Advanced Electric Drive Modelling

Solving conflicting goals in electric motors through new development approaches

Lösung von Zielkonflikten bei E-Motoren durch neue Entwicklungsansätze

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Lead Engineer e-Machine Simulation

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Project Experience

- >5 years experience in automotive field on e-Drive development
  - 48V-HV architectures (P1-P4)
  - High-speed e-machines
  - High-power-density traction drives
  - Variable flux machines
  - Externally excited synchronous machines
- Lead and execution of R&D projects
- Responsible for CAE methods and workflows:
  - e-Drive concept definition and optimization by CAE
  - Model-based development and test virtualization
  - Correlation of simulation and testing

Industrial Experience

- 2019-present: Lead Engineer e-Machine Simulation, AVL List GmbH
- 2016-2019: Simulation Engineer e-Drive simulation, AVL List GmbH

Education

- 2014-2016: MSc, Electrical Power Engineering, Chalmers University of Technology, Gothenburg, Sweden
- 2010-2014: BSc, Electrical Engineering, Universidad de Navarra, Spain

Patents and publications

- 11 patent applications regarding electric drives
- 16 publications and conference presentations about electric drives

Agenda

- Introduction
- Electric machine model condensation and integration in electric drive system model
- Thermal adaptive control and overmodulation
- NVH optimization through control
- Summary
- AVL High-Speed e-Axle - 30000rpm electric machine
- Validation references

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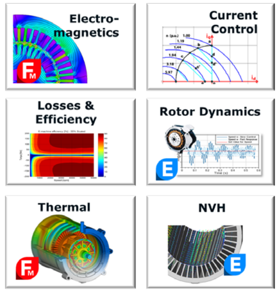
Introduction

- Test equipment for e-Drive
- Turnkey lab solutions

- Testing & Benchmarking
- E-Drive characterization
- Control SW calibration

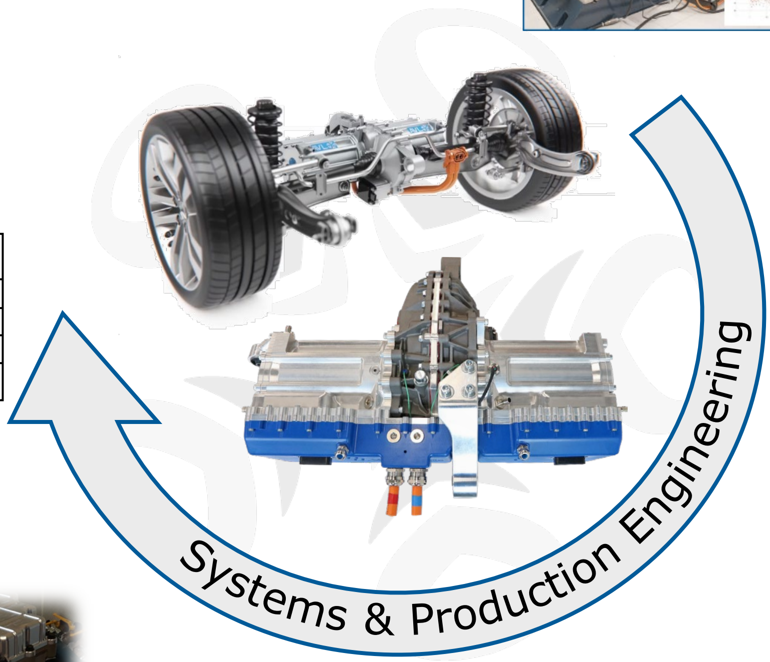
- RQ engineering



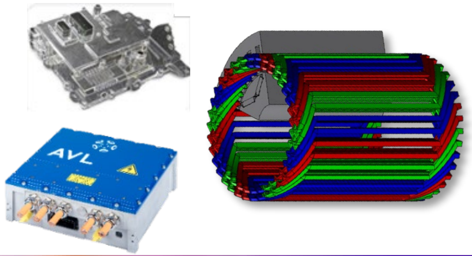
- Component development
- System Integration
- EMAG Simulation
- Thermal Simulation
- Mechanical Simulation
- Electric Simulation
- EMC Simulation
- NVH Simulation

- System validation
- Planning, optimization & monitoring

Validation target:	
300.000 km cycle life	✔
12 years calendar life	✔
EMC targets fulfilled	✔
Performance OK	✔



- Prototype build
- Front-loading of virtual calibration models



- Electrical & Mechanical Design Engineering
- Design for Production
- Inverter & MCU development (SW & HW)

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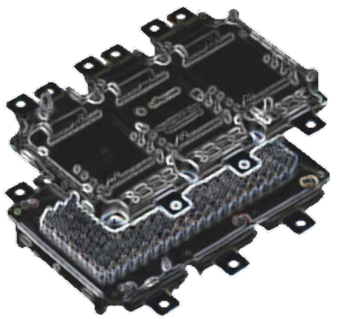
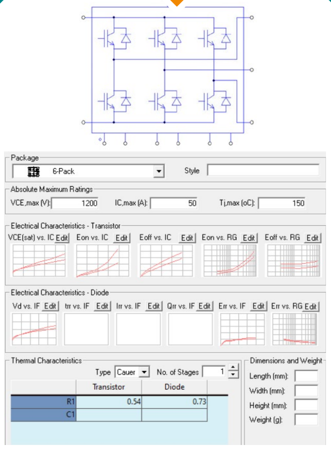
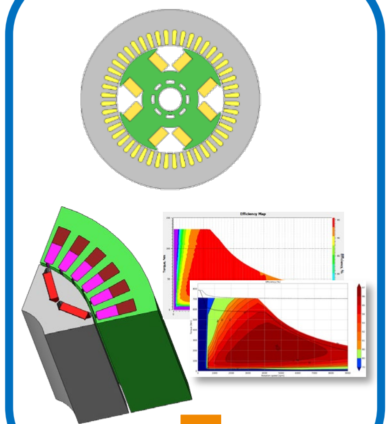
Electromagnetic simulation

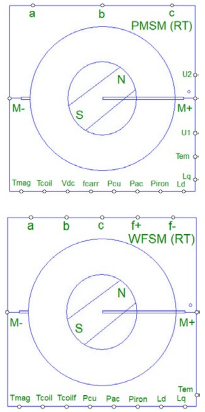
From detailed FEM models to condensed circuit components

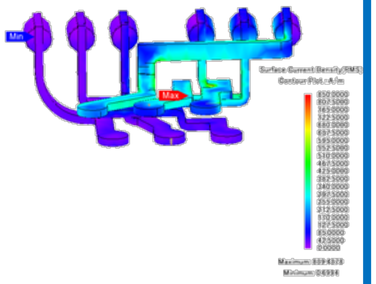
Power module	E-Machine	Busbar	Cables	Capacitances

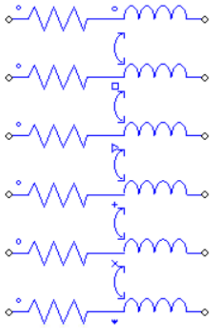


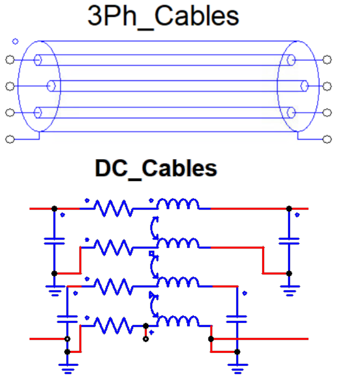


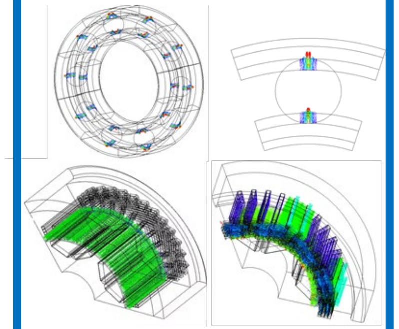


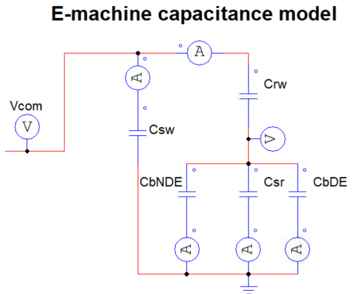




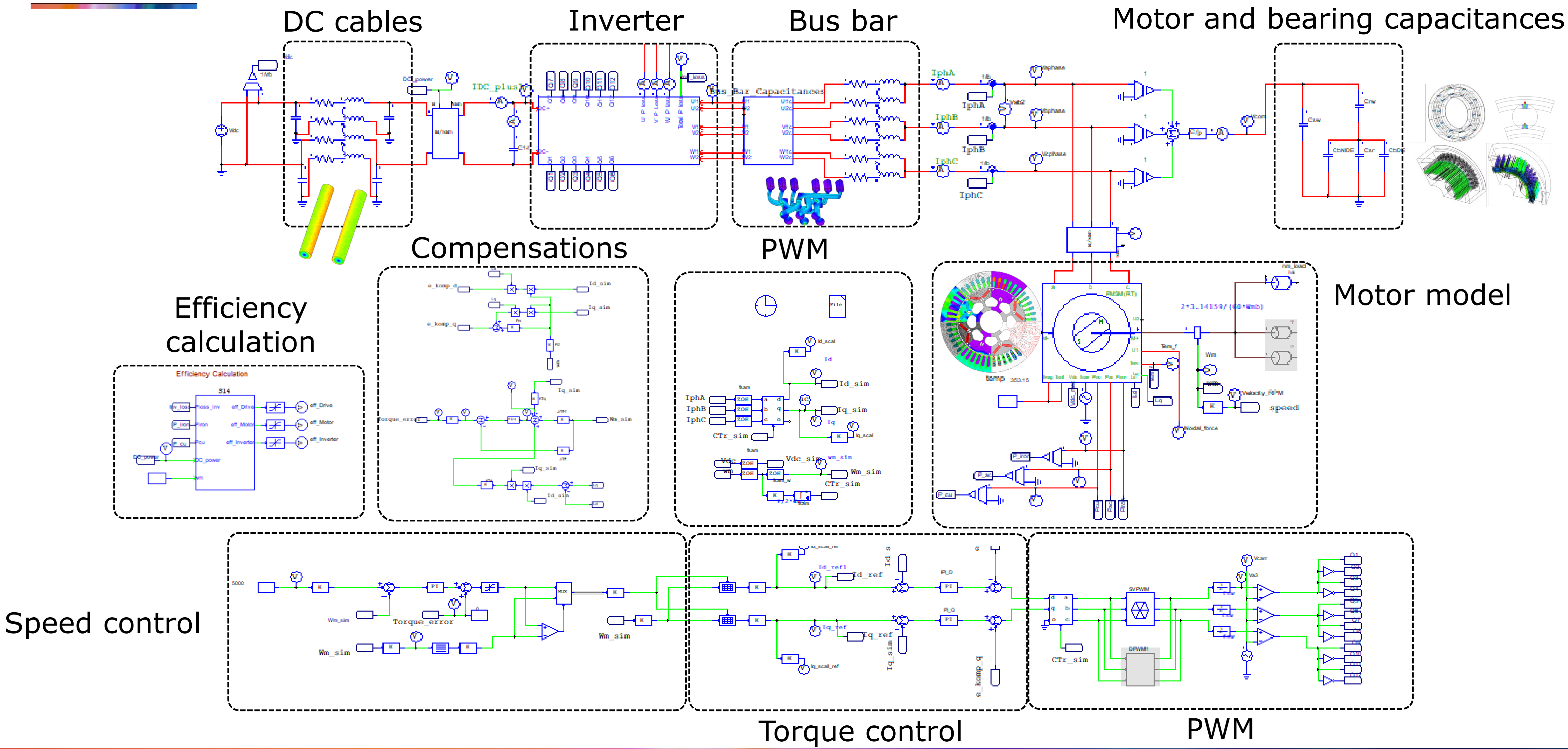








E-machine high-fidelity plant model
Integration into full system



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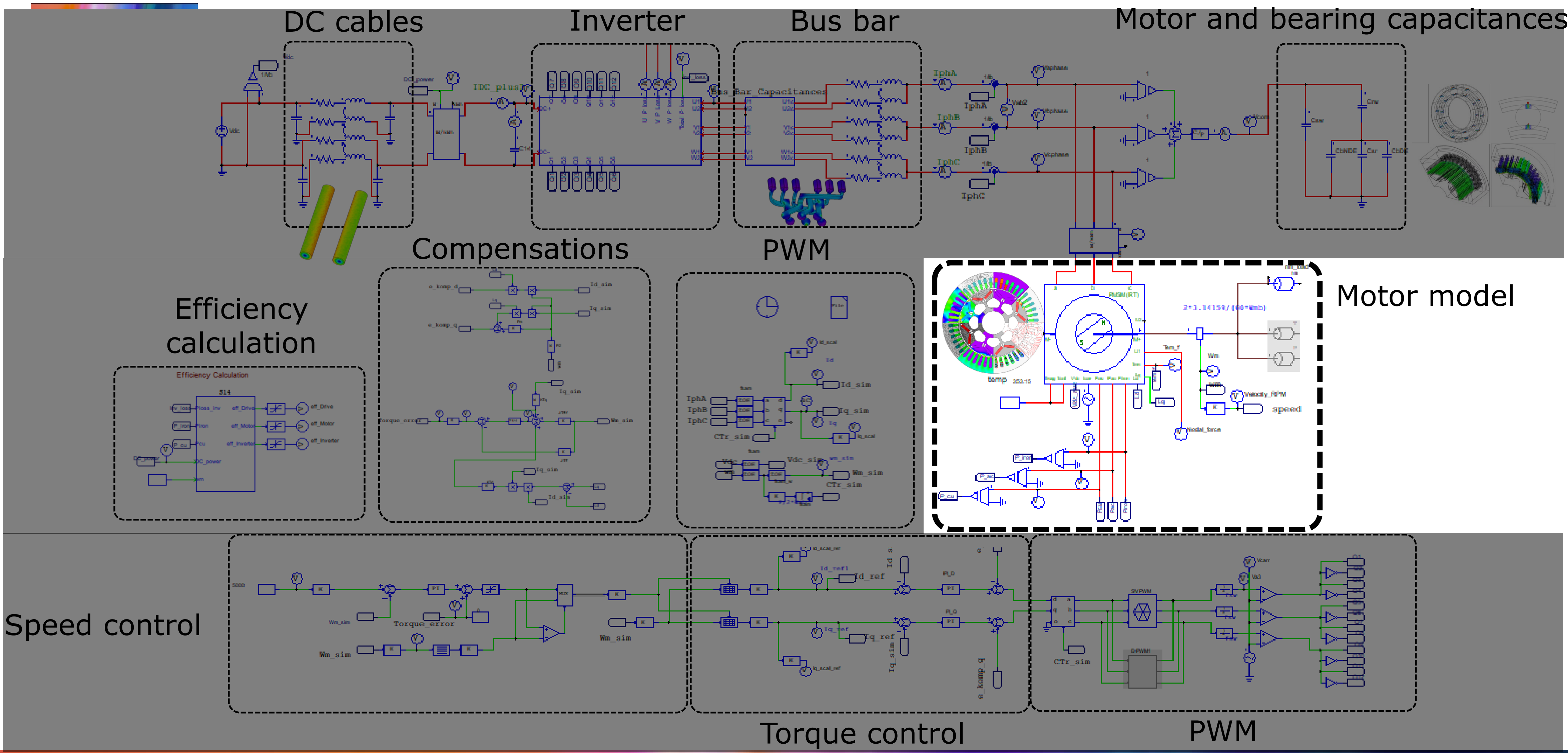


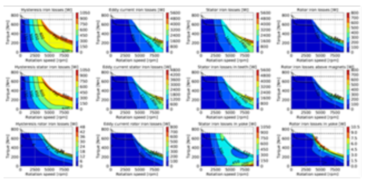
Electromagnetic simulation

E-machine high-fidelity plant model

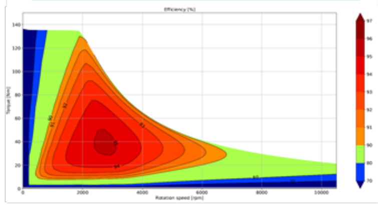
From 2D/3D model to reduced order model for control

AVL

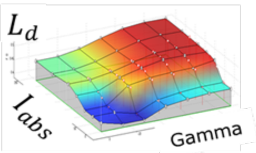
Loss decomposition



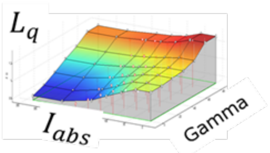
Efficiency map



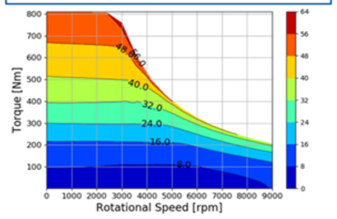
D-axis inductance



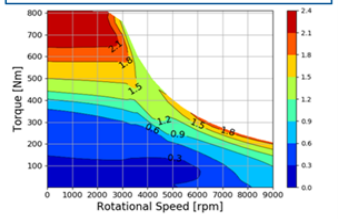
Q-axis inductance



Torque ripple 48th order



Stator radial force (T48, S0)



