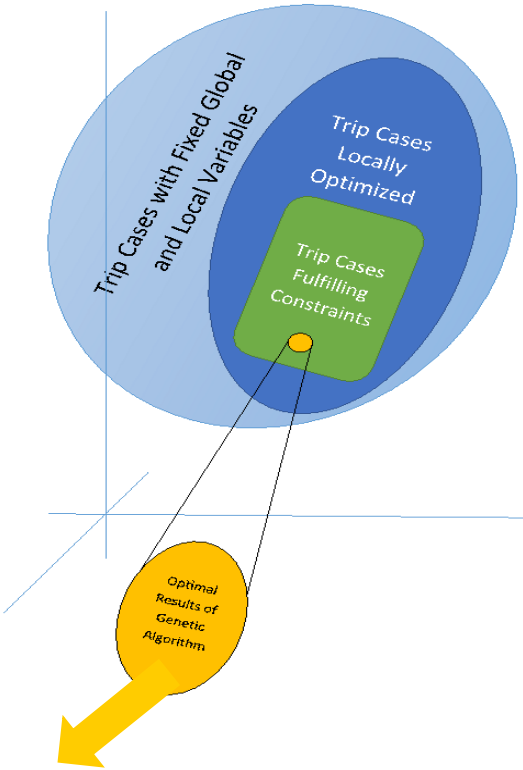
- Hybrid P2/4 Architecture Generic Approach
- High number of optimization variables
- Local optimization by power splitting
- Global genetic algorithm optimization using trip-valid global variables





Activities in 1-WP01 Electric and Hybrid Powertrains

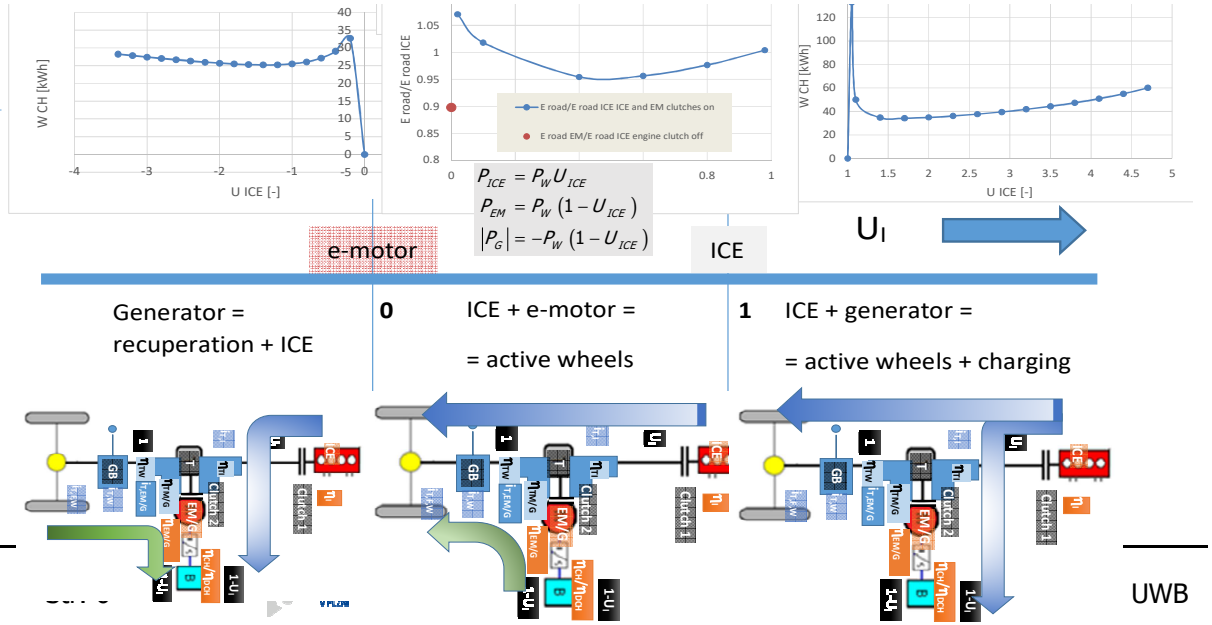
Benchmarking code for ultimate energy consumption at defined route with defined constraints



Optimum Vehicle Speed Definition of Power Limit Power Split

Local optimization based on the best choice of gear and power splitting between ICE and electric part.

It depends on power requirement from route (limited by global variables). Charging strategy depends on past and future charging efficiency.



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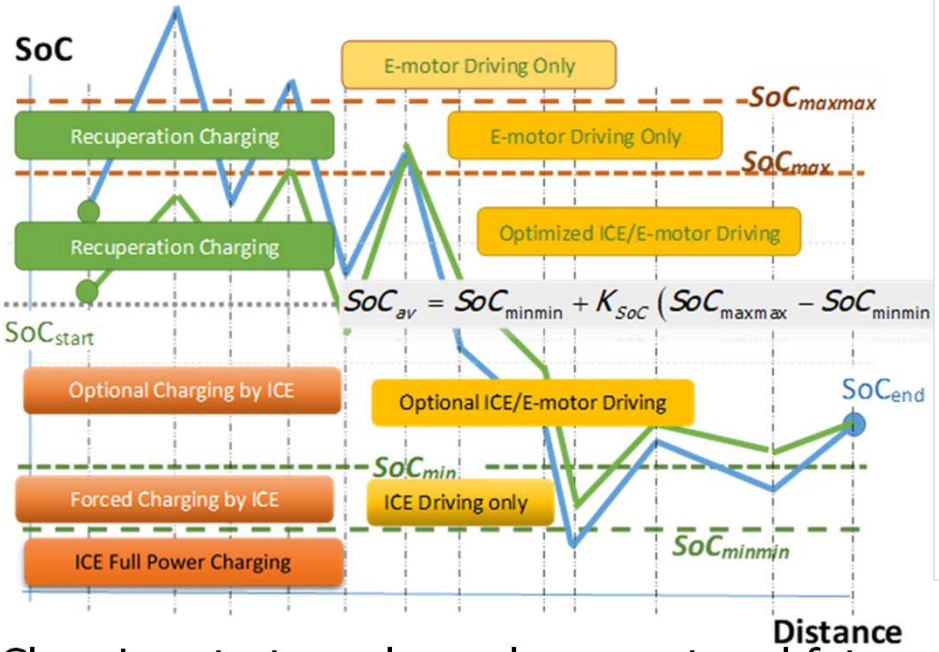
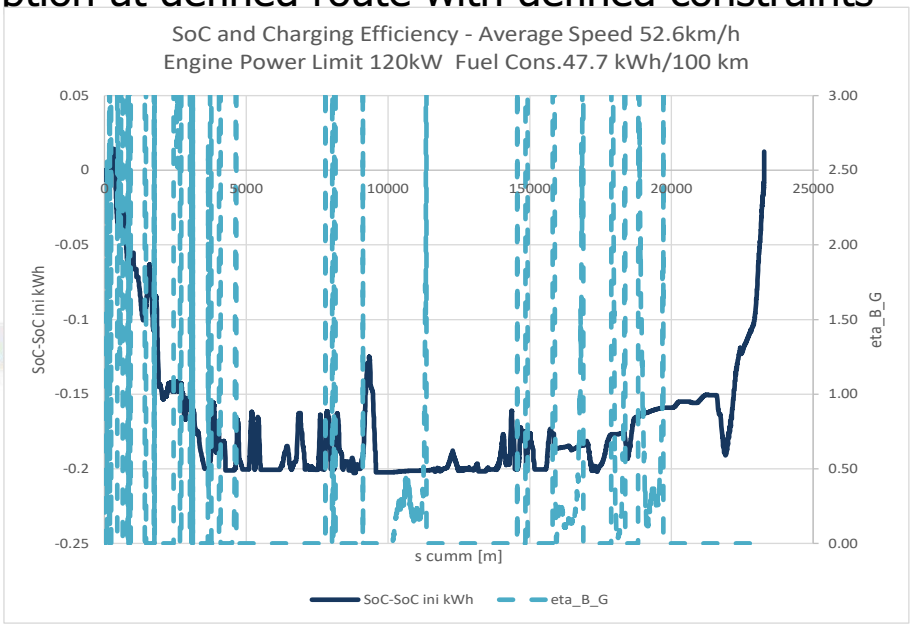
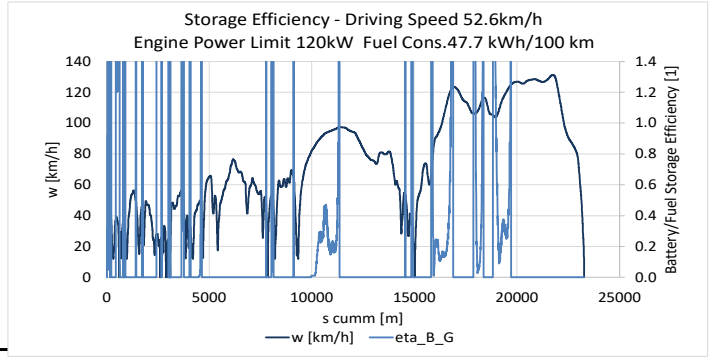


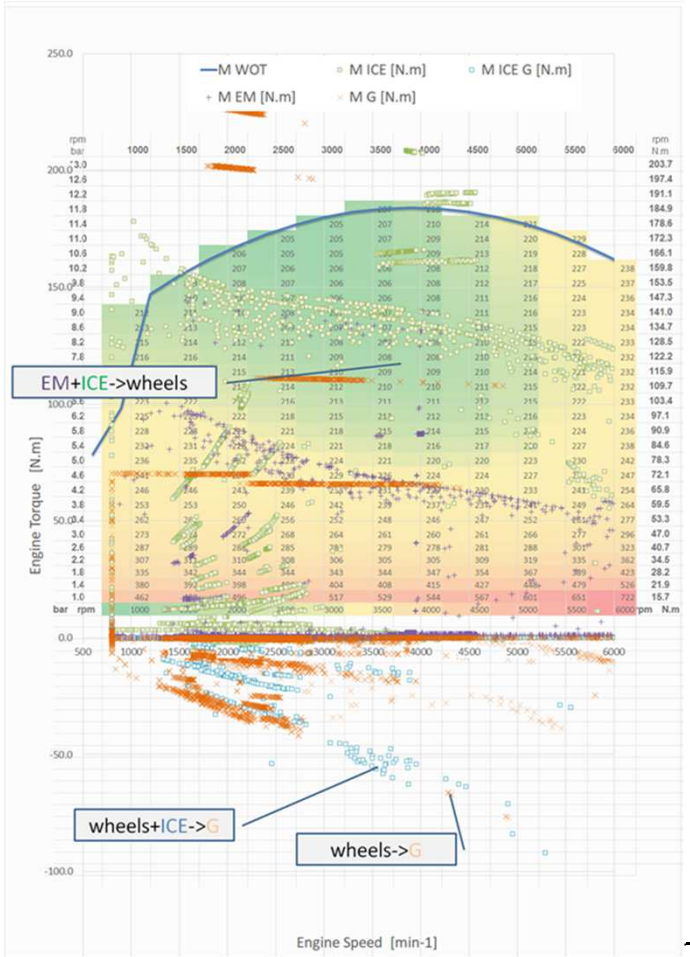


Charging strategy depends on past and future charging efficiency at distances, which are optimized as global variables, and limits of charging recommendation or requirement, which are global variables, as well. Example – WLTC.



Activities in 1-WP01 Electric and Hybrid Powertrains

Benchmarking code for ultimate energy consumption at defined route with defined constraints



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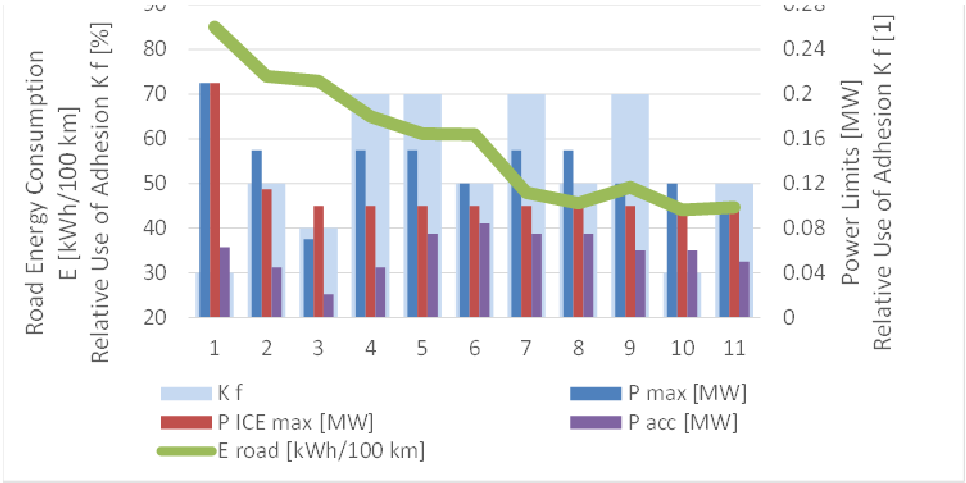
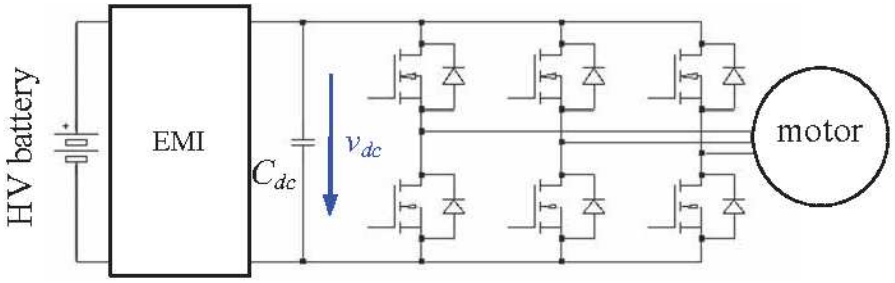


Activities in 1-WP01 Electric and Hybrid Powertrains

1-WP01-003 Wide bandgap devices based main traction converter with high power density (Main output)

Traction converter

- Compact design, high switching frequency (mass and volume reduction of electrical equipment)
- 650V/900V/1200V devices according to the DC voltage/battery
- WBG (Wide-bandgap) devices - SiC / GaN (GaN for 1200V ??)
- Power range 100kW+
- High power density (100kW / liter)

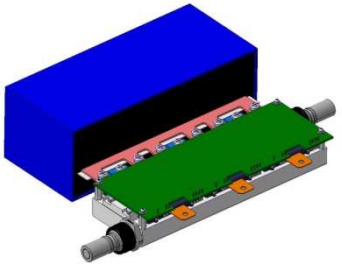


SiC modules CREE

CREE XM3 module used for WP01-003

DCM™ 1000

- Existing custom packaging technology by Danfoss
- Placed CREE bare dies SiC MOSFETs 1200V



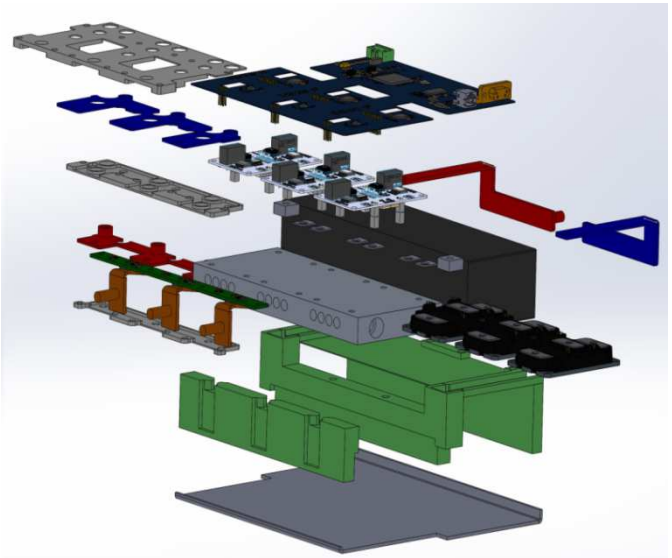
3D models of traction converter with DCM 1000 made by RICE and planned as a output for year 2021

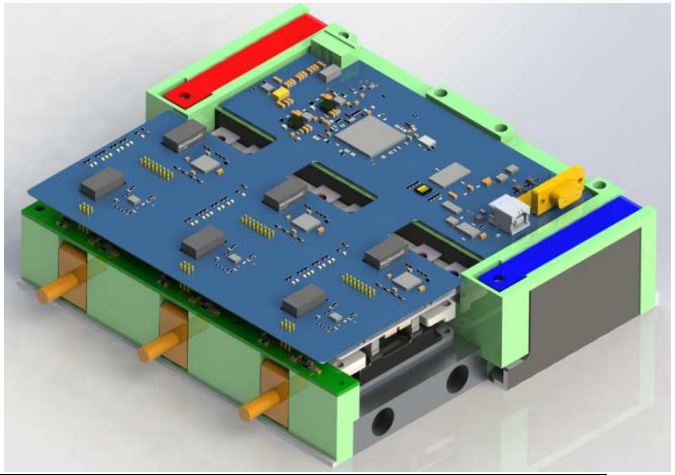
Activities in 1-WP01 Electric and Hybrid Powertrains

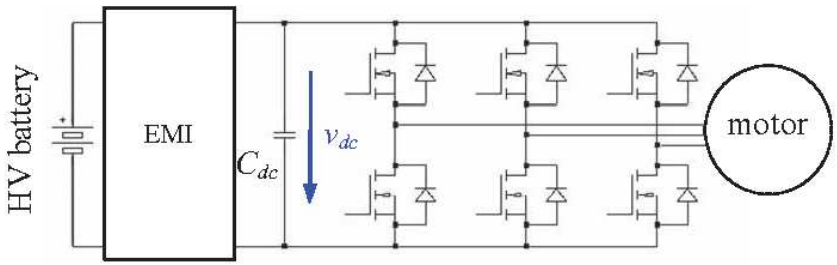
1-WP01-003 Wide bandgap devices based main traction converter with high power density (Main output)

SiC Traction converter

- CREE XM3 module used for the output WP01-003
- Converter compact design with embeded DC link capacitor, current sensors, drivers and control board with CPU
- high switching frequency (mass and volume reduction of electrical equipment)
- 1200V SiC devices according to the DC voltage/battery
- Power range ~ 250kW







Activities in 1-WP01 Electric and Hybrid Powertrains

1-WP01-003 Wide bandgap devices based main traction converter with high power density
(Main output)