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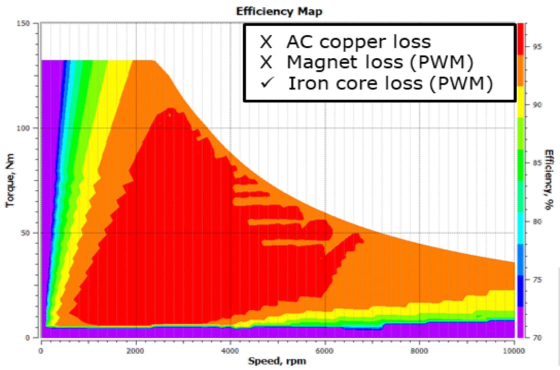
JMAG-RT®



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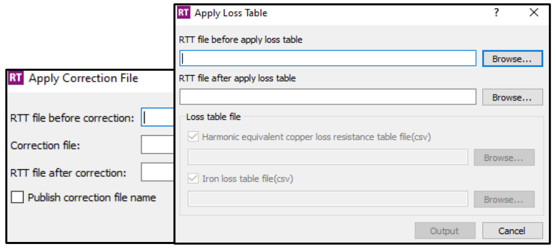
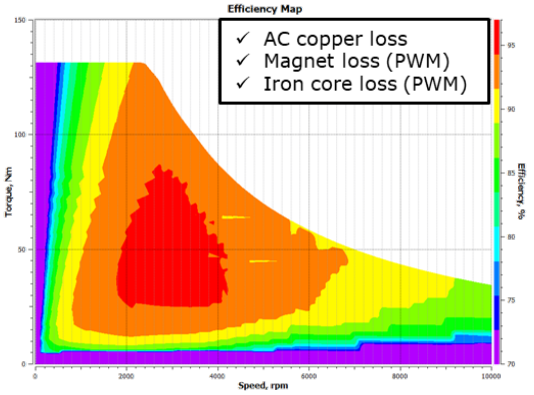
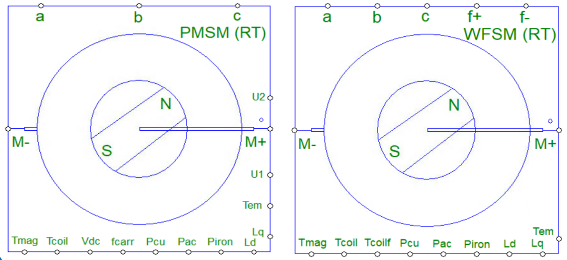


Increased accuracy of plant model



PSIM

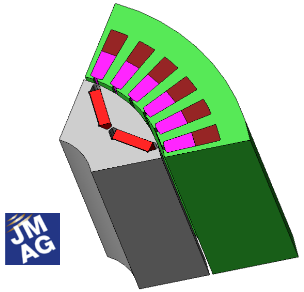


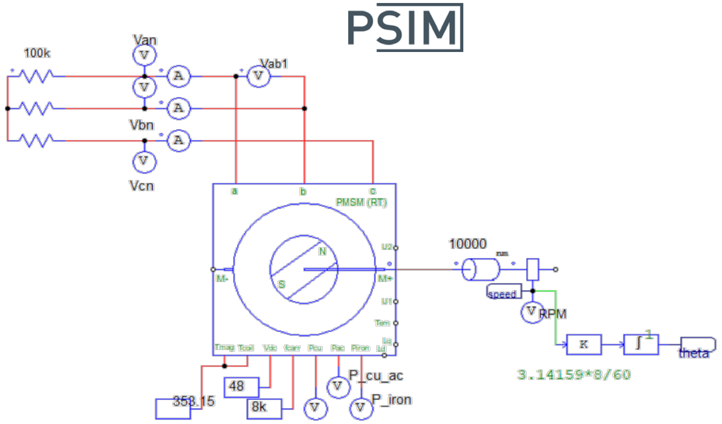
E-machine high-fidelity plant model

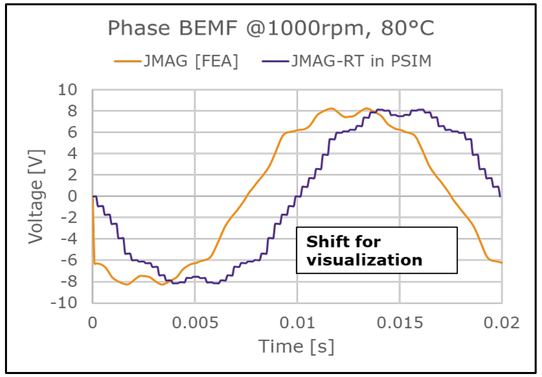
No-Load (BEMF) with spatial harmonics for PMSM & EESM

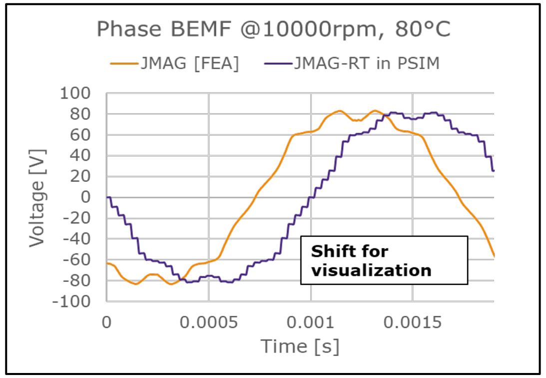
2D/3D versus reduced order model for control, validation with back EMF

PMSM

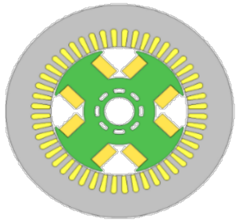


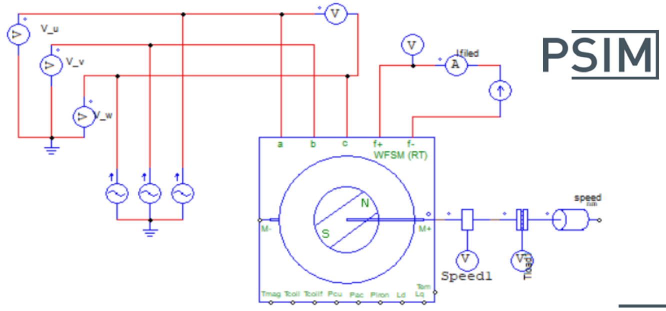


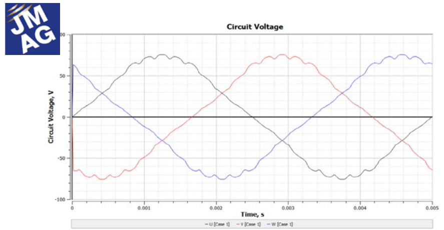


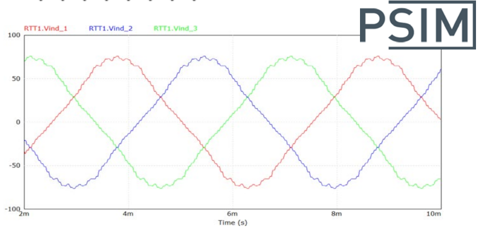


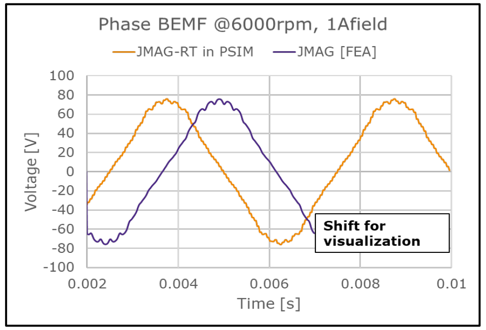
EESM

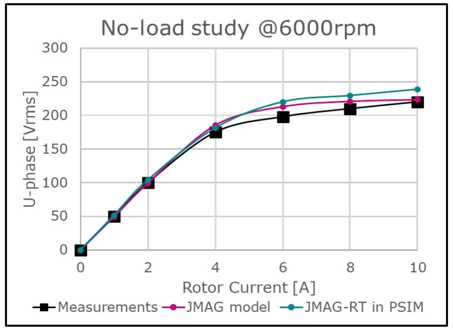










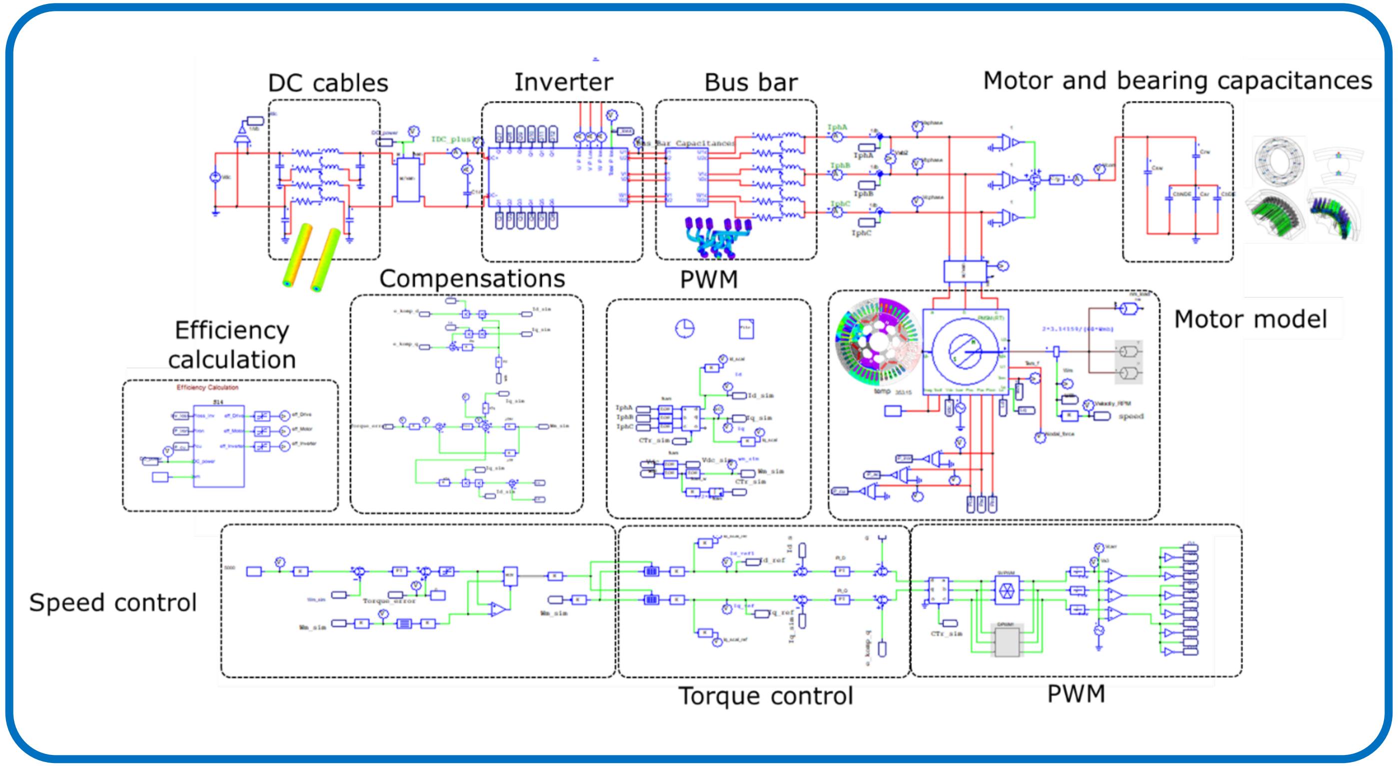


E-machine high-fidelity plant model

Integration into full system – Inputs and outputs

Full electric drive unit modelling allows for any electric simulation

Inputs:
- DC Voltage
- Control
- Modulation
- Components
- Temperature



Outputs:
- Voltage FFT
- Current FFT
- Bearing current
- Component losses
- Torque Speed

E-Drive advanced control
Random Pulse Width Modulation (RPWM)

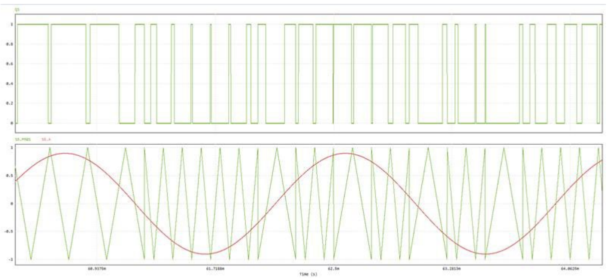
Random PWM should reduce NVH around switching frequencies

Theory approach | **MODELING** | **SIMULATION RESULTS**

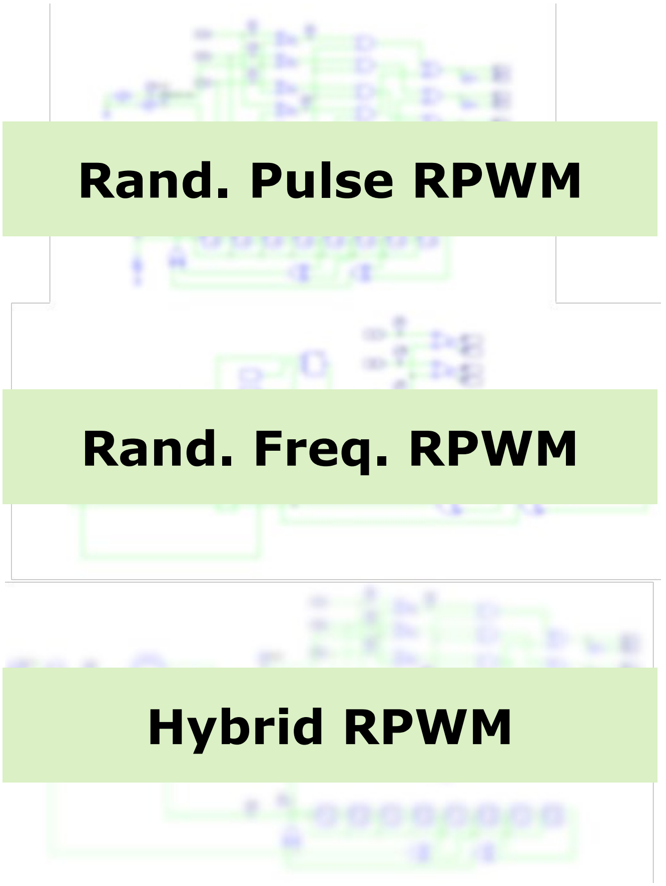
Theory approach

Randomization of PWM pulses
- **By random pulse placement**
  - With randomization of carrier duty cycle
- **By random carrier frequency**
- **By randomization of both (hybrid)**

SV based Hybrid RPWM



MODELING



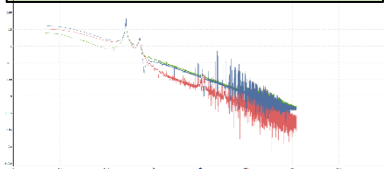
Rand. Pulse RPWM

Rand. Freq. RPWM

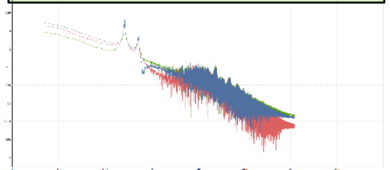
Hybrid RPWM

SIMULATION RESULTS

FFT of phase currents with normal SVPWM

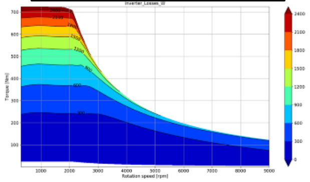


FFT of phase currents with SV based Hybrid RPWM

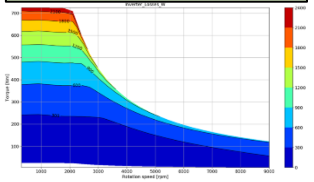


Inverter Losses

SVPWM 12kHz

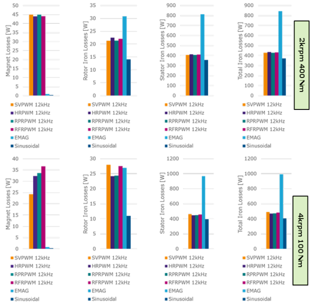


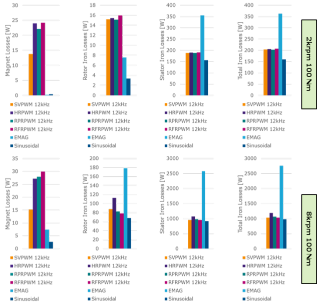
SV based HRPWM 12kHz



- In case of the HRPWM slightly lower losses can be obtained in the inverter
- Further investigation in different mid frequencies would be necessary to validate results

Machine Losses



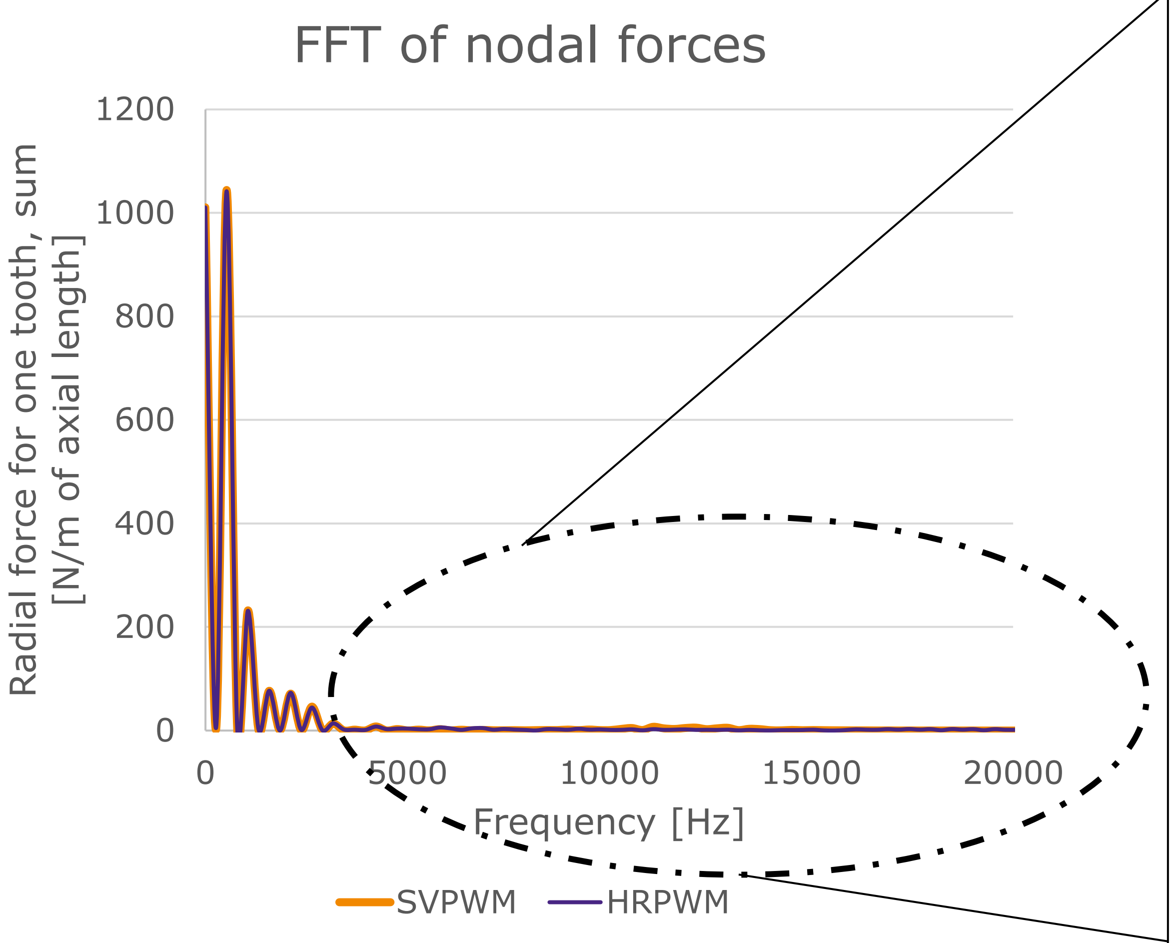


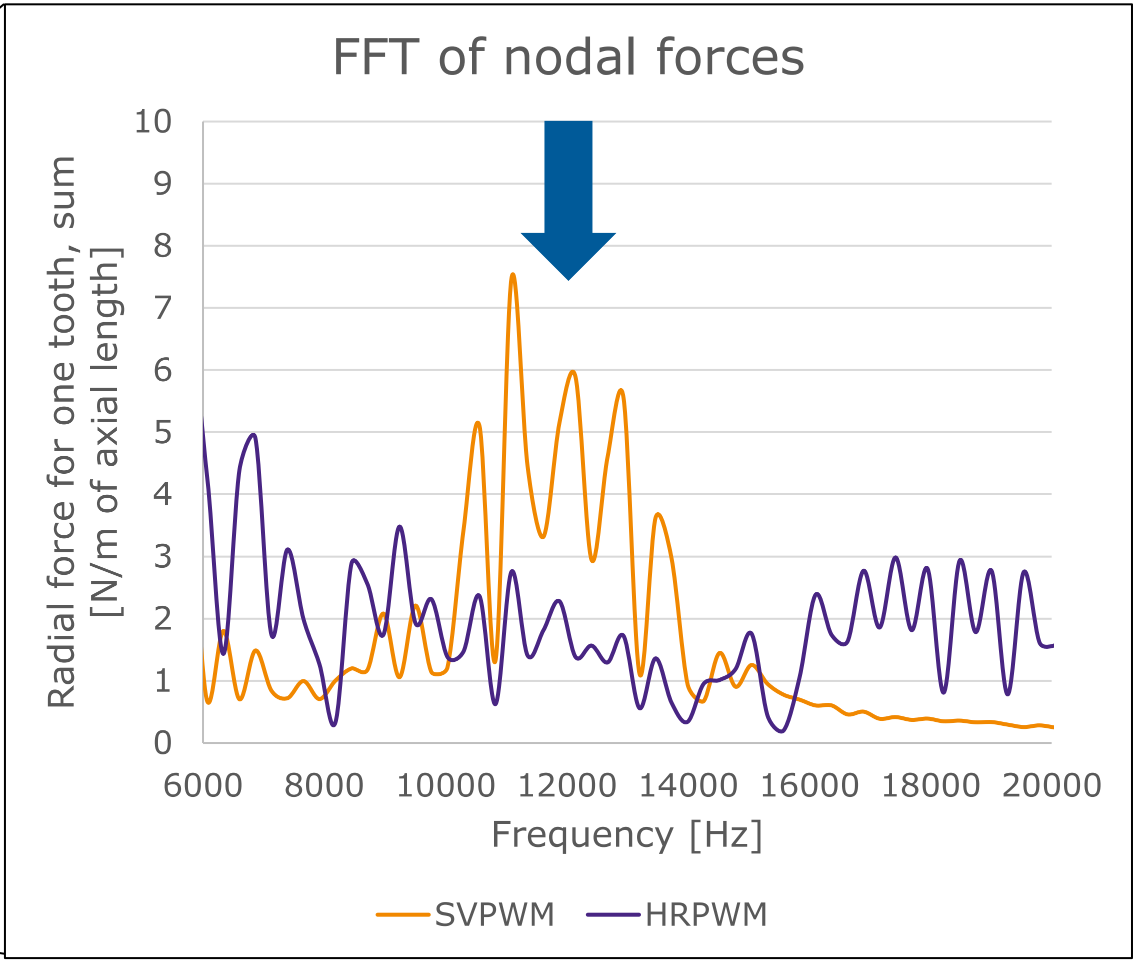
- Overall, the losses do not differ crucially from the normal SVPWM
- Only in the magnet losses we see a slight rise in case of the Random PWM techniques

E-Drive advanced control

Random Pulse Width Modulation - Nodal Force comparison at 12kHz 4krpm 100Nm

The randomized PWM technique results in lower nodal forces for PWM frequencies, as expected, and increases the harmonics outside the PWM spectrum



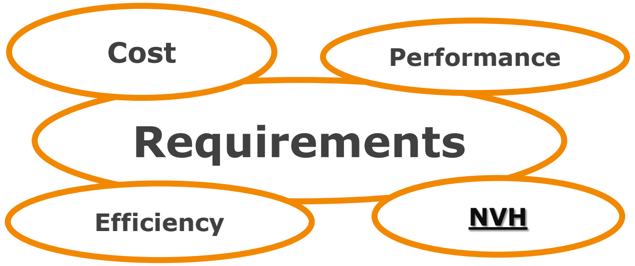


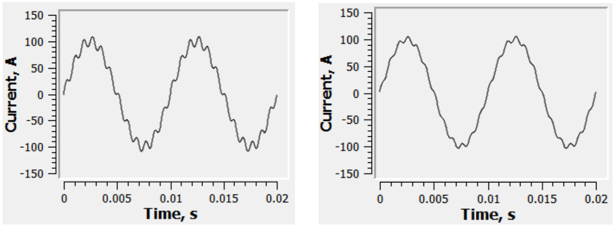
E-Drive advanced control

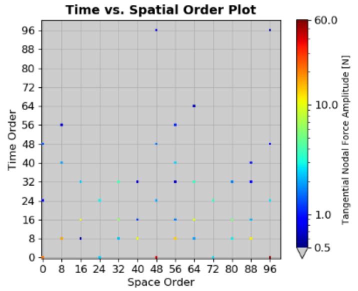
Harmonic injection simulation

Current injection / elimination should reduce NVH due to PWM ripple at low orders

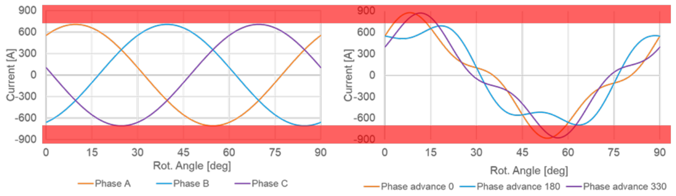
MODELLING	SIMULATION	OPTIMIZATION

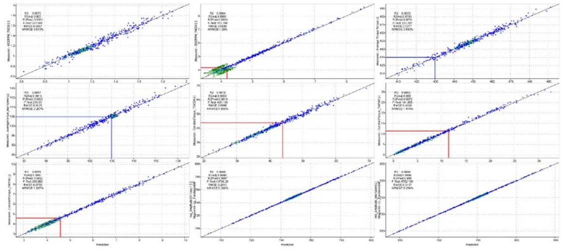


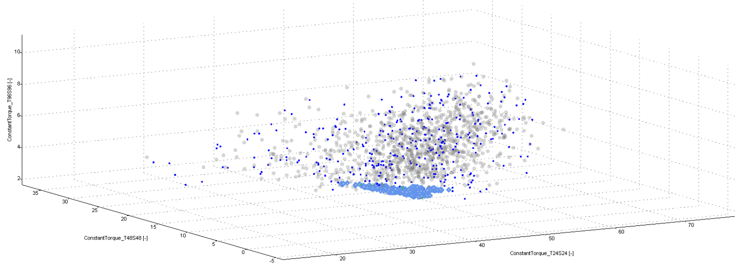




Overvoltage / overcurrent







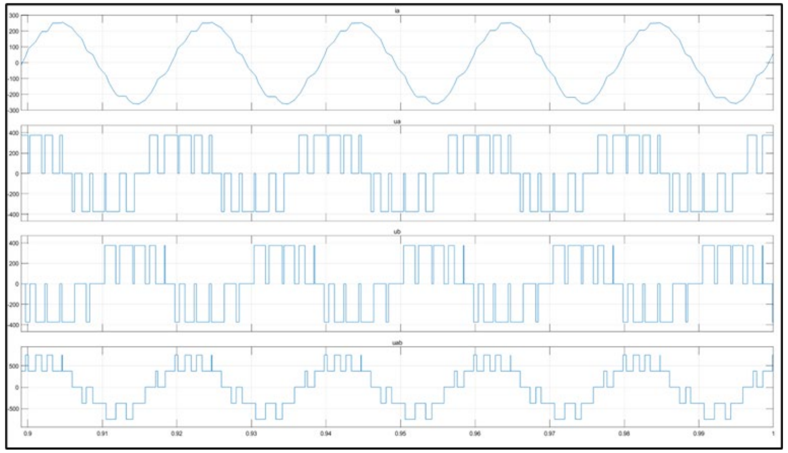
E-Drive advanced control
Selective Harmonic Elimination (SHEPWM)

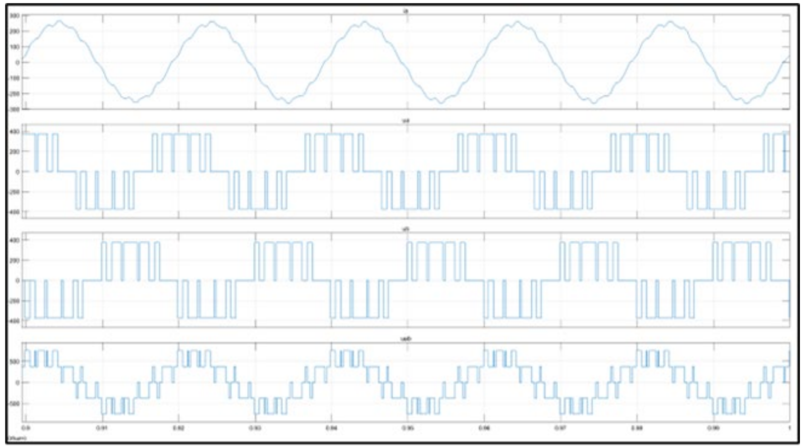
Current injection / elimination should reduce NVH due to PWM ripple at low orders

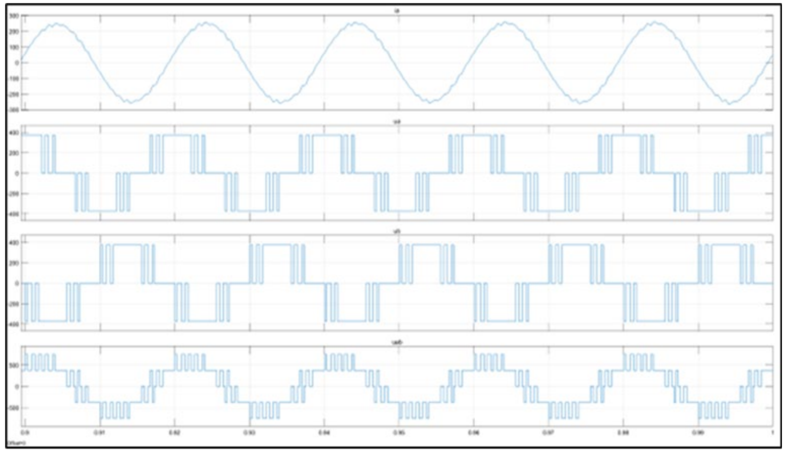
SVPWM

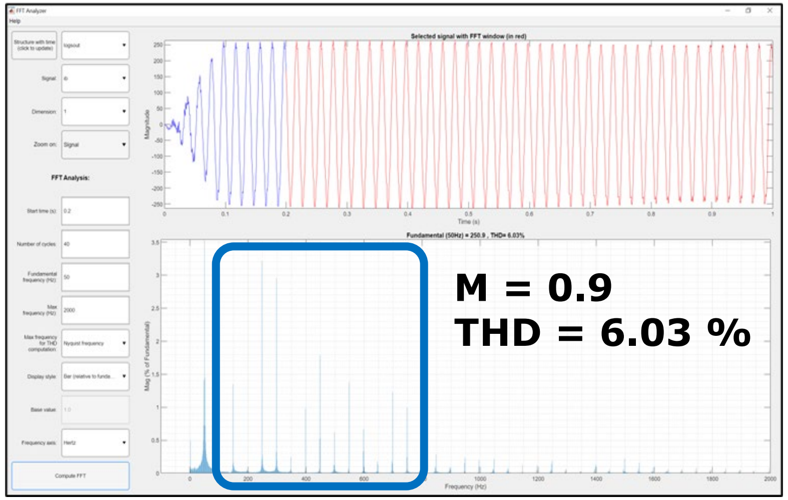
SHEPWM
Newton-Raphson method
- Instant results → can be implemented online
- Less efficient in harmonics eliminations

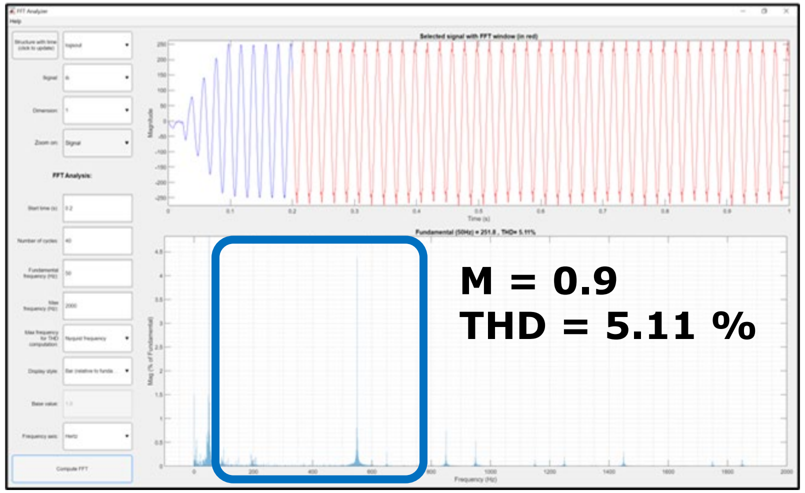
SHEPWM
PSO method
- More time consuming → implemented offline
- **Very** efficient in harmonics eliminations