SiC converter power density

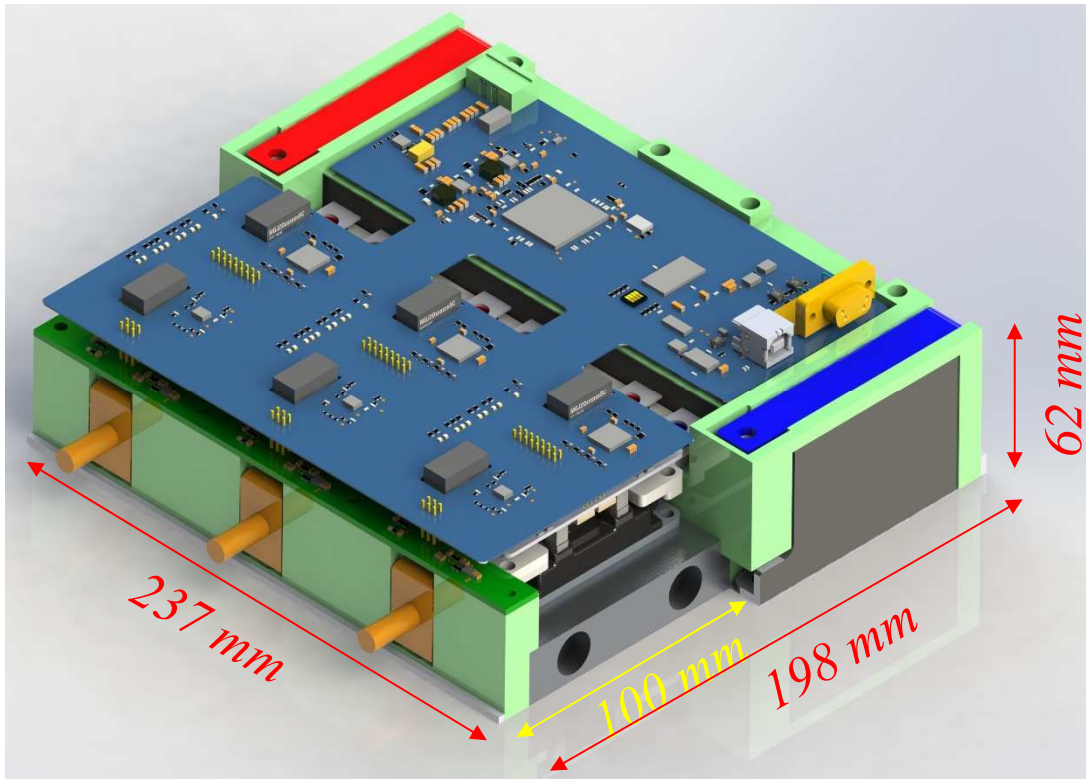
(Depends on volume definition)

With DC link capacitor 260uF/900V

- Converter volume - 2,86 litres
- Estimated converter power 250kW
- Power density ~ **87 kW / liter**

Without DC link capacitor

- Converter volume - 1,44 litres
- Estimated converter power 250kW
- Power density ~ **173 kW / liter**

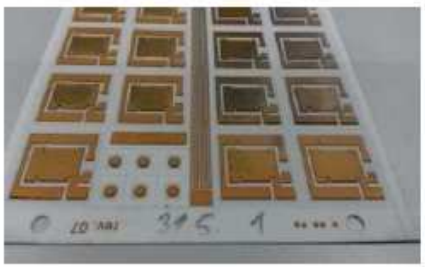


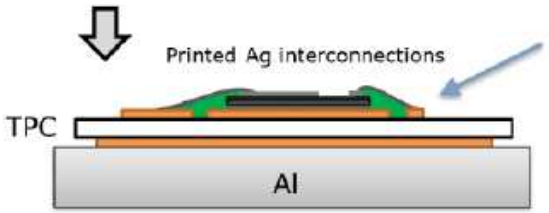
Activities in 1-WP01 Electric and Hybrid Powertrains

1-WP01-003 Wide bandgap devices based main traction converter with high power density (Main output)

Power modules development by RICE based on the TPC technology

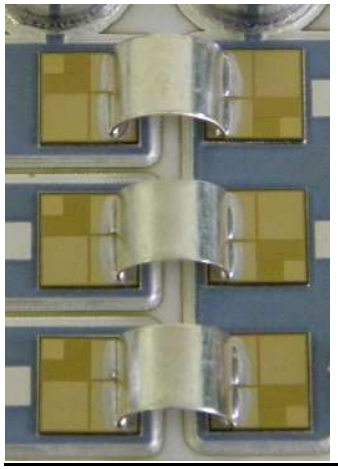
- **Printed Cuprum on the ceramic substrate with different thickness**

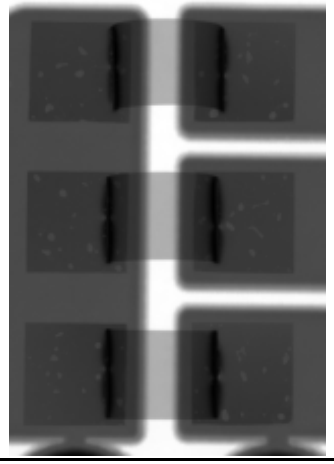




TPC - Thick Printed Copper Technology substrates examples

Die assembly results

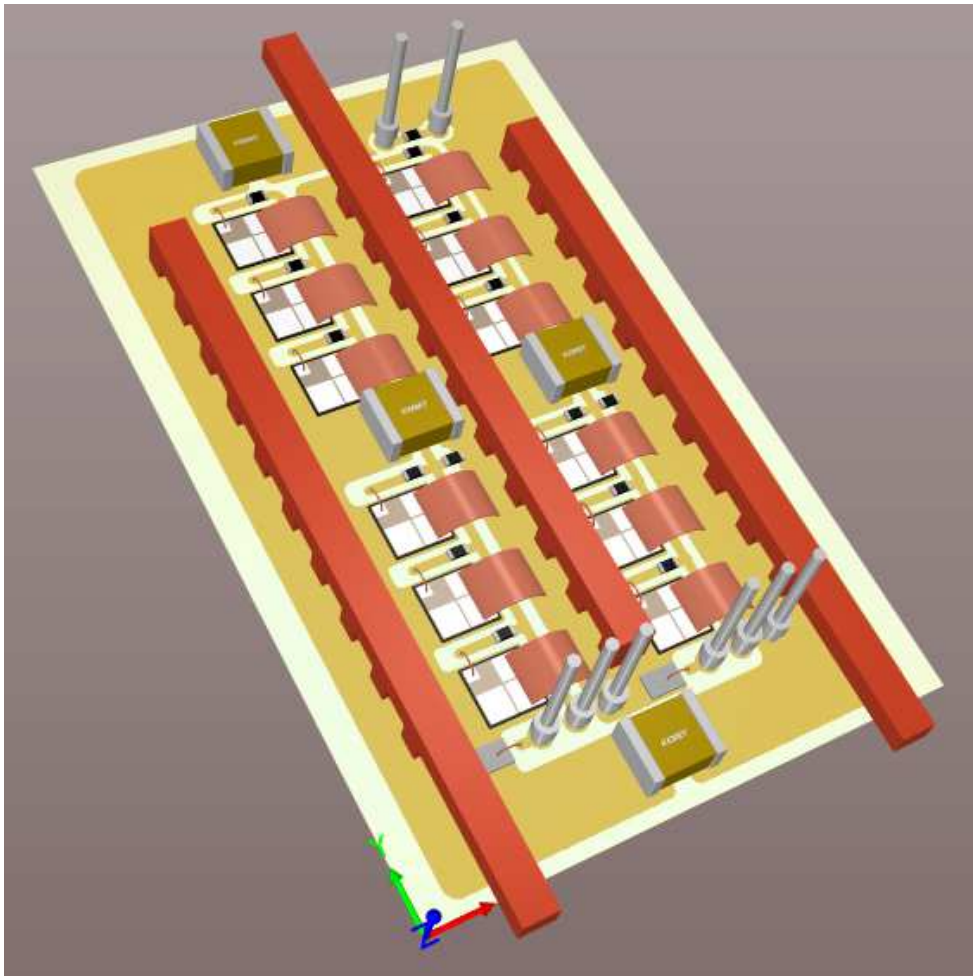




- 100um Ag, Al_2O_3 96 %, 1 mm
- Ag plated Cu strips
- **QPM3-0750-0012C - SiC** MOSFET 750V 12mΩ (CREE)
- Tested on the prototype of SSCB (Solid State Circuit Breaker)

Activities in 1-WP01 Electric and Hybrid Powertrains

1-WP01-003 Wide bandgap devices based main traction converter with high power density
(Main output)



Customize development of „SMART" modules

- SiC Half-bridge 2x6 dies developed by TPC technology allows combination of power and signal circuits on the base plate
- Snubber capacitors and gate resistors embedded
- Desaturation diode dies
- NTC temperature sensor

Activities in 1-WP01 Electric and Hybrid Powertrains

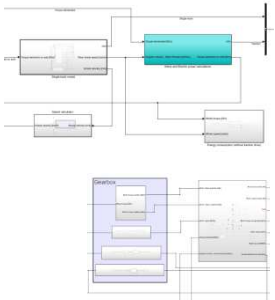
1-WP01-004 Technological demonstrator of main components of traction equipment (G)

Complex drive unit model - Single-track vehicle model

Vehicle simulator Eaton + RICE

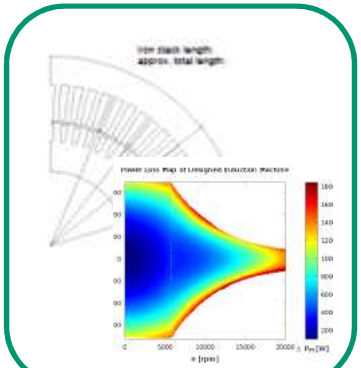
Machine electro-magnetic design

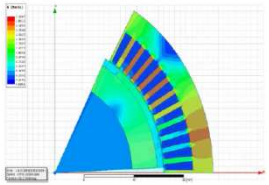
Vehicle level specification



Motor specification

Motor efficiency, currents, voltage and PF maps

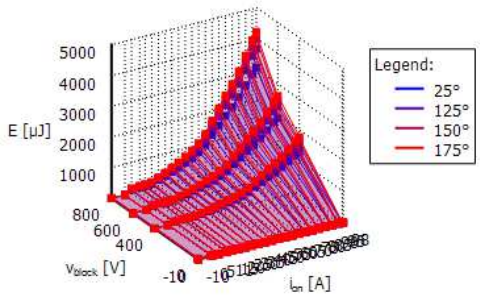


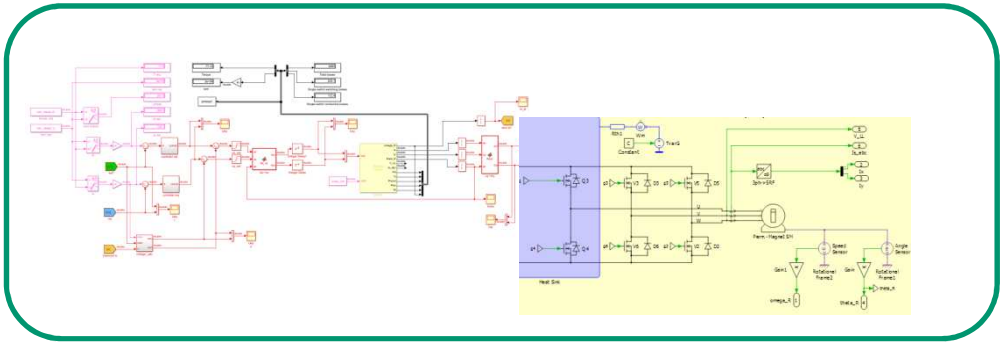


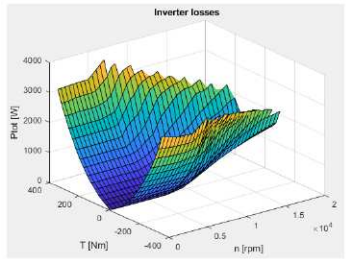
Inverter specification

Inverter efficiency maps
Power device switching and conductive losses
Power devices junction temperature

Machine phase currents, d-, q- currents and PF maps







Converter model with power devices thermal modelling

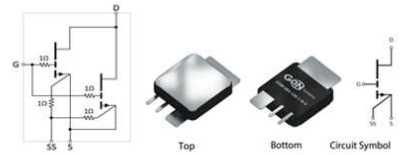
Activities in 1-WP01 Electric and Hybrid Powertrains
1-WP01-005 Technological demonstrator of main components of traction equipment (G)

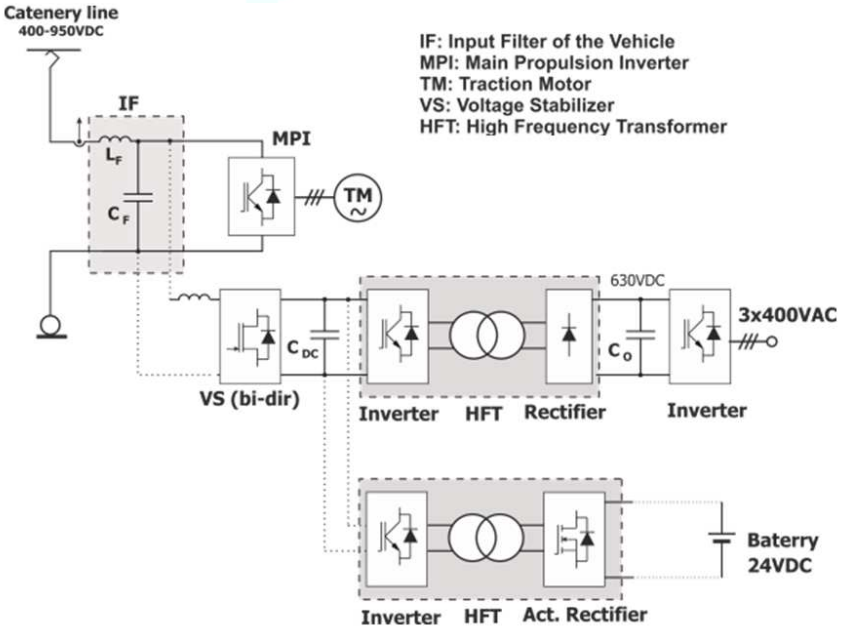
On-board traction power electronics converters – auxiliary drives

On-board traction power electronics converters - auxiliary drives

- WP01-005 (G) Technological demonstrator of main components of traction equipment
- DC/DC isolated HF transformer for safety operation of auxiliary drives
- Target switching frequency more than 500kHz to reduce mass and volume of HFT
- Power converters based on the GaN technology to achieve high f_{sw}
- Estimated power ~ 10kVA
- U_{in} ~ 380V ⇒ 650V GaN HEMT

GaN Systems – GSM-065-240-1-N-0 (Preliminary Information)		
Type	Paralelní HEMT	
Technology	GaN	
Voltage	U_{DS}	650 V
Current	I_D	240 A
Channel resistance	$R_{DS(on)}$	6 mΩ
Gate charge	Q_G	50 nC
Output charge	Q_{oss}	452 nC
MAX temperature	T_{max}	150 °C



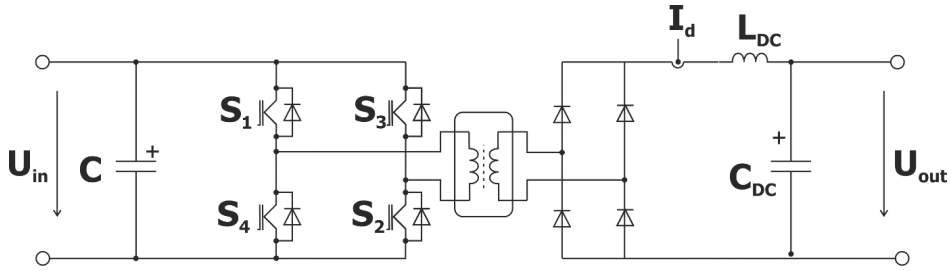


Activities in 1-WP01 Electric and Hybrid Powertrains

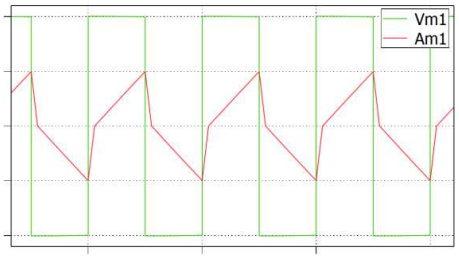
1-WP01-005 Technological demonstrator of main components of traction equipment (G)

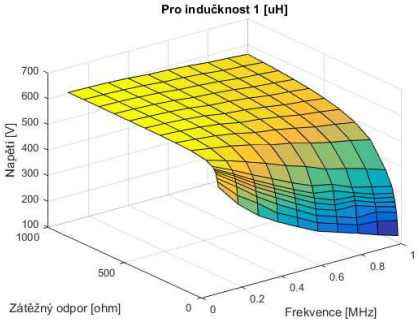
Auxiliary drives parameters:

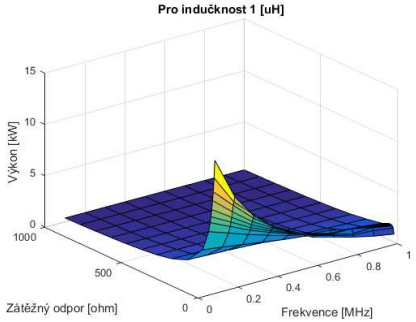
- *Power ~ 10kVA*
- *fsw ~ 500kHz - 1MHz*
- *Uin ~ 380V*