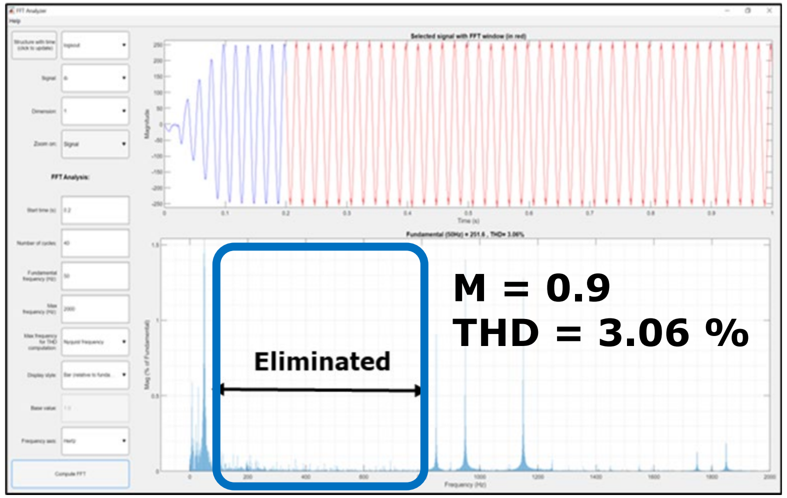








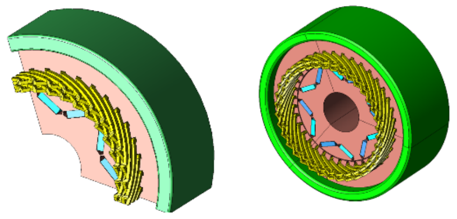




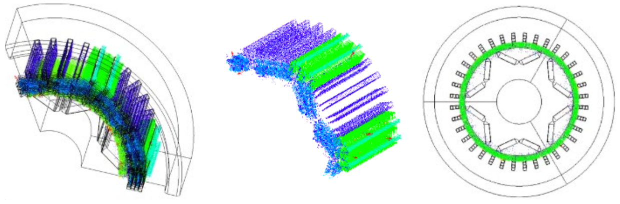
EMC modelling of electric drive
Common mode analysis

Bearing current simulation and mitigation with EMC filter

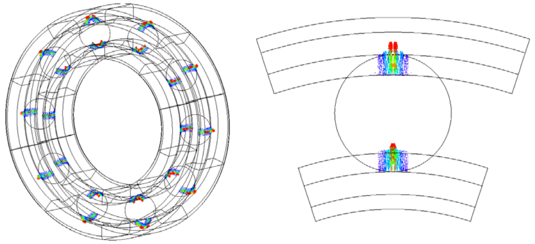
COMPONENT PARAMETRISATION	MODELLING	SIMULATION AND OPTIMISATION



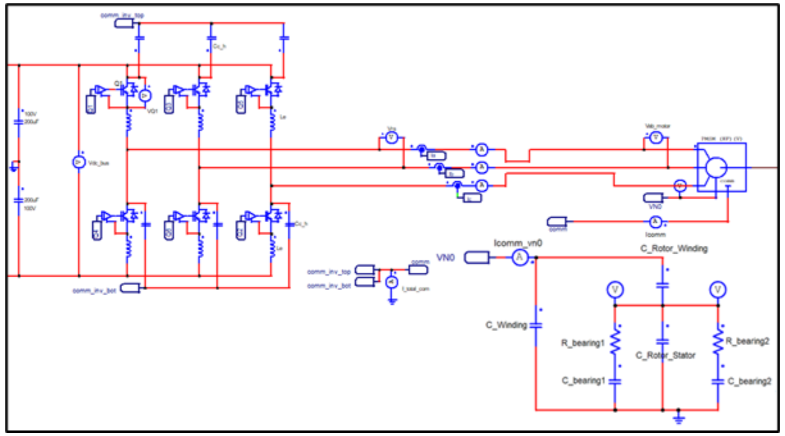
E-machine stray capacitance

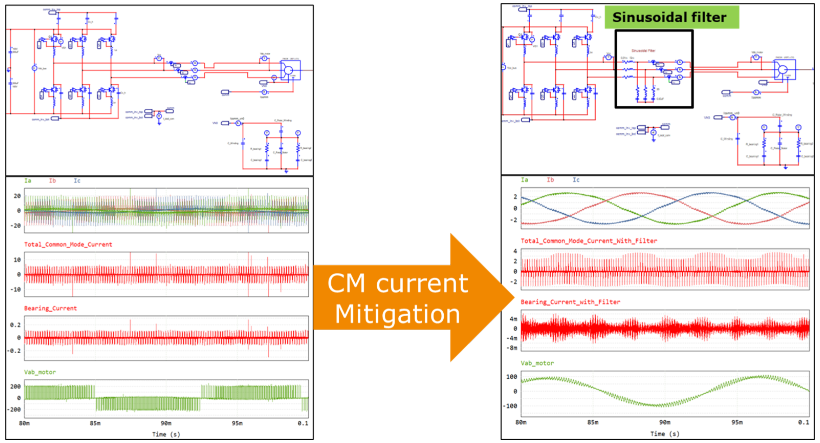


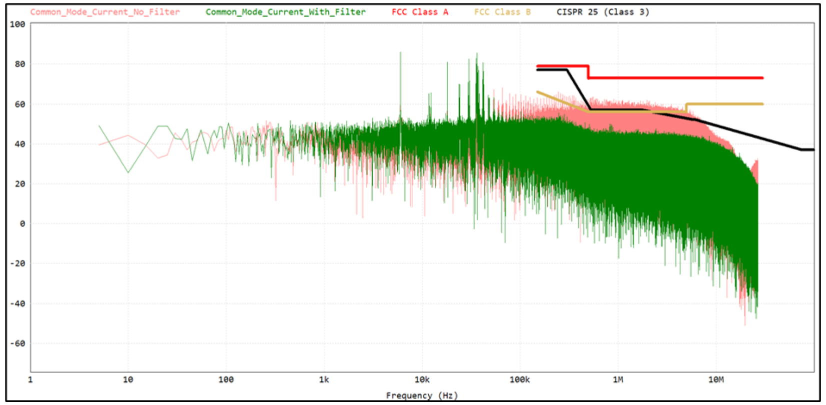
Bearing capacitance



Modelling of full e-Axle:
- **Battery/Fuel cell model**
- **Cables**
- **Transient switching model of inverter (<u>with its stray parasitic</u>)**
- **Inverter control techniques**
- **Real-Time model of E-machine (<u>with its stray parasitic</u>)**
- **Vehicle/Testbed grounding concept**





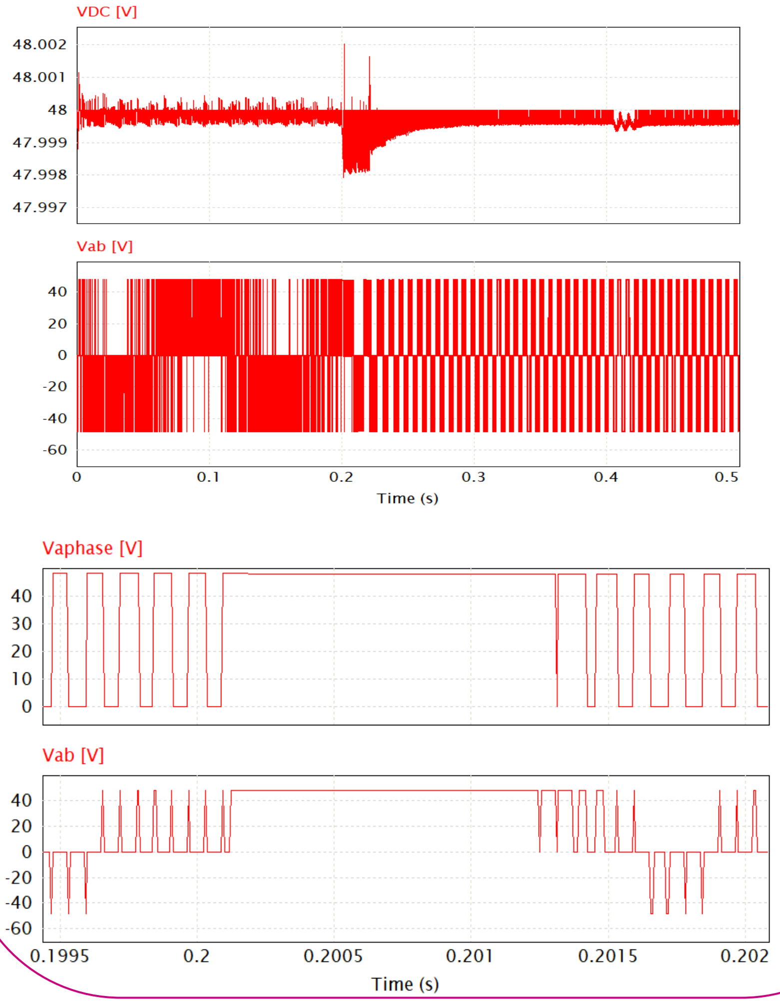


EMC modelling of electric drive

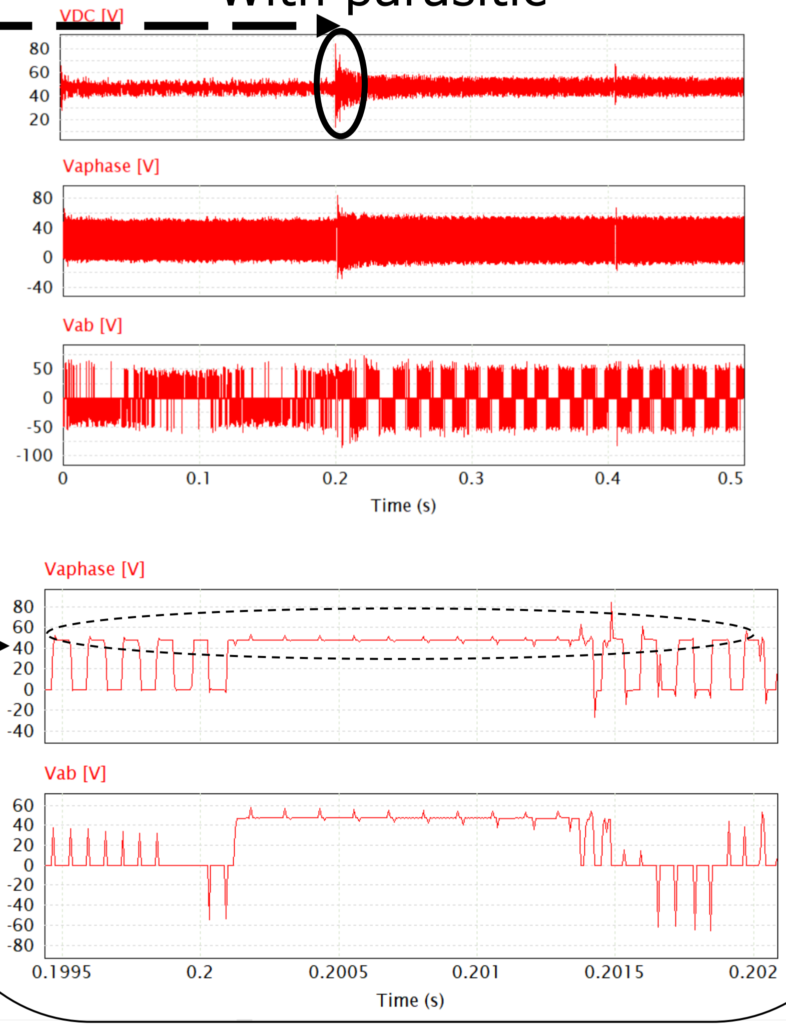
E-Drive parasitic effect on step response control

Very big influence on safety and EMC from cable and busbar parasitics

Without parasitic



With parasitic



DC voltage instability. Safety risk for inverter

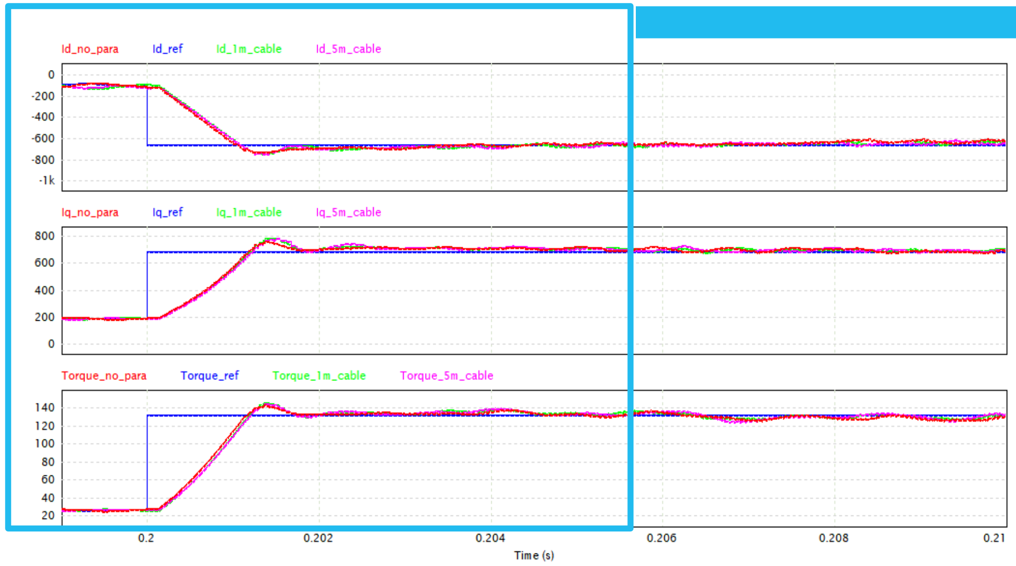
Due to the parasitic parameters, *Ringing effect* occurs in the voltage (EMC)

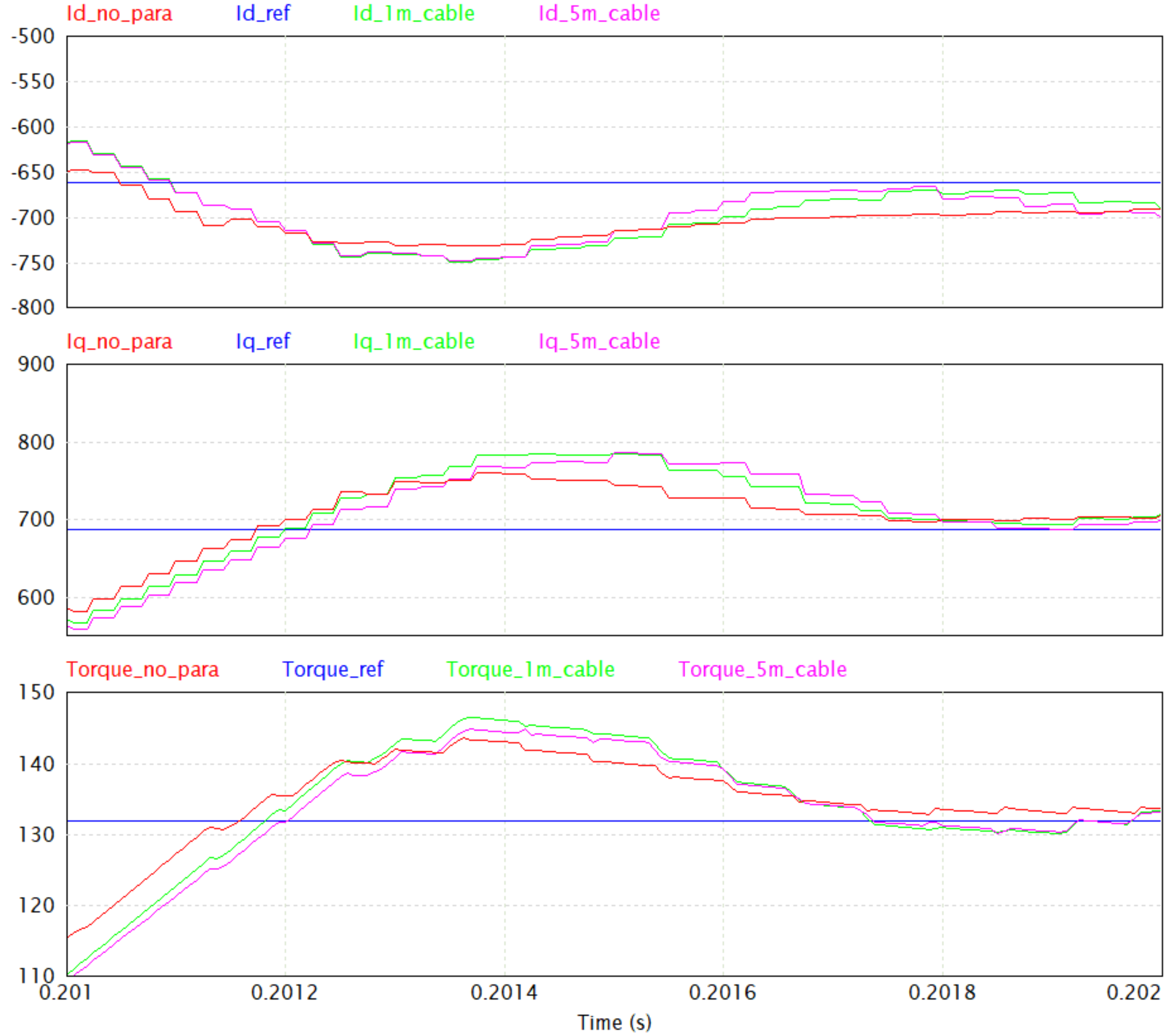
EMC modelling of electric drive

E-Drive parasitic effect on PI controller response

Very big influence on overshoot and rise time from cable and busbar parasitics

Peak overshoot value	Iq [A] / [%]	Id [A] / [%]
No parasitic	**761.3 / 10.6**	**-731,3 / 10.6**
With parasitic 1m DC cable	**785.2 / 14.1**	**-748,3 / 13.1**
With parasitic 5m DC cable	**786.4 / 14.2**	**-748,9 / 13.2**