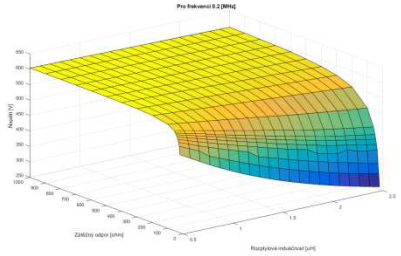


Hard switching topology





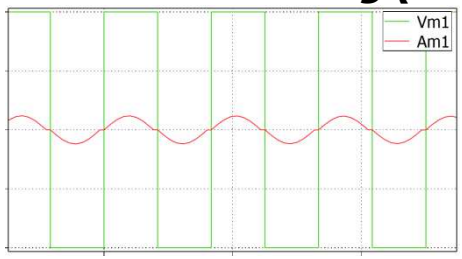


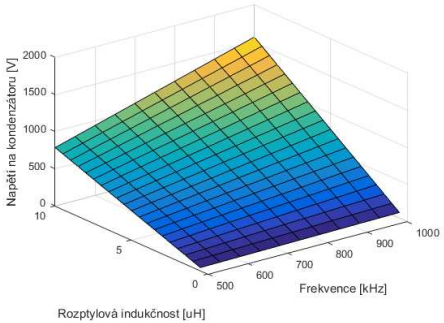


Maximal required leakage inductance of HFT

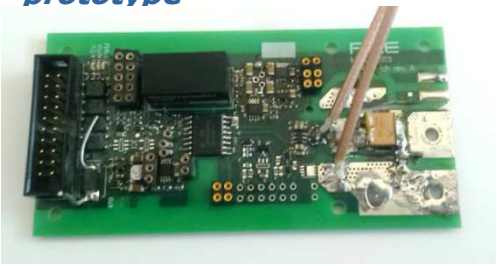
- $L_\sigma < 0{,}5\ \mu H$

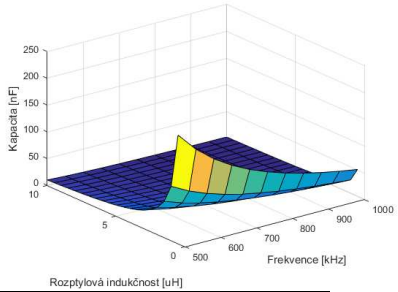
Soft switching (resonant) topology





GaN converter - H-bridge (half-bridge) - alfa prototype

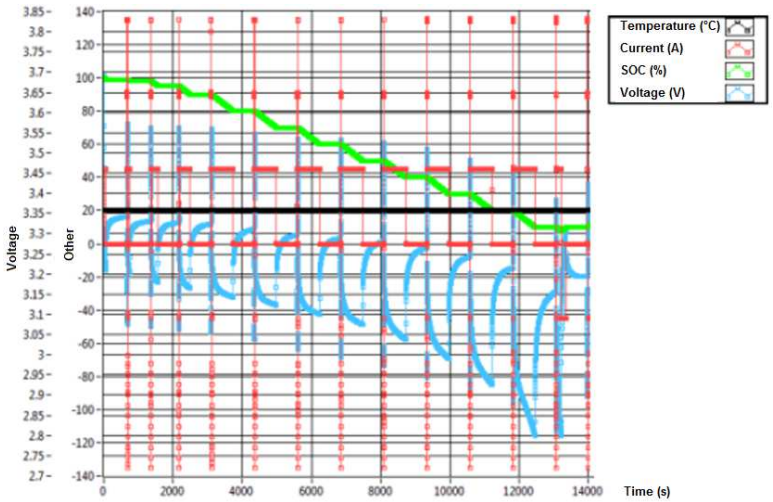


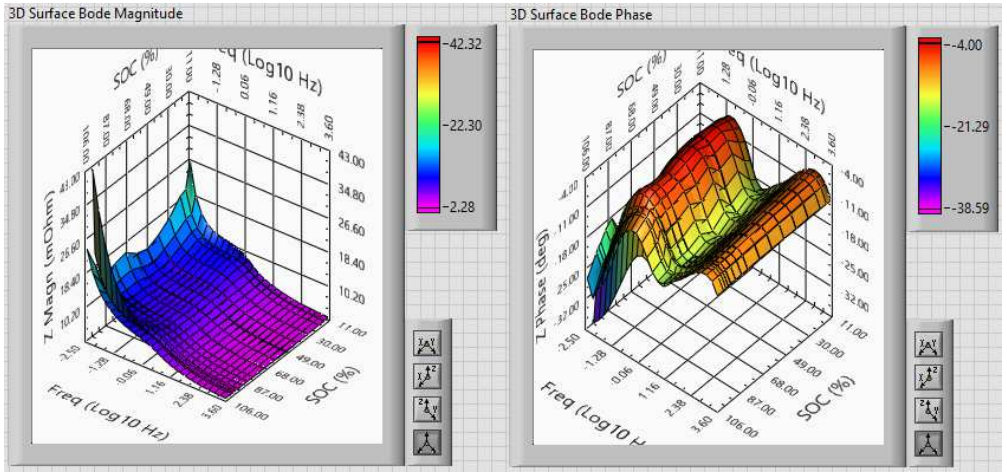


Activities in WP01 Electric and Hybrid Powertrains
1-WP01-002 Design assistance model of traction battery

Testing of electrical energy storage devices at CTU FTS

- Maximum battery current 300 A, maximum voltage 20 V, battery temperature range from -12 °C to +50 ° C.
- Testing electrochemical accumulators, supercapacitors and batteries
- Testing in both time domain (short-term, long-term) and frequency domain (Electrochemical Impedance Spectroscopy).



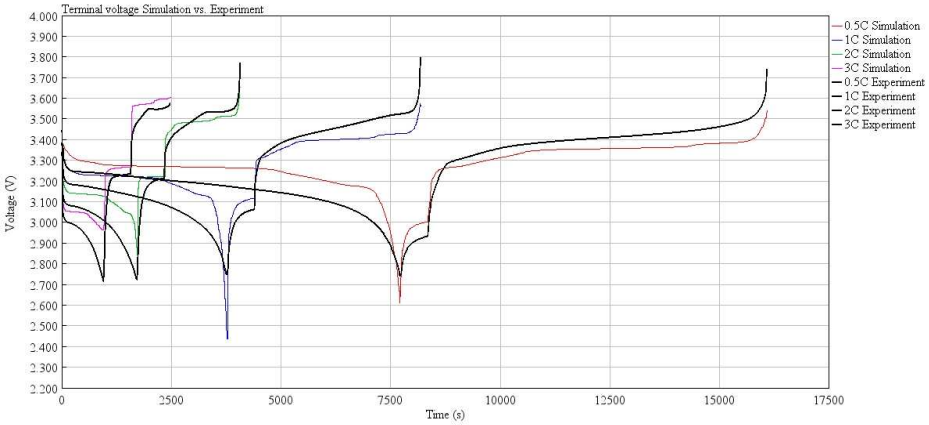


LTO battery 2.4V/10.4Ah – Impedance depending on SOC at -10°C

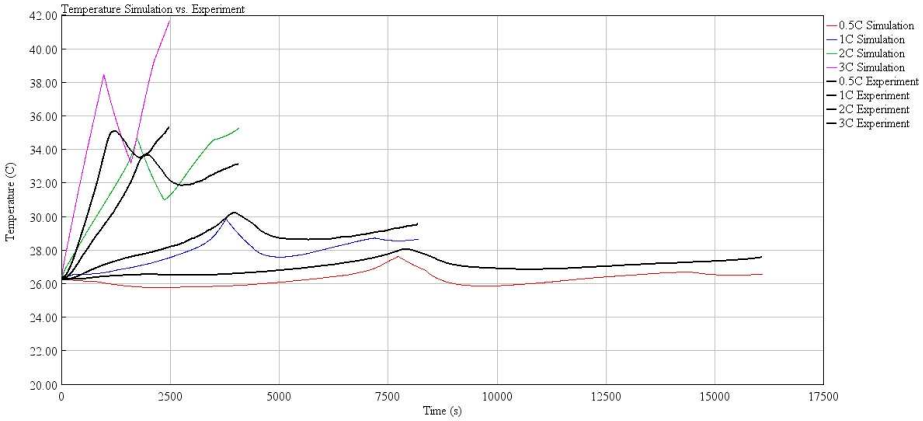
Activities in WP01 Electric and Hybrid Powertrains
1-WP01-002 Design assistance model of traction battery

Model Calibration in GT-Autolion

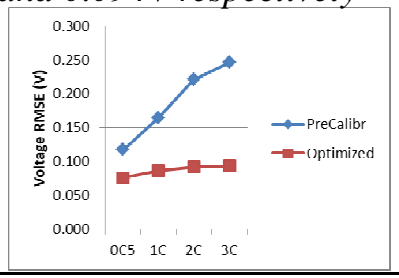
- Capacity tests
  - optimization of Contact resistance, diffusivity, entropic heat and heat transfer coefficient

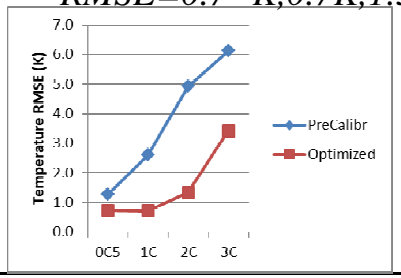


LiFeYPO4 cell 3.2V/40Ah – voltage comparison for 0.5C, 1C, 2C and 3C currents. RMSE=0.076V,0.087V,0.092V and 0.094V respectively



LiFeYPO4 cell 3.2V/40Ah – temperature comparison for 0.5C, 1C, 2C and 3C currents. RMSE=0.7 K,0.7K,1.3K and 3.4K respectively

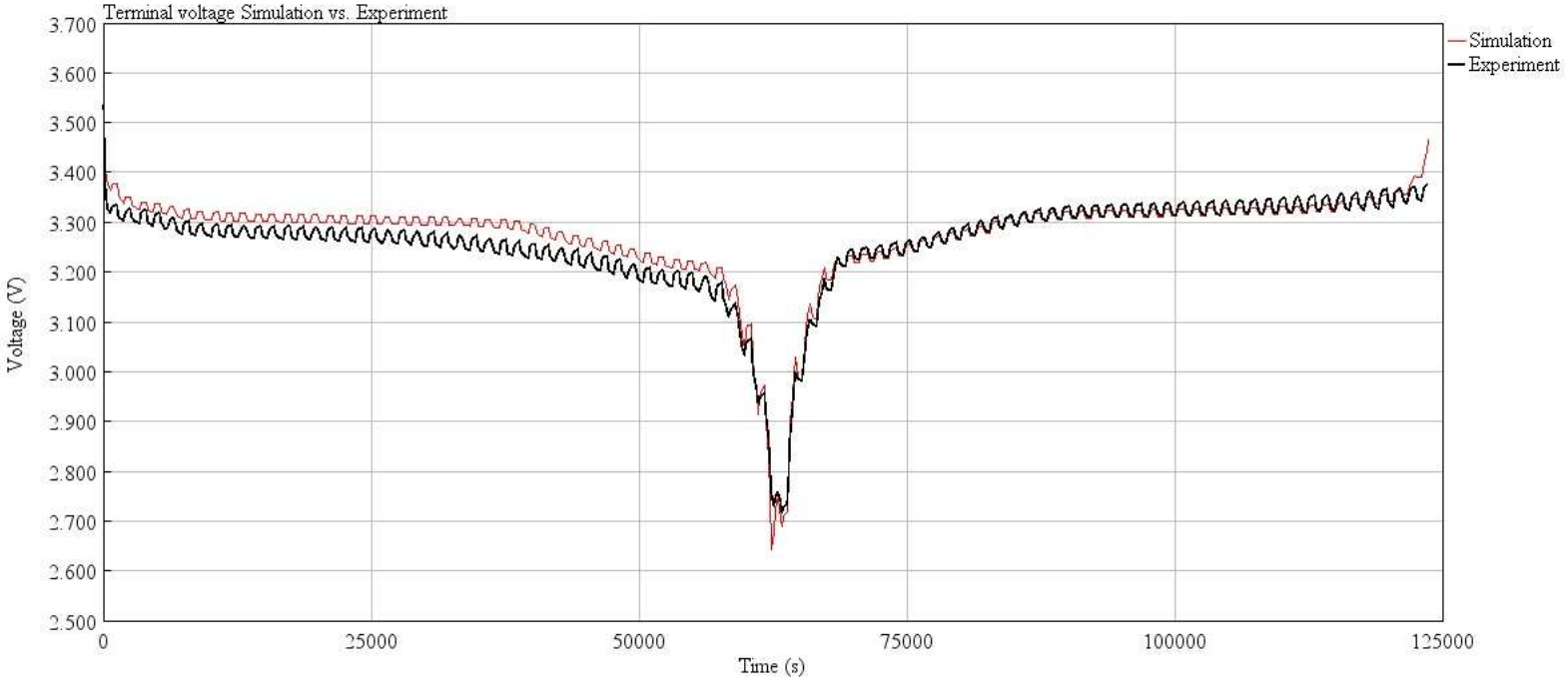




Activities in WP01 Electric and Hybrid Powertrains
1-WP01-002 Design assistance model of traction battery

Model Calibration in GT-Autolion

- OCV tests (Pulse discharge/charge cycle combined with OCV relaxation)
  - Optimization

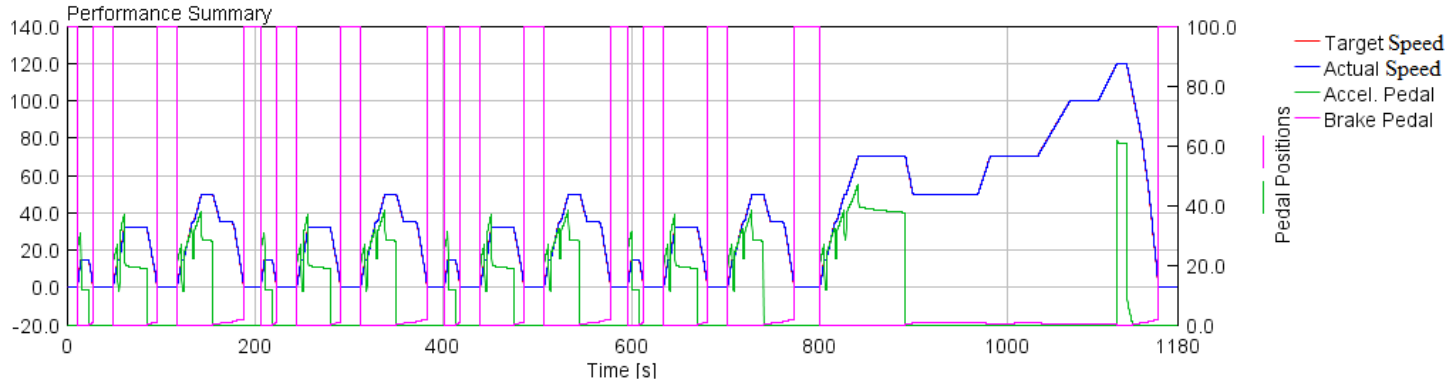


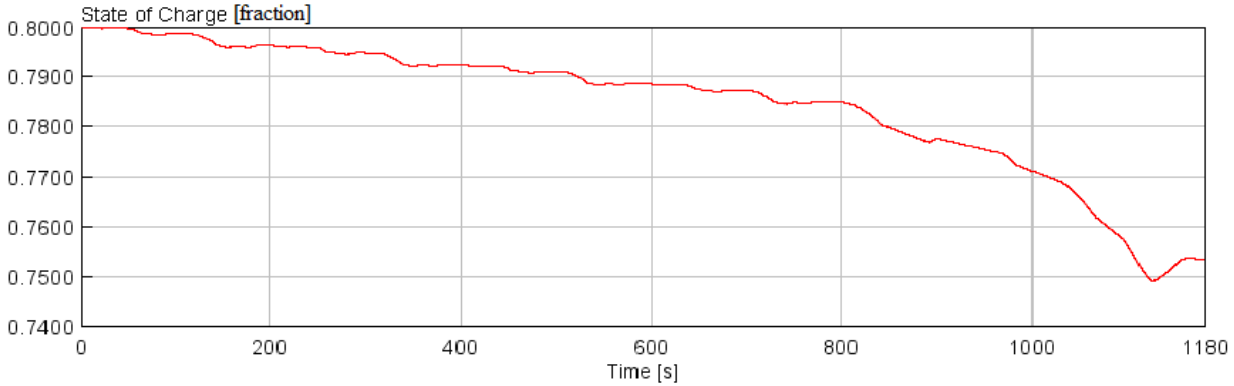
LiFeYPO4 cell 3.2V/40Ah – voltage comparison, optimizing 6 parameters. RMSE=0.027V

Activities in WP01 Electric and Hybrid Powertrains
1-WP01-002 Design assistance model of traction battery

Using calibrated model of battery in BEV model in GT-SUITE

- Example of NEDC drive cycle test, Battery 192V/176Ah





Activities in WP01 Electric and Hybrid Powertrains
1-WP01-006 SW for electric traction systems optimization

Software for the traction properties simulation of a vehicle with electric drivetrain is designed for the optimization of the layout and components design of electric powertrains. SW (Matlab) executes drivetrain calculations for an electric vehicle. Parameters of main components are used:

- Motor
- Gears
- Converter
- Battery
- Motor efficiency maps

Driving cycle SORT2 and real life driving cycles measured on vehicle route are used.

Final date: 10.12. 2020

CTU in Prague, FME

Activities in WP01 Electric and Hybrid Powertrains
1-WP01-006 SW for electric traction systems optimization

SW inputs:

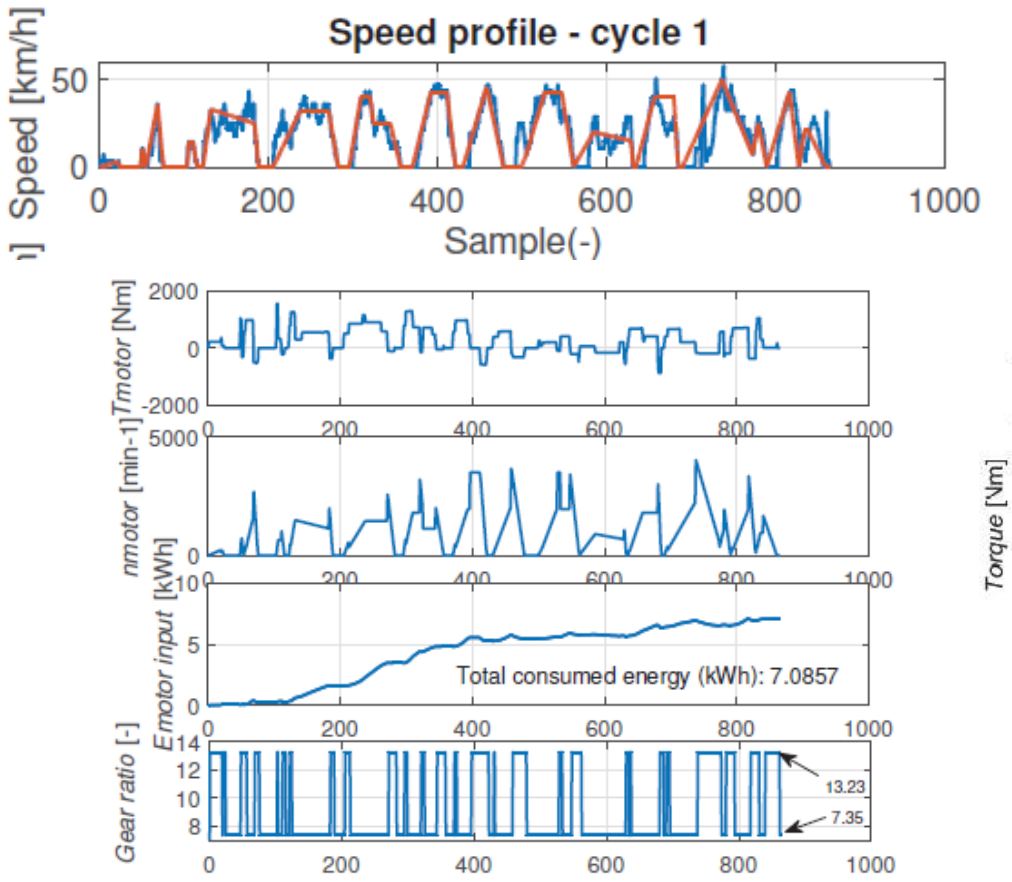
- Vehicle parameters (weight, static wheel radius, gear efficiency, moments of inertia, coefficient of rotating masses, maximal speed)
- Drive resistances
- Drivetrain parameters and efficiency maps, traction charakteristic
- Route parameters and speed profile

SW outputs:

- Motor power, speed and torque
- Drivetrain input power
- Motor current id, iq components
- Energy consumption
- Efficiency map with operating points

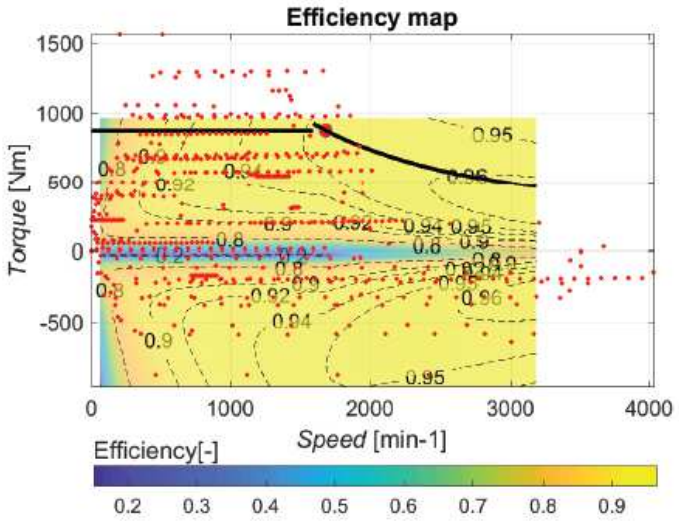
Activities in WP01 Electric and Hybrid Powertrains
1-WP01-006 SW for electric traction systems optimization

Simulation SW outputs example:



Speed profile – measured and interpolated

Motor calculated values and efficiency map with requested operating points



Activities in WP01 Electric and Hybrid Powertrains

1-WP01-007 Theoretical and experimental verification of optimized electric drive for automotive applications

Realisation of theoretical analysis of induction motor, proposed for automotive applications. Determination of induction machine optimized criteria for working in optimal like for motor, so for generator regimes. On the basis of theoretical results experimental stand for its verification has been developed and built.

Together with theoretical results verification testing system for induction motor measurement was modified for data collection enabling continuous drive diagnostics (monitoring of motor actual basic parameters including of efficiency calculation).