PI controller is tuned for vehicle settings

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Thermal adaptive control

Integration into full system

Full electric drive unit modelling allows for any electric simulation

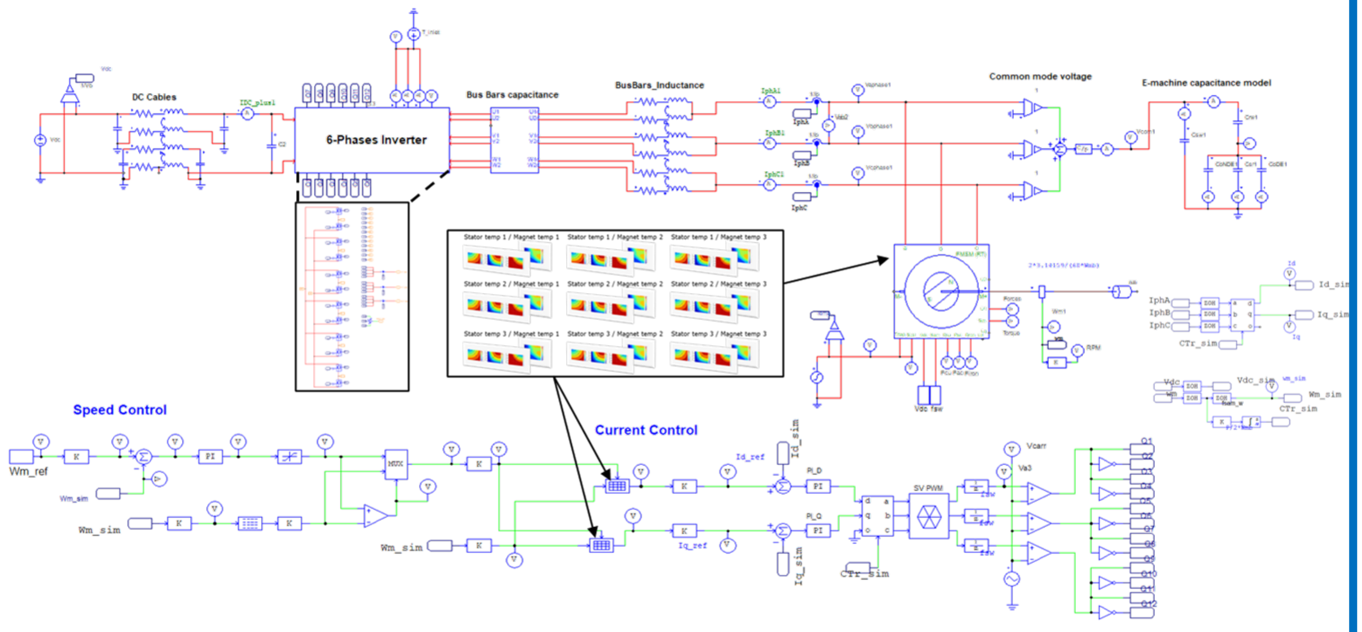
DC Voltage

Control

Modulation

Components

Temperature



Voltage FFT

Current FFT

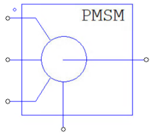
Bearing current

Component losses

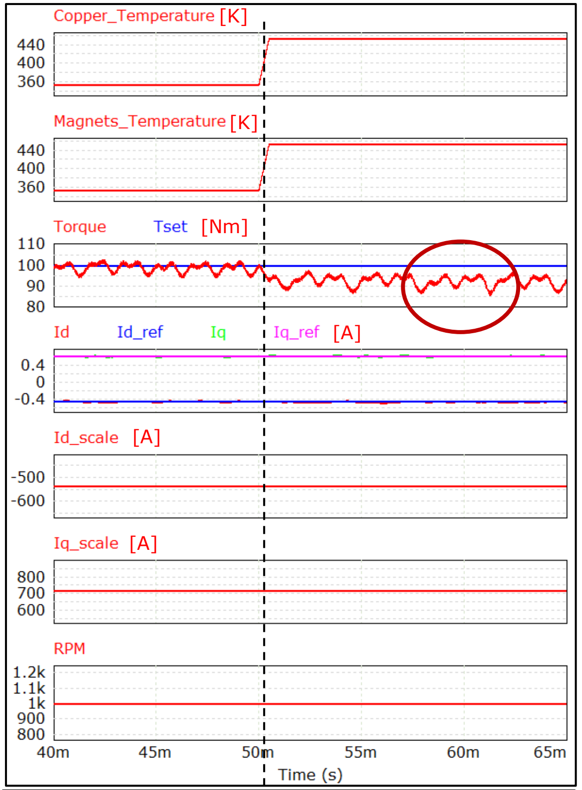
Torque Speed

Thermal adaptive control

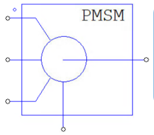
Effect of temperature-adaptive calibration on electric machine performance



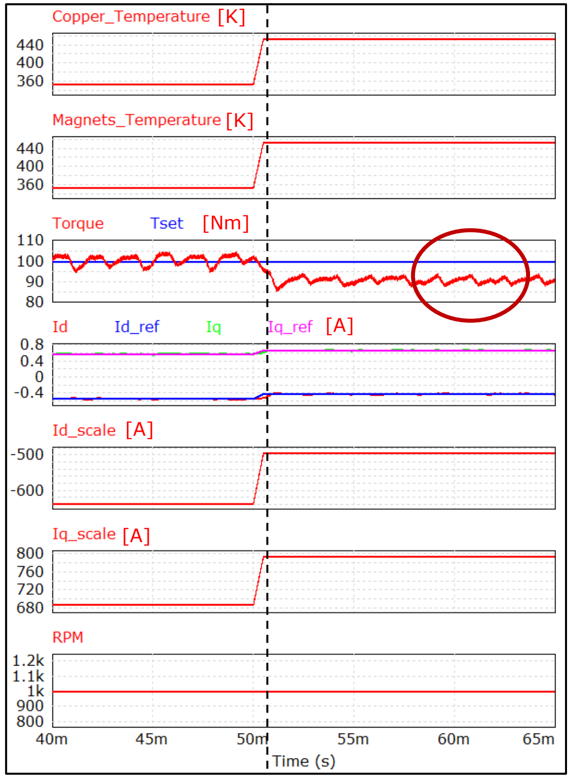
Standard control
"No thermal calibration"



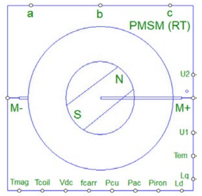
- **Loss of torque**
- **Loss of optimal control**



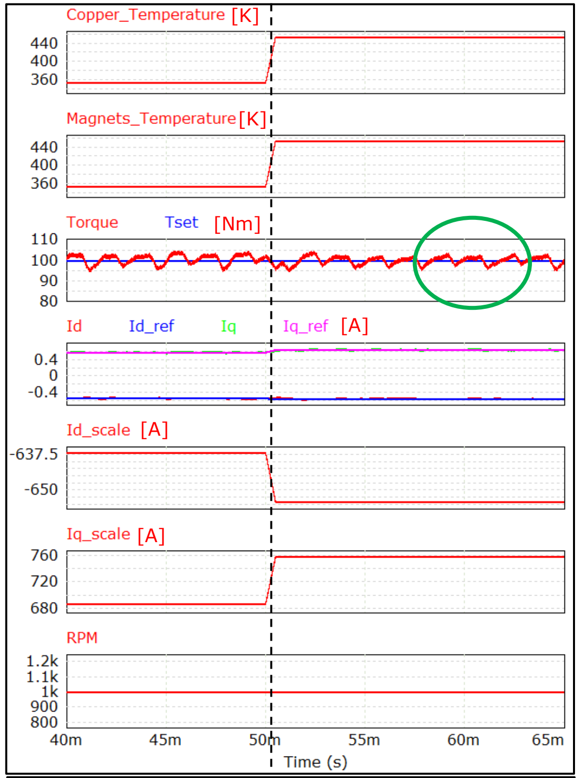
Standard control
"Thermal calibration for copper (stator) temperature only"



- **Loss of torque**
- **Loss of optimal control**



Thermal dynamic control
"Thermal calibration for copper (stator) and magnets (rotor) temperatures"



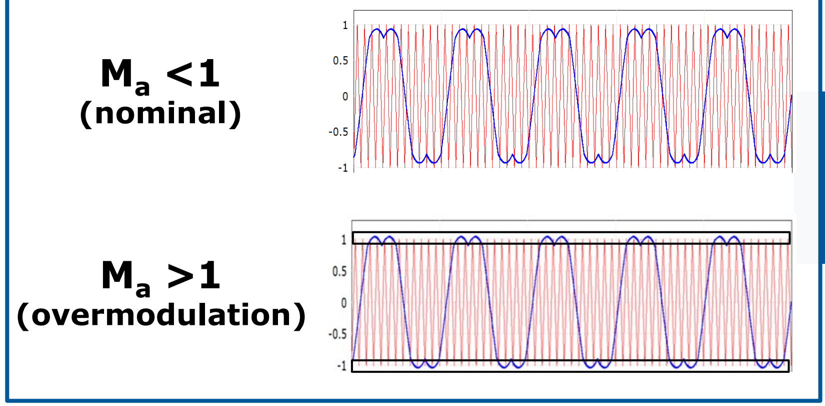
- **With temperature dynamic adaptive control → No torque loss occurs**

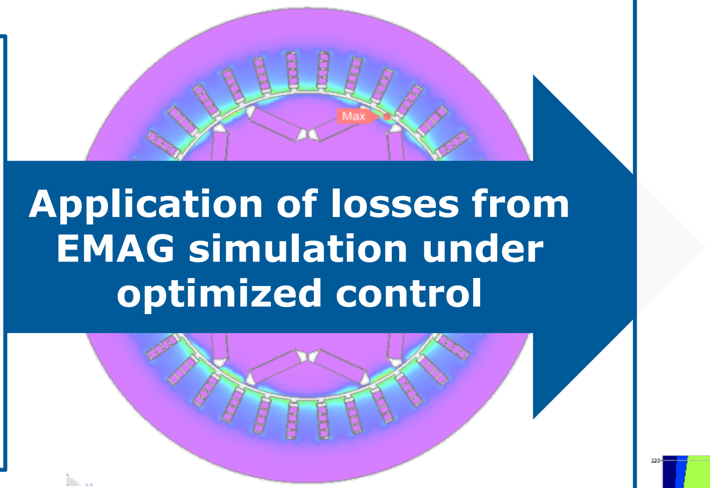
Overmodulation

Effect of overmodulation on electric machine temperature

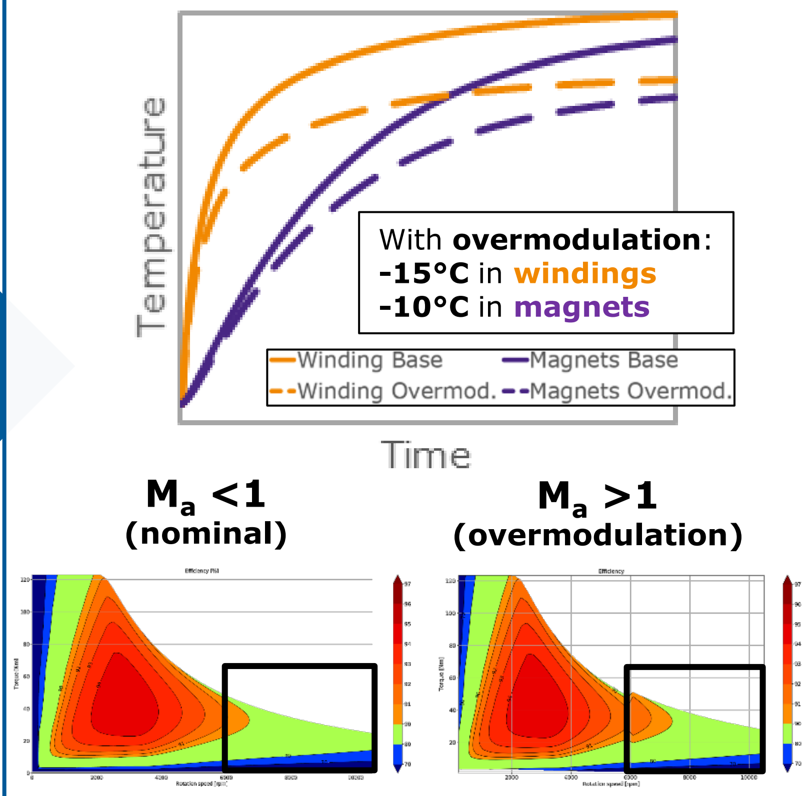
- For same torque and speed: lower winding and magnet temperature due to smaller field weakening current
- In general: higher available power and efficiency at high speed

CONTROL OPTIMIZATION





THERMAL RESULTS



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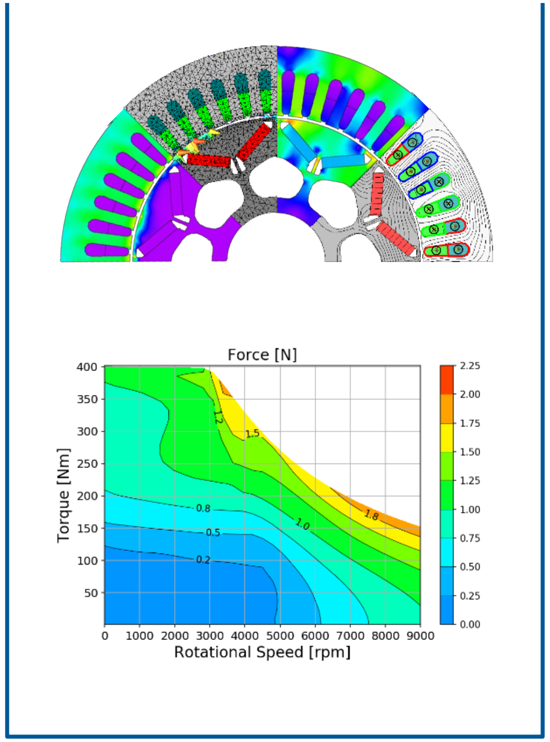
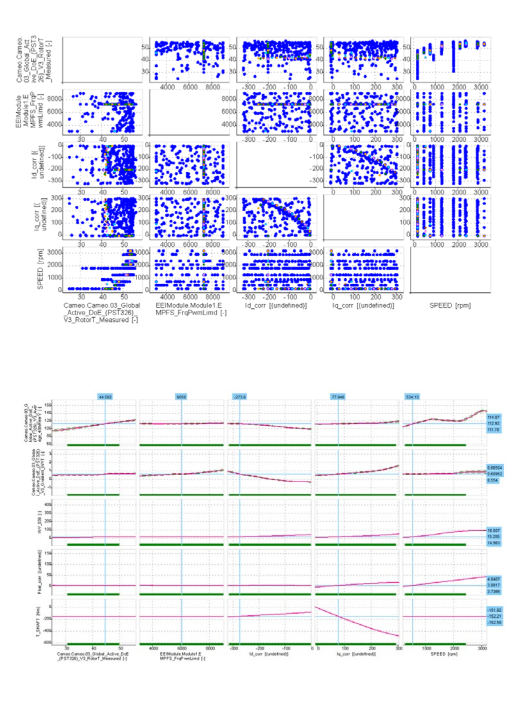
NVH optimization through control
Methodology overview

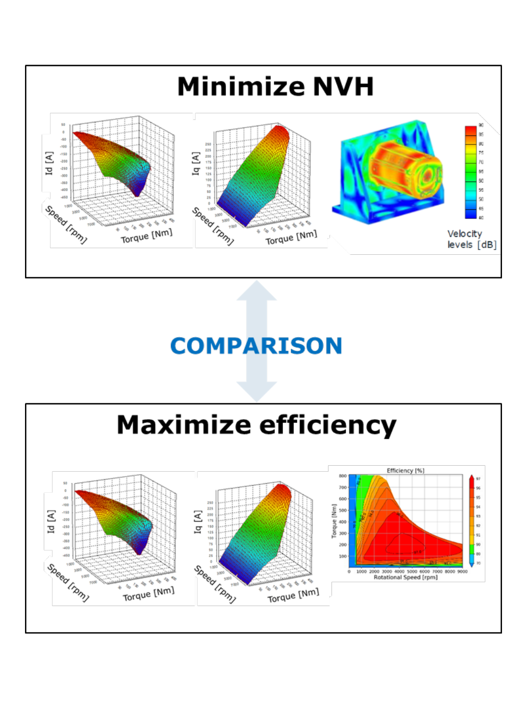
Optimization of NVH with electric machine control