Main goals in 2020 was to achieve optimised control of electric drive working in generator regime.

Needed results were achieved.

In the future electric drive dynamic parameters will be studied.

Activities in WP01 Electric and Hybrid Powertrains

1-WP01-007 Theoretical and experimental verification of optimized electric drive for automotive applications

Typical results for motor regime

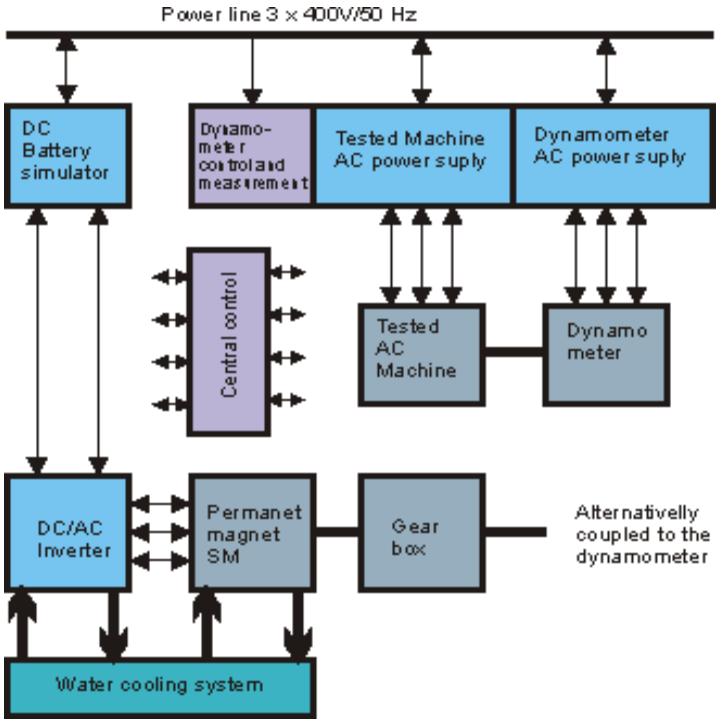


Fig. 1 Block diagram of testing bench.

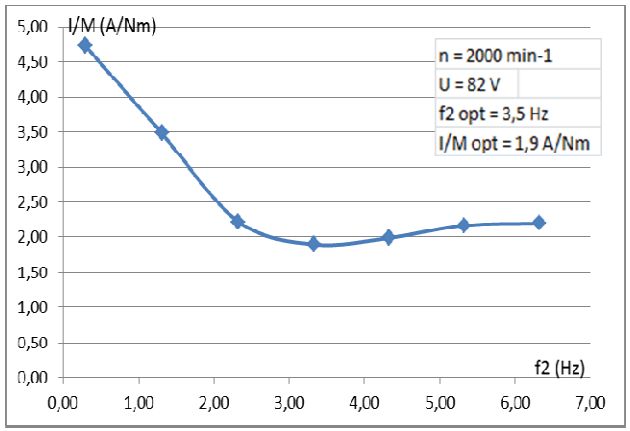


Fig. 2 Characteristic dependence of $I/T = f(f_2)$ for motor regime
I… stator current
T …torque
f_2… rotor current frequency

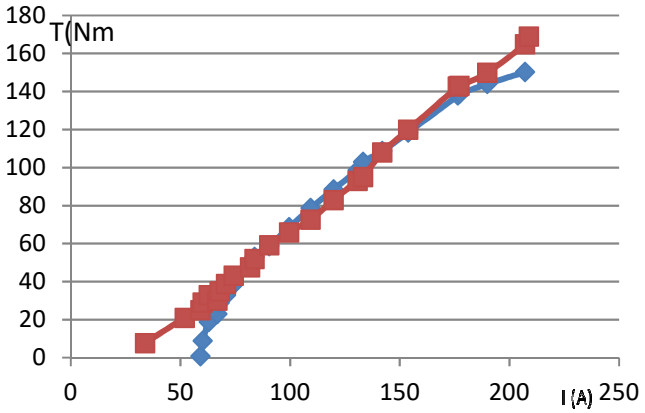


Fig. 3 Motor TEM 112, Dependence of $T = f(I)$ for $n = 3000$ rev.min-1, red line for optimised f_2 red line for optimised f_2 . Blue line for $U/f =$ const.

Activities in WP01 Electric and Hybrid Powertrains

1-WP01-007 Theoretical and experimental verification of optimized electric drive for automotive applications

Typical results for generator regime

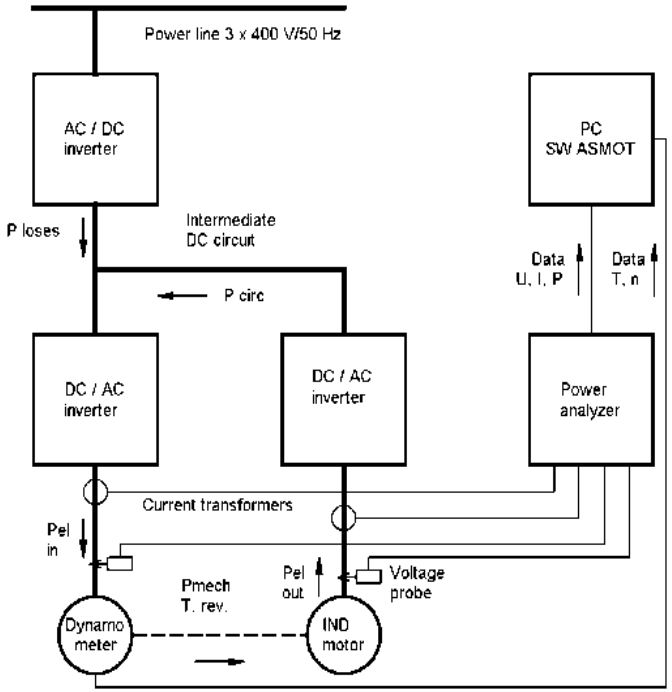


Fig. 4 Block diagram of testing bench for generator regime measurement.

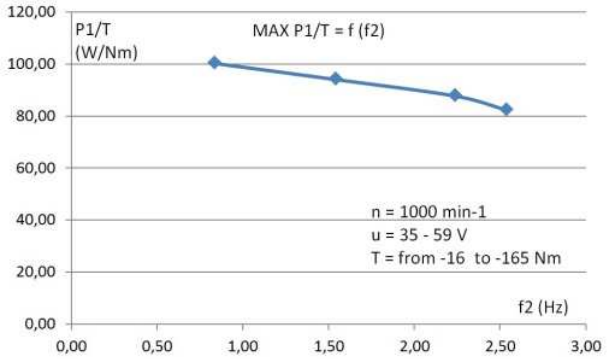


Fig. 5. Optimised working area P1/T = f(f2) of induction motor operated in generator regime at 1000 rev. per min.

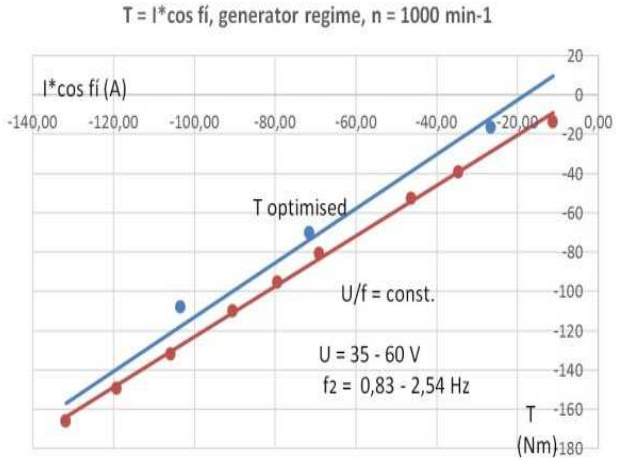


Fig. 6. Relations between breaking torque and active current generated at recuperation regimes for U/f = constant (red line) and optimised rotor current frequency f_2 (blue line) at 1000 rev. per min.

Fulfillment of goals and deliverables of Activities in 1-WP01 Electric and Hybrid Powertrains

Current State of Deliverables, Milestones and Fulfillment of Goals

1-WP01-001 Benchmarking code for ultimate energy consumption at defined route with defined constraints will be fulfilled in 12/2020

1-WP01-003 Wide bandgap devices based main traction converter with high power density (G) will be fulfilled in 12/2020

List of Due Deliverables and Their Added Value

1-WP01-001 yields new approach to optimization of hybrid vehicles with predictive features but not too demanding high computational power. It is in the benchmark position now, it will be amended by the direct connection to control algorithm in SiL – simulation code of the whole vehicle.

1-WP01-003 yields new compact design of traction converter with high switching frequency, reduced mass and volume. Its design is based on ultimate power switch technology.