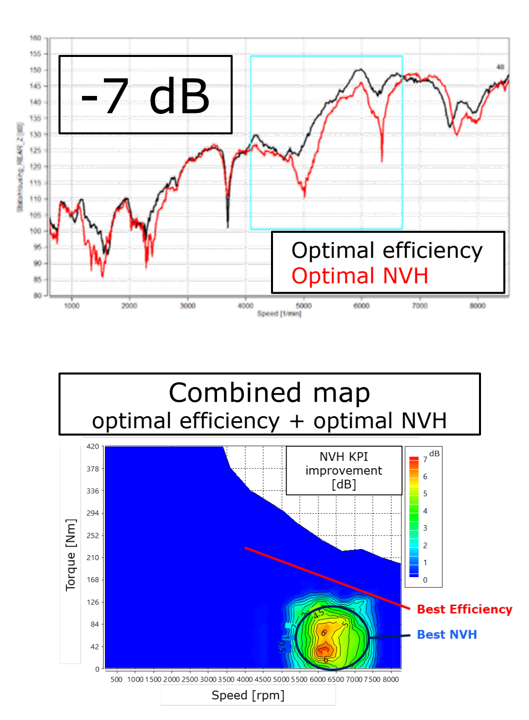
FROM SIMULATION TO TESTBED VALIDATION

Electromagnetic simulation — Stator forces → **DoE generation for control maps** → **Control map optimization** → **Implementation to e-Drive testbed**







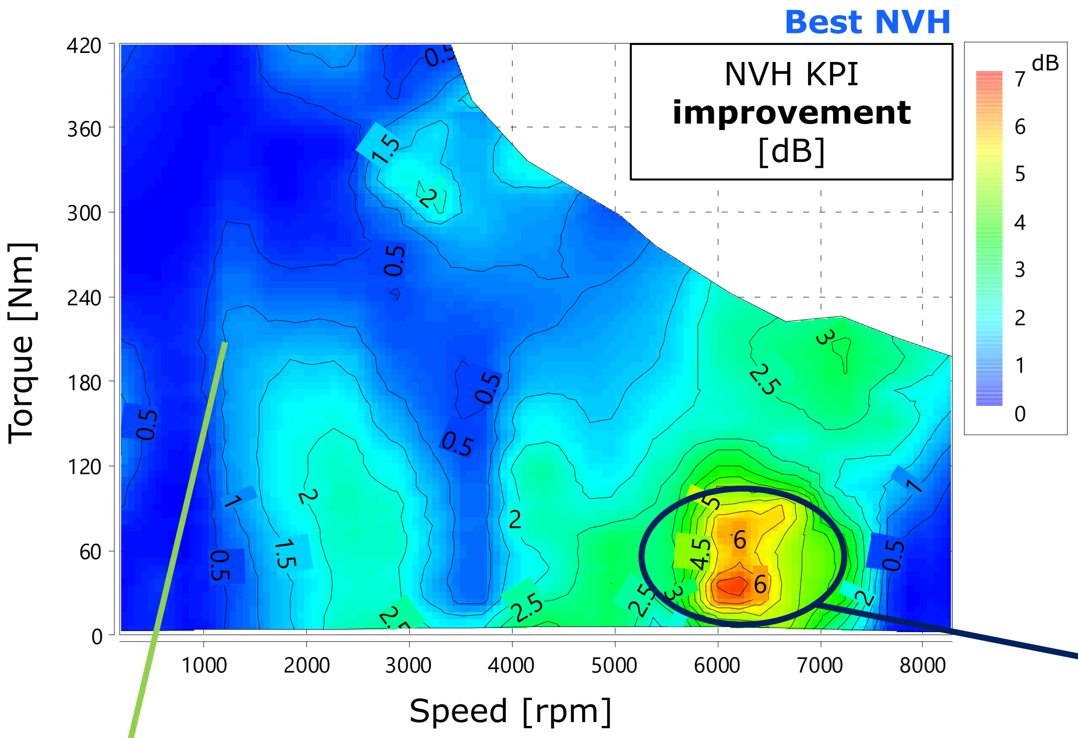


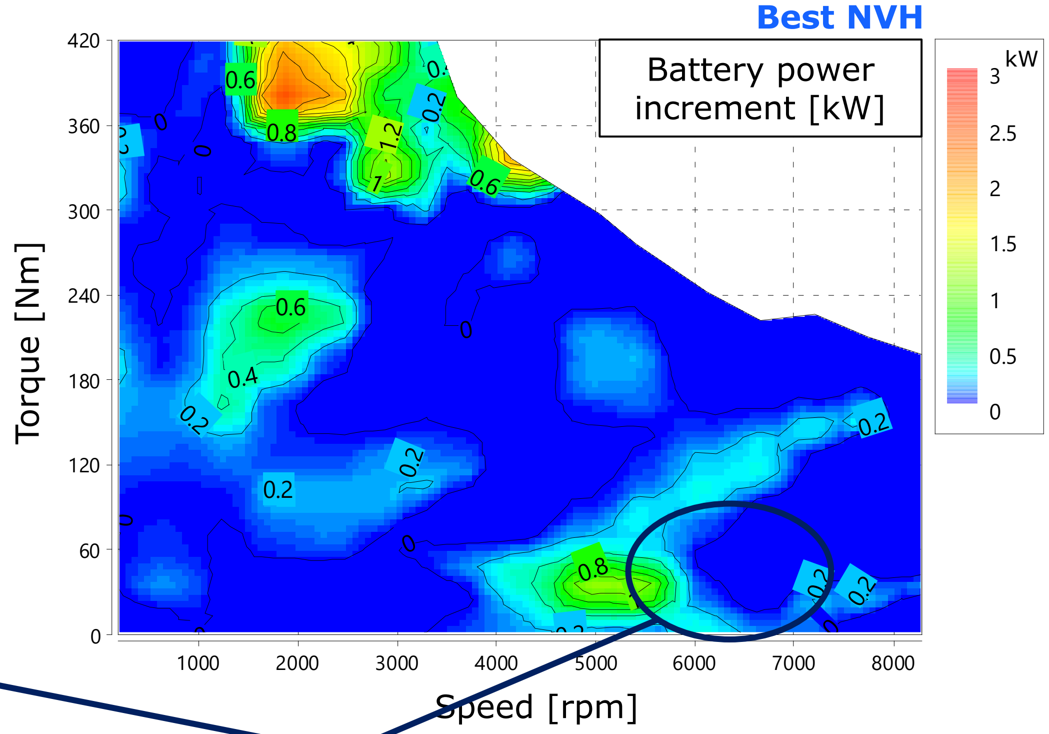
NVH optimization through control

Best efficiency vs. best NVH (Testbed results)

How much can I improve my NVH with MCU calibration only?

How much does this cost me in terms of battery power?





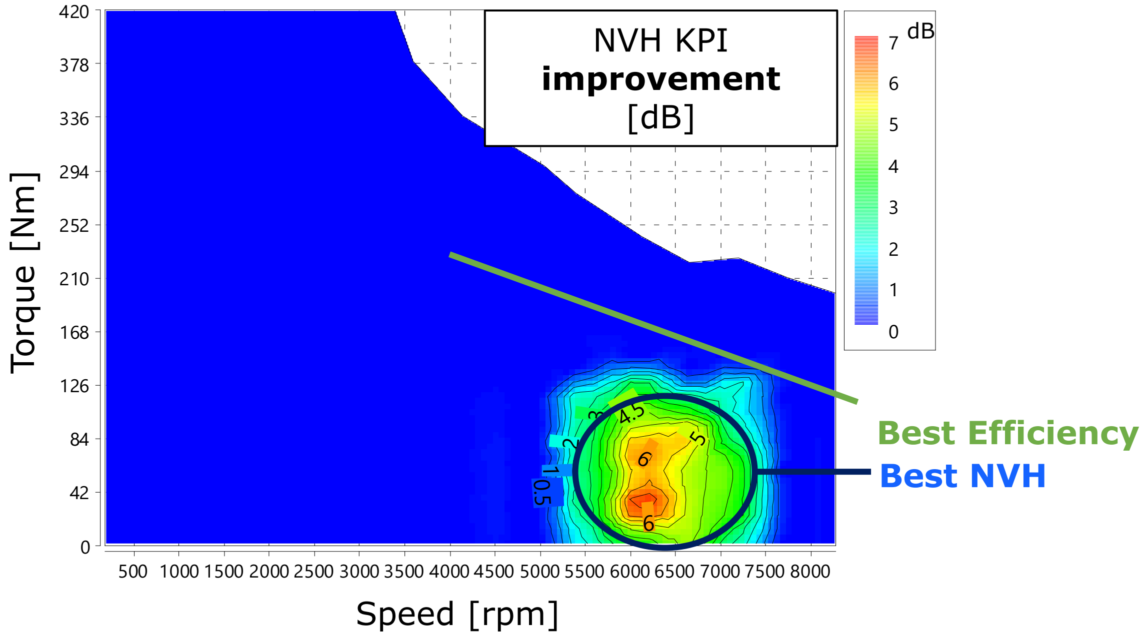
Keep control strategy "BEST-EFFICIENCY"

High NVH improvement with low efficiency loss -> switch control strategy to "BEST-NVH"

NVH optimization through control

Best efficiency vs. best NVH (Testbed results)

Combined calibrations for optimal performance



- Only 1 calibration run required
- No HW updates needed
- Only calibration parameter updates needed
- Up to 7dB improvement without extra losses

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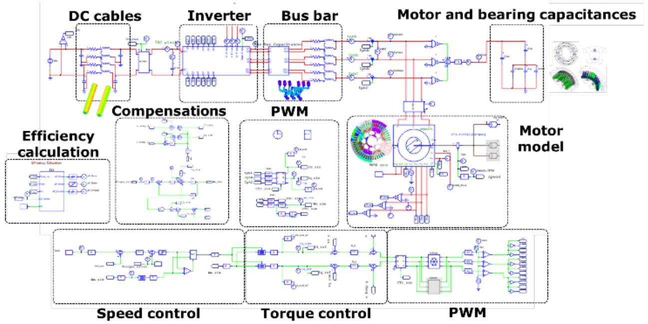
Electric Drive Development

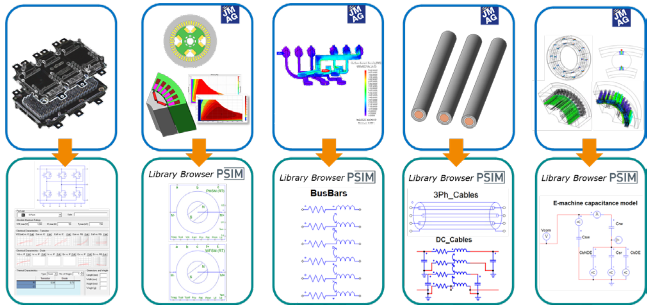
Holistic control optimization of electric machine + inverter + control

MODELLING | **SIMULATION & VALIDATION** | **OPTIMIZATION**

Full electric drive electrical simulation

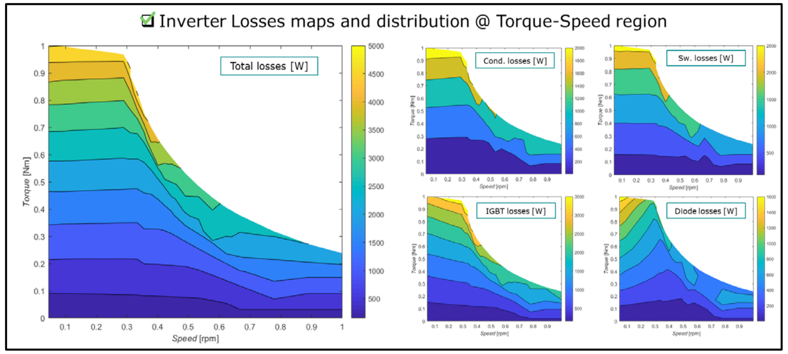


1D condensation from FEM simulation of components

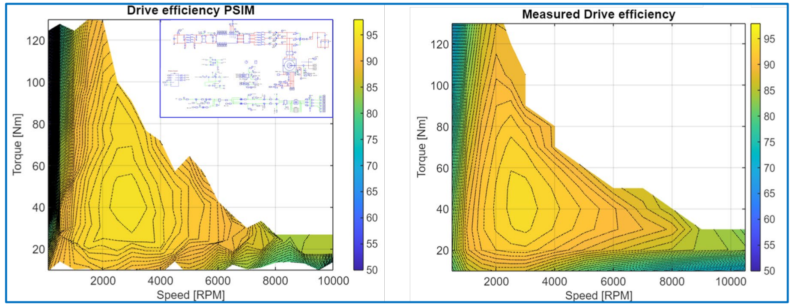


Control and loss analysis

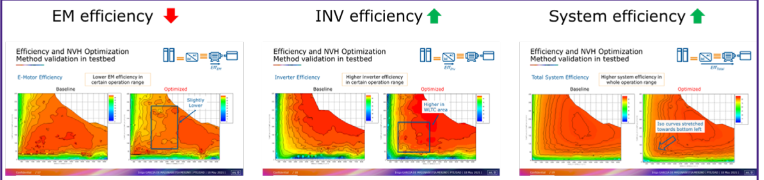
- Converter total and separate losses
- Fixed vs variable switching
- Dc-link voltage ripple
- ContPWM vs DWPMx
- Overmodulation
- PI control optimization
- Conductive EMC



Full electric drive efficiency validation

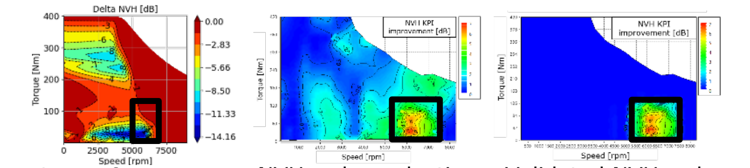


System



Example:
- -4% WLTP cycle energy consumption
- EM efficiency is lower
- This makes the optimization complex and requires system focus.

NVH

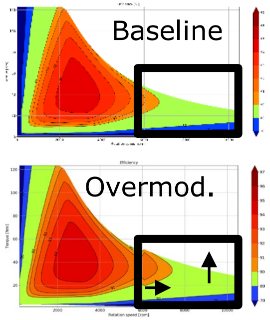


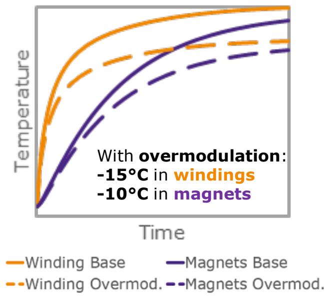
Stator force time-space order reduction in FEM simulation

NVH order reduction in testbed incl. mech. resonances

Validated NVH order reduction in resonance + max. eff. elsewhere

Thermal w. overmod.





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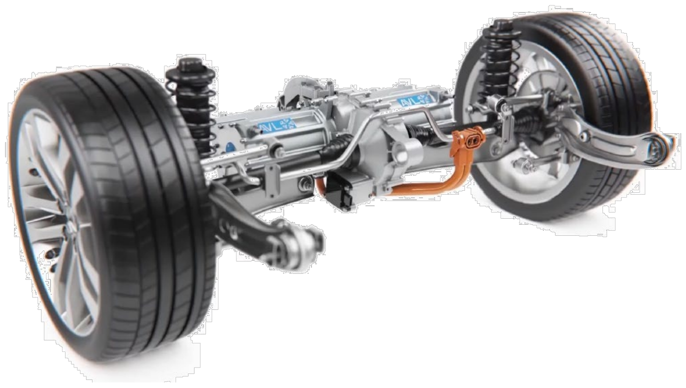
Reference

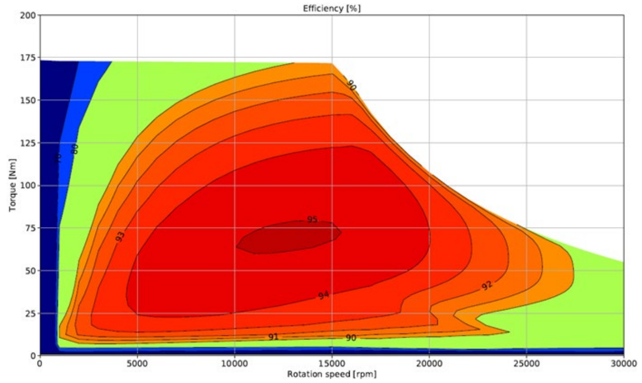
AVL High-Speed e-Axle (30,000rpm electric machine)



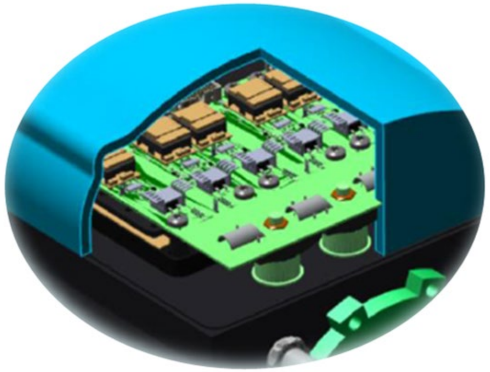
- **+ 2 x 250 kW_{peak}**
- **+ 30,000 rpm max**
- **+ High power density**

  25% less weight than actual market
- **+ Scalability**
- **+ No heavy rare-earth**

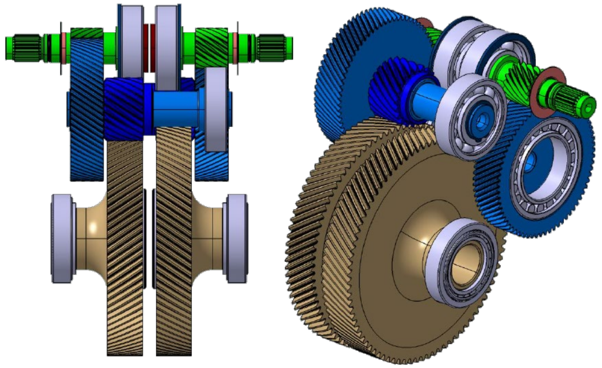
HIGH EFFICIENCY E-MACHINE



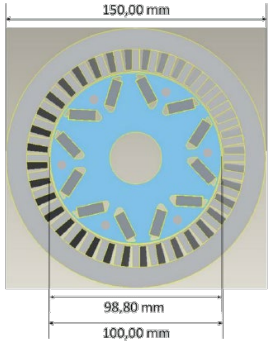
800 V SILICON CARBIDE POWER MODULES



SINGLE SPEED, TWO STAGE LAY-SHAFT TRANSMISSION



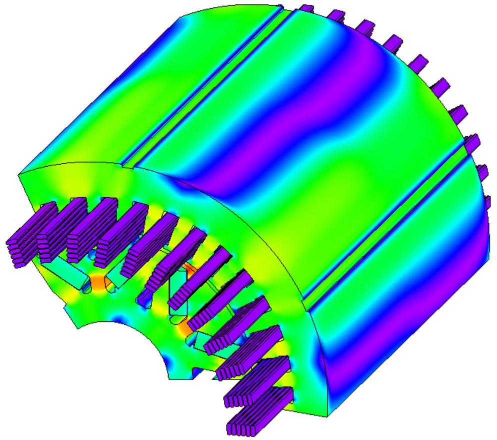
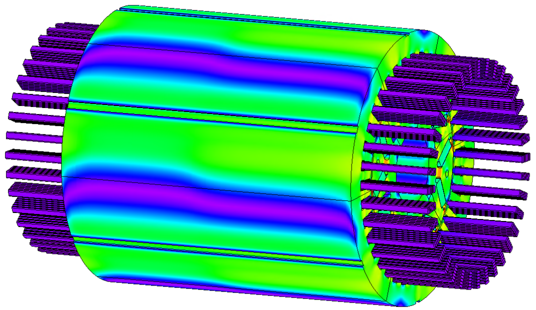
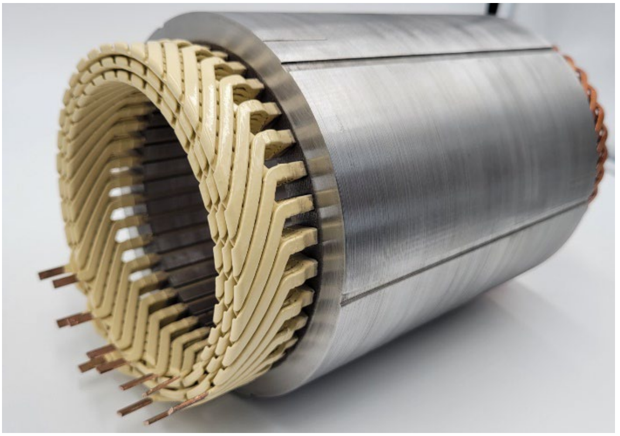
IPM TOPOLOGY FULFILLING HIGH REQUIREMENTS FOR ROTOR STRENGTH



simplified e-machine topology

Electric Drive Development

30000 rpm electric machine, generation 2

EM DEVELOPMENT IN SIMULATION	MECHANICAL DESIGN	PROTOTYPE BUILDING
 		 

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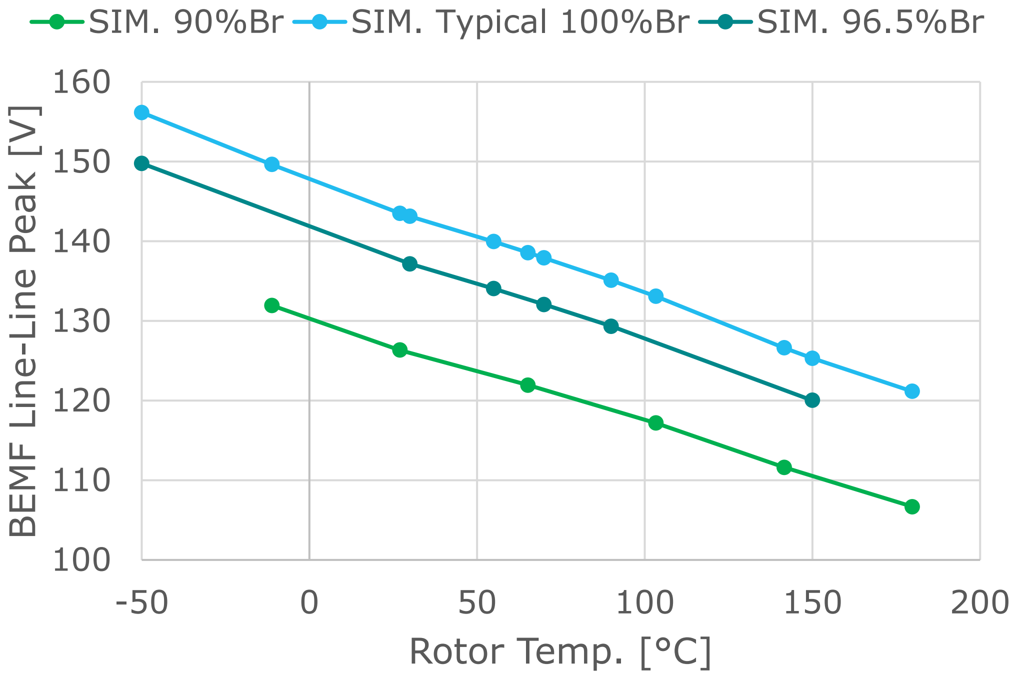
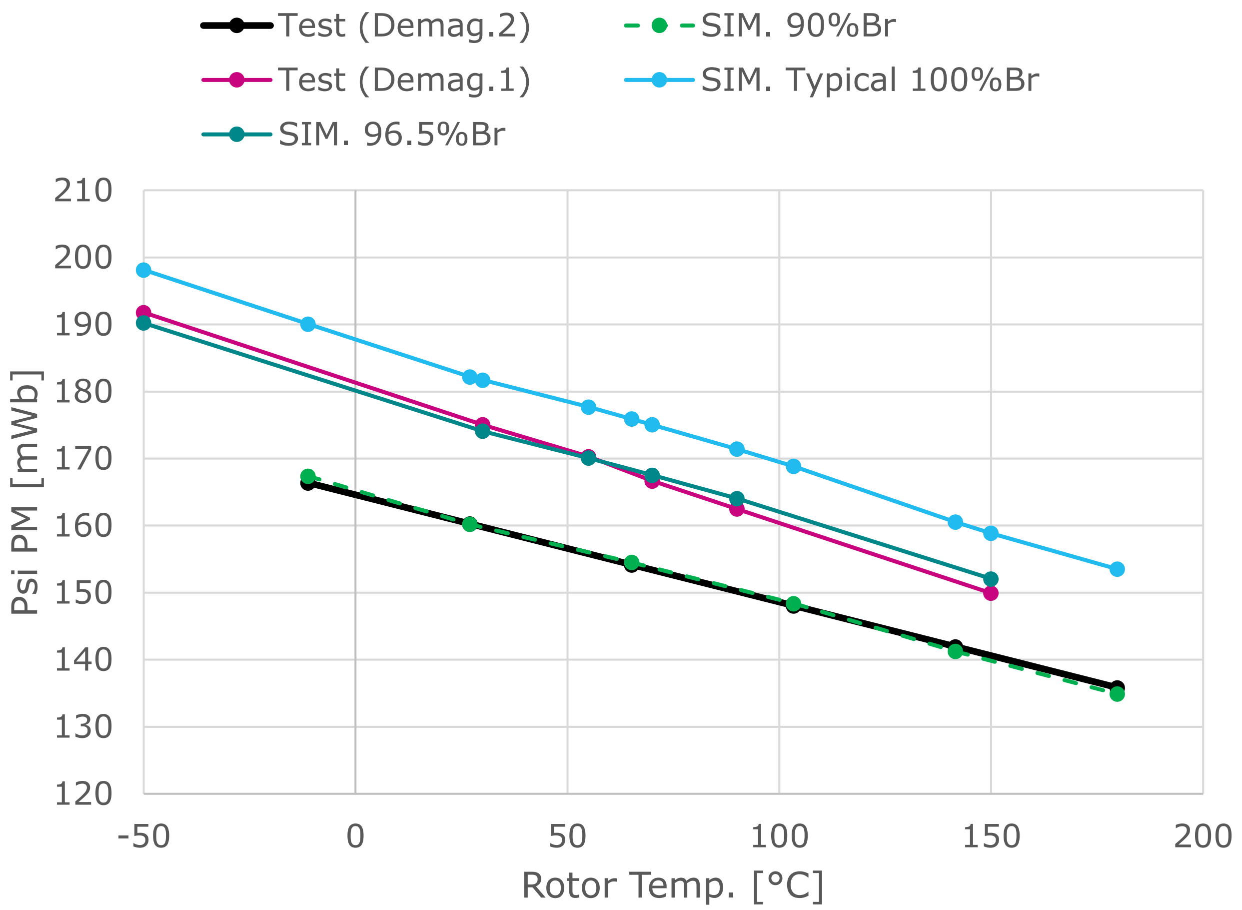
REFERENCE PROJECT

Demagnetization study for traction drive– Electromagnetic correlation

Simulated Flux linkage (Psi_PM) and BEMF show good correlation with the measurements at every demagnetization state (1 & 2) of electric machine

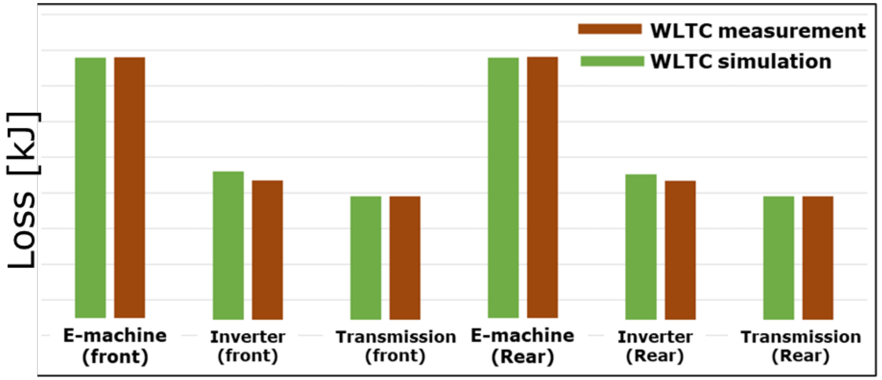




REFERENCE PROJECT

3in1 e-Axle Development to SOP – Efficiency correlation

- Full development of 3-in-1 EDU, with very good efficiency correlations for all components and both front and rear EDUs.
- For the electric machine in detail, highest deviations happen at the operation ranges with highest measurement uncertainty, with <1% deviation in most operation points



Simulation [%] – Measurement [%]

Difference between measured efficiency and simulated efficiency

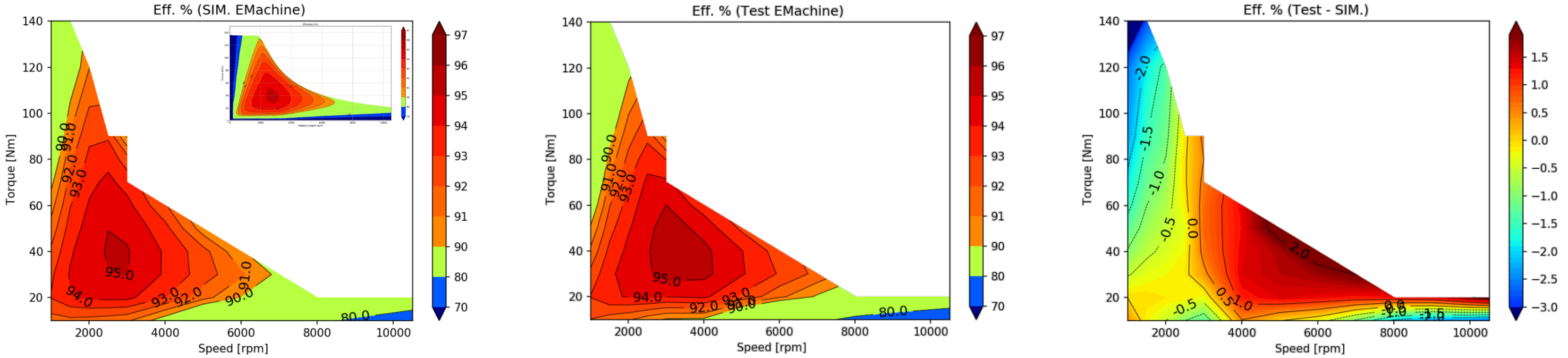
Electric machine

T [Nm] / n [rpm]																	
4.31	2.97	2.53	1.79	2.02	1.29												
4.77	5.91	1.53	1.92	1.27	1.18	0.93											
4.22	4.94	2.49	1.48	1.01	0.68	0.85											
4.14	2.33	1.98	1.33	1.34	0.85	0.94											
3.86	-1.63	1.53	1.30	0.91	0.39	0.75											
3.39	4.59	1.59	0.99	0.57	0.45	0.52	0.19										
3.11	-0.49	1.73	0.44	0.44	0.62	0.64	0.23										
2.95	0.54	0.20	1.03	0.88	0.39	0.21	0.08										
2.96	3.18	2.15	0.80	0.99	0.60	0.56	0.17	-0.07									
2.48	1.86	2.03	0.95	0.36	0.29	0.24	0.15	-0.04									
1.84	0.88	0.85	0.27	0.12	0.52	0.25	0.22	-0.03	-0.50								
1.94	0.68	1.35	0.23	0.55	0.21	0.29	0.03	0.00	-0.31								
2.28	-3.13	-0.38	0.27	0.10	-0.02	-0.23	0.07	-0.03	-0.17	-0.45							
0.83	-2.62	-1.14	0.47	0.51	0.16	0.44	-0.04	-0.14	0.02	-0.08	-0.77						
1.24	5.60	0.82	1.14	-0.33	0.22	0.07	-0.05	-0.15	-0.11	-0.03	-0.41						
1.89	3.28	0.02	0.31	0.28	-0.06	0.07	-0.13	-0.01	-0.13	-0.06	-0.19	-0.39					
1.45	3.76	0.12	0.11	0.43	-0.24	-0.02	-0.20	-0.12	-0.25	-0.17	-0.24	-0.41	-0.66				
0.88	1.80	1.85	0.67	-0.44	0.12	0.02	-0.02	-0.15	-0.18	-0.27	-0.22	-0.27	-0.43	-0.95	-1.90		
1.28	1.79	0.84	0.05	-0.22	-0.07	0.36	-0.29	-0.31	-0.24	-0.35	-0.33	-0.38	-0.39	-0.51	-0.81	-1.46	
0.71	0.83	-1.47	0.04	-0.50	-0.27	-0.22	-0.20	-0.21	-0.25	-0.05	-0.45	-0.32	-0.50	-0.43	-0.54	-0.93	0.60
1.24	-0.57	0.36	0.25	0.22	-0.68	-0.21	-0.59	-0.30	-0.24	-0.24	-0.06	-0.37	-0.16	-0.35	-0.33	-1.34	0.92
0.03	4.83	-0.01	-0.11	0.11	0.28	0.21	0.14	0.25	-0.23	-0.42	-0.47	-0.13	-0.17	-0.15	0.08	-0.33	1.43
-0.87	-4.78	-0.76	-0.32	-0.82	-0.20	-0.94	-0.04	0.07	-0.41	-0.04	0.12	-0.22	0.09	0.27	0.69	0.90	2.45
0.45	4.65	0.94	-0.85	-0.96	-0.81	-0.85	-0.29	-0.16	0.01	-0.38	0.73	-0.02	0.71	1.62	1.53	2.39	-0.49
-2.55	0.85	0.99	-1.24	-0.56	-0.07	-0.37	-1.12	-0.73	1.23	-0.61	-0.94	-0.71	0.97	-0.16	0.30	1.01	0.88