Current contribution of Activities in 1-WP01 Electric and Hybrid Powertrains

Dissemination:

Denk, P.: "Optimization of the road vehicle driving (in Czech: Optimalizace jízdy silničního motorového vozidla)". Doctoral Dissertation, Supervisor Šika, Z., Czech Technical University in Prague, Praha 2019

Macek, J. , Toman, R. , Denk, P. , Steinbauer, P., "Hybrid Powertrain Optimization Tools". LIst Conference of Czech And Slovak Combustion Engine Research, Czech Technical University in Prague, 2020, pp. 110-128, ISBN 978-80-01-06744-4

Toman, R., "Parallel Plug-in HEV Topologies Evaluation Using Dynamic Programming", LIst Conference of Czech And Slovak Combustion Engine Research, Czech Technical University in Prague, 2020, pp. 220-228, ISBN 978-80-01-06744-4

Kohel, P., Toman, R., Development of a control algorithm for a parallel hybrid powertrain. MECCA 01, 2020, pp.15-28, ISSN 1214-0821, doi:10.14311/mecdc.2020.01.03

Čeřovský, Z. - Mindl, P. – Mňuk, P.: Induction motor optimised supply voltage and frequency control. International Conference on Electrical Drives & Power Electronics (EDPE) The High Tatras, 24-26 Sept. 2019

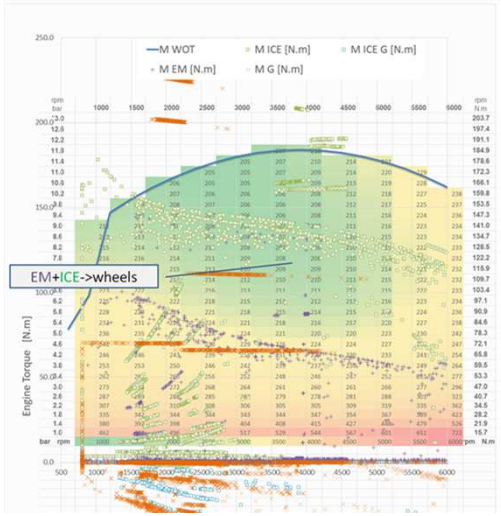
Čeřovský, Z. - Mindl, P. – Mňuk, P.: Optimální regulace napětí a kmitočtu asynchronního motoru napájeného z elektronického měniče, XXXVI. konference o elektrických pohonech ELPO, Plzeň, 11. – 12. 6. 2019

Vacarda, M. – Mindl, P.: PID regulace rekuperačního měniče superkapacitoru v hybridním pohonu. XXXVI. konference o elektrických pohonech ELPO, Plzeň, 11. – 12. 6. 2019

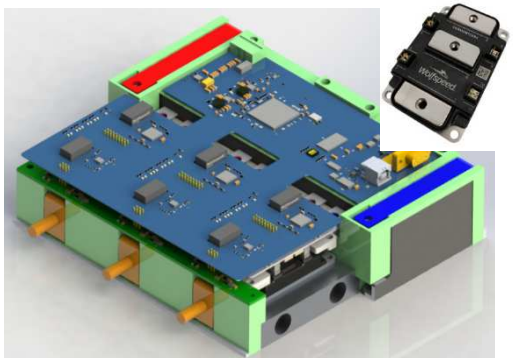
Čeřovský, Z.- Mindl, P. – Mňuk, P.: Optimization of induction machine generator regime in electro mobile, Příspěvek na konferenci FISITA, Praha 2020, v přípravě.

Čeřovský, Z.- Mindl, P. – Mňuk, P.: Optimized Supply Voltage and Frequency Control of Induction Motor. Výzkumná zpráva ČVUT FEL 2020

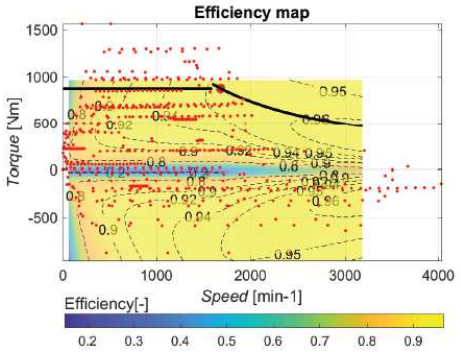
Výtah z prací 2019-2020 na 1-WP01 Elektrické a hybridní hnací jednotky



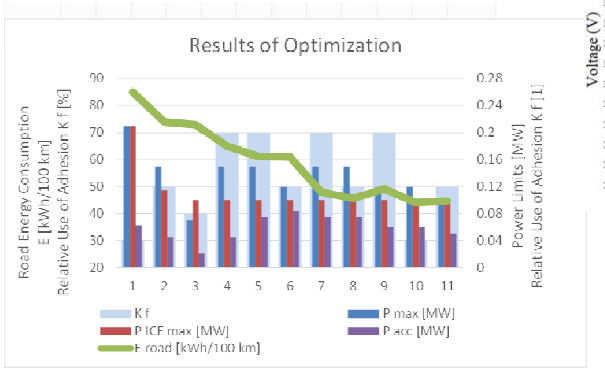
1-WP01-001 Limitní možnosti snížení spotřeby pomocí optimalizačního programu – ČVUT FS, CVUM

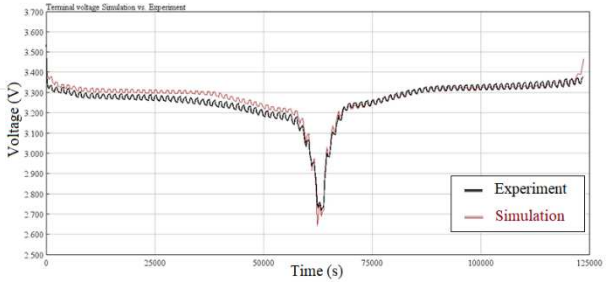


1-WP01-003 Trakční měnič s vysokou hustotu výkonu založený na polovodičích s velkou šířkou zakázaného pásu – RICE FEL/ZČU

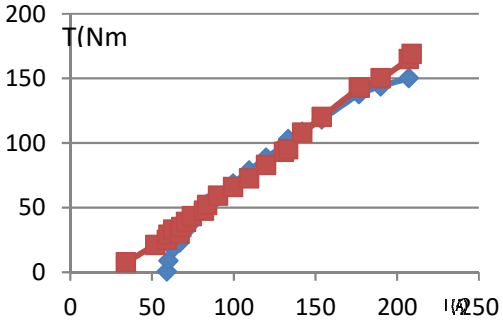


1-WP01-006 SW pro optimalizaci elektrických trakčních systémů – ČVUT, FS



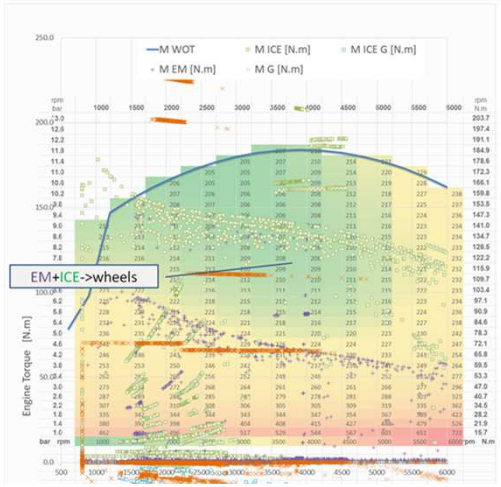


1-WP01-002 Návrhový asistenční model trakční baterie ČVUT FD

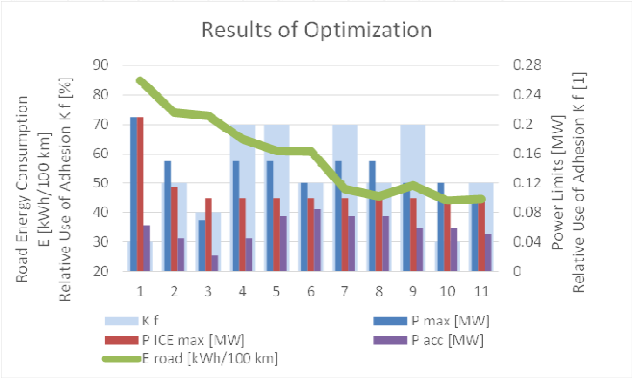


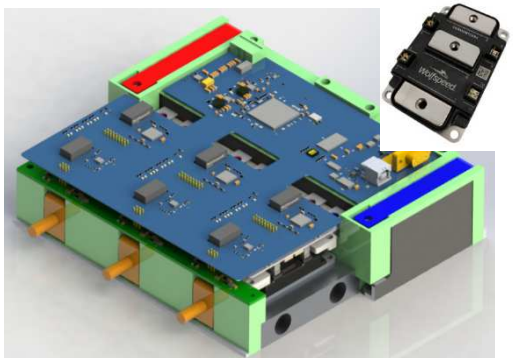
1-WP01-007 Theoretical and experimental verification of optimized electric drive for automotive – ČVUT, FEL

Results of 1-WP01 Electric and Hybrid Powertrains – Achieved 2019-2020

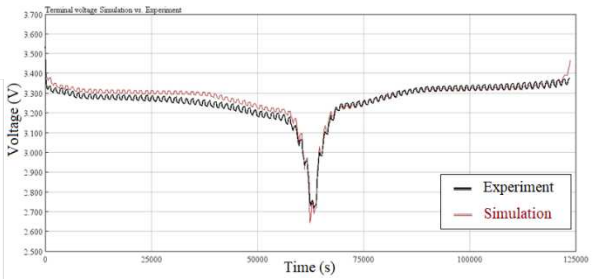


1-WP01-001 Benchmarking code for hybrid vehicle driving – CTU FME

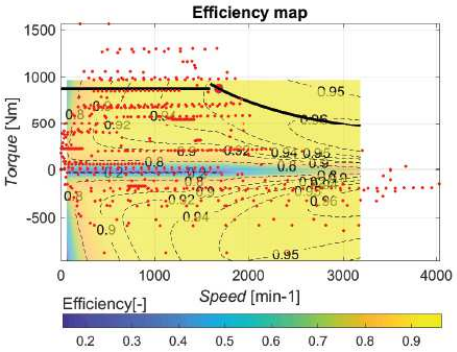




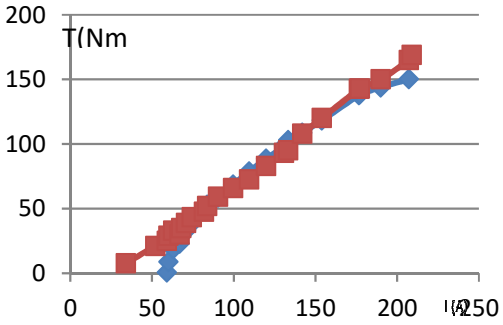
1-WP01-003 Wide bandgap devices based main traction converter with high power density – RICE UWB FEE



1-WP01-002 Design assistance model of traction battery – CTU FTS



1-WP01-006 SW for electric traction systems optimization – CTU FME



1-WP01-007 Theoretical and experimental verification of optimized electric drive for automotive – CTU FEE