REFERENCE PROJECT

48V 30kW+ electric machine– Electromagnetic correlation

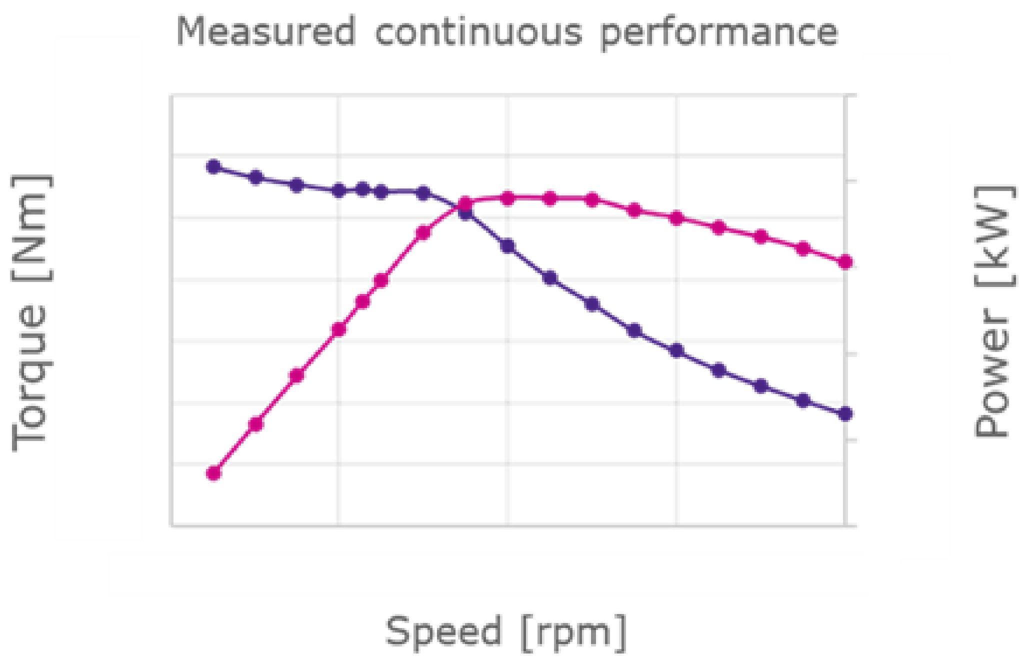
- Maps showing correlation between efficiency measured at Testbed versus simulation
- E-machine efficiency obtained from testbed included transmission efficiency(losses), therefore it is assumed fixed efficiency of transmission of 97%, and excluded from the E-machine maps for comparison to simulation (uncertainty)
- At 80°C: Motor mode showing slightly better efficiency measured at testbed compared to simulation

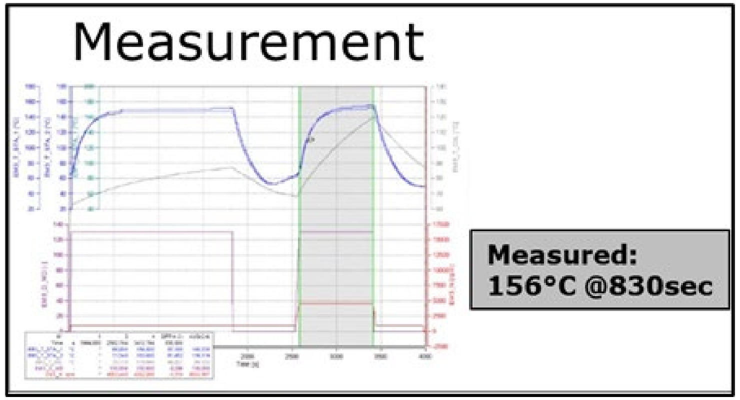


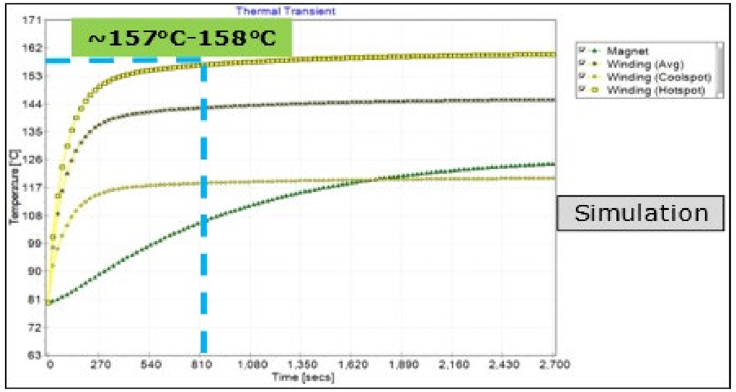
REFERENCE PROJECT

3in1 e-Axle Development to SOP – <u>Thermal correlation of cooling jacket</u>

Full continuous performance measurement and correlation with great correlation accuracy





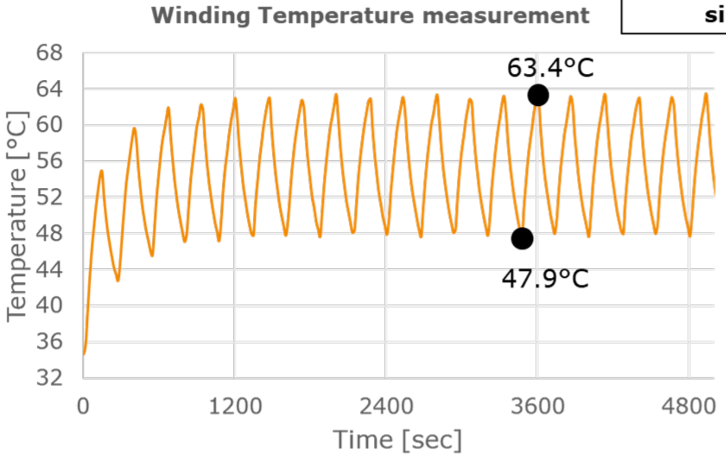


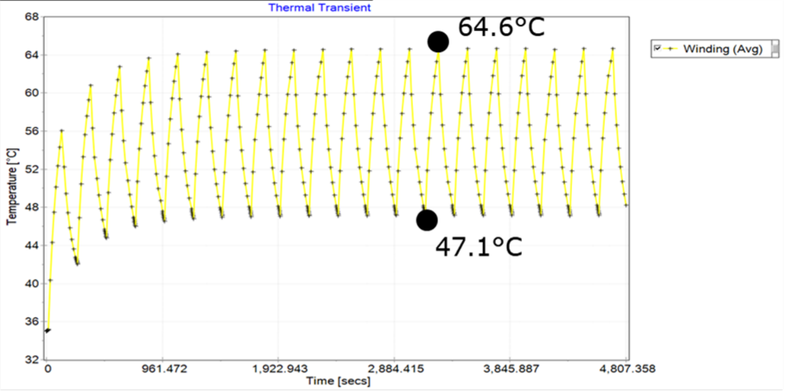
REFERENCE PROJECT

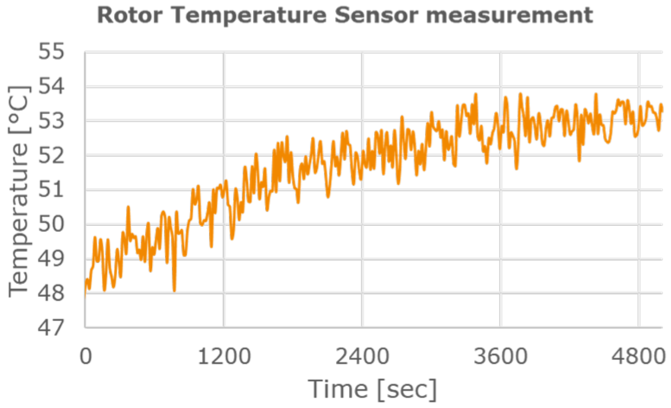
High torque electric machine– Thermal correlation of direct oil cooling

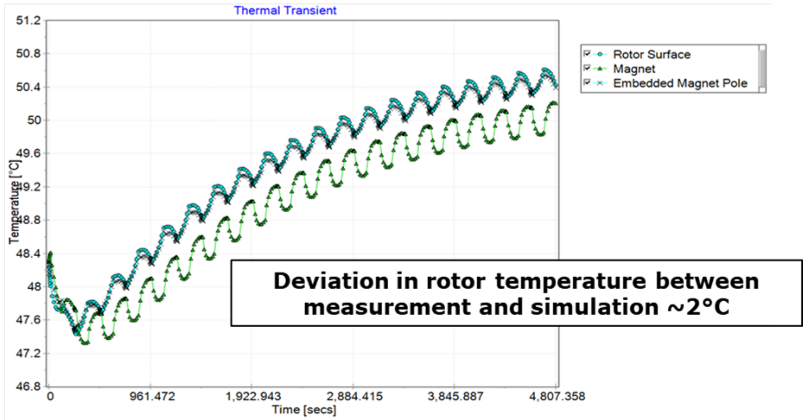
Stator measurement with thermocouples and rotor measurement with infrared sensor

Good correlation between measurement and simulation of winding temperature





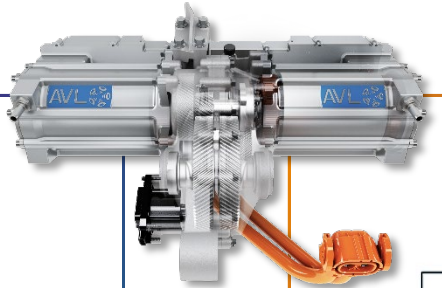




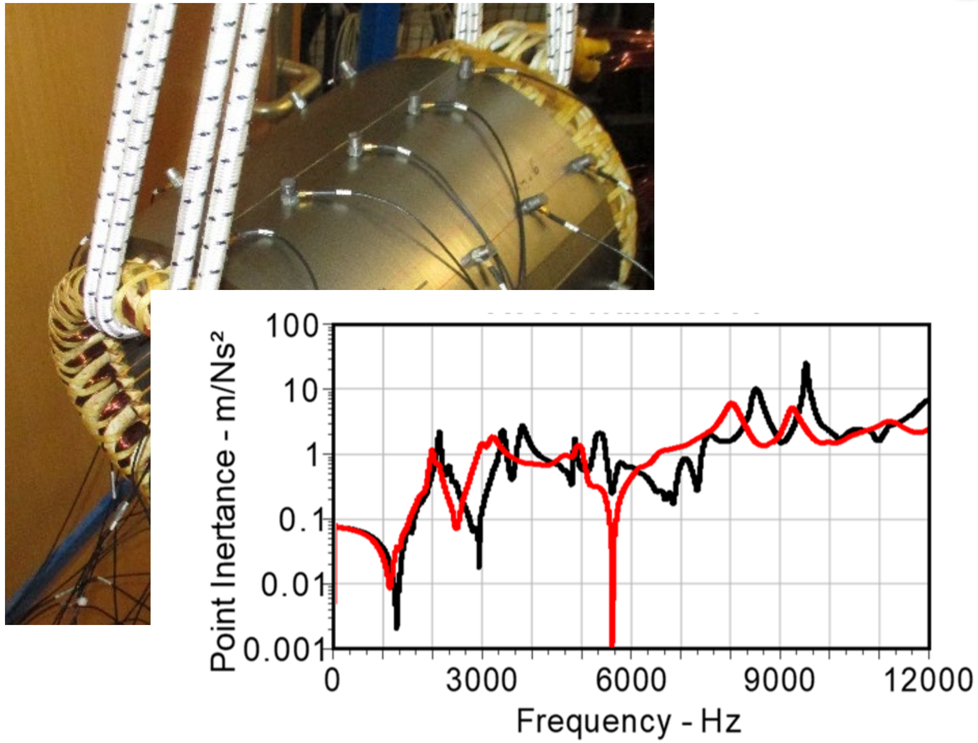
REFERENCE PROJECT

AVL High-Speed E-Axle– NVH hammer test correlation

Very good correlation for NVH under electromagnetic load

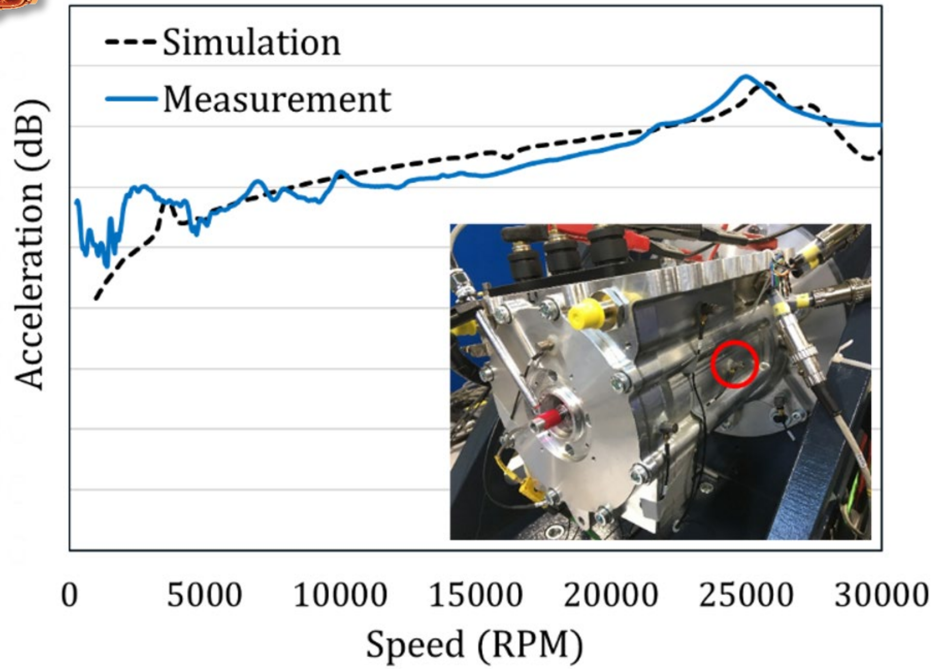


Hammer Test of Prototype



Hammer test in warm and cold condition

Operating Condition Correlation

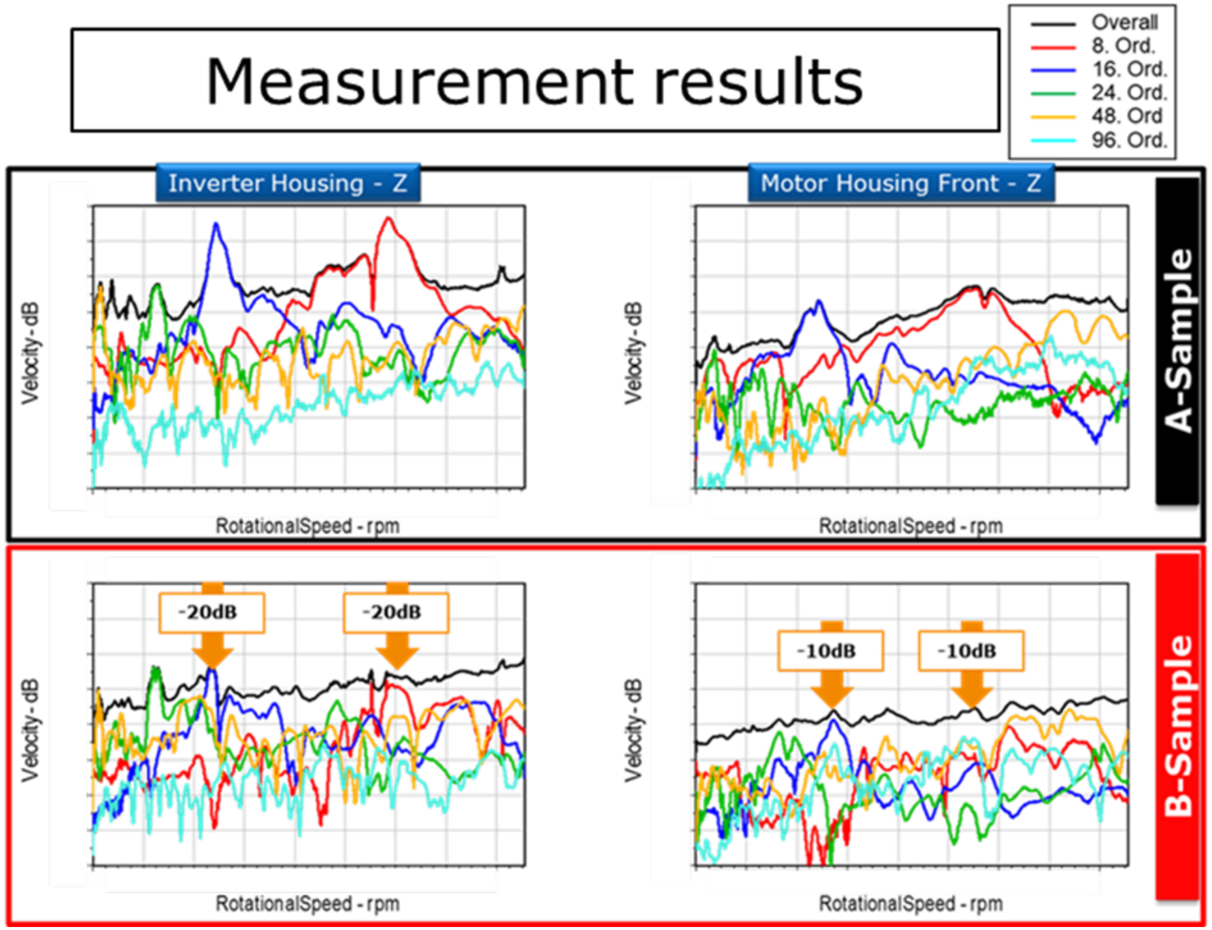


Transfer Function Correlation

REFERENCE PROJECT

3in1 e-Axle Development to SOP – NVH optimization

Great improvement for target surface velocities with NVH optimization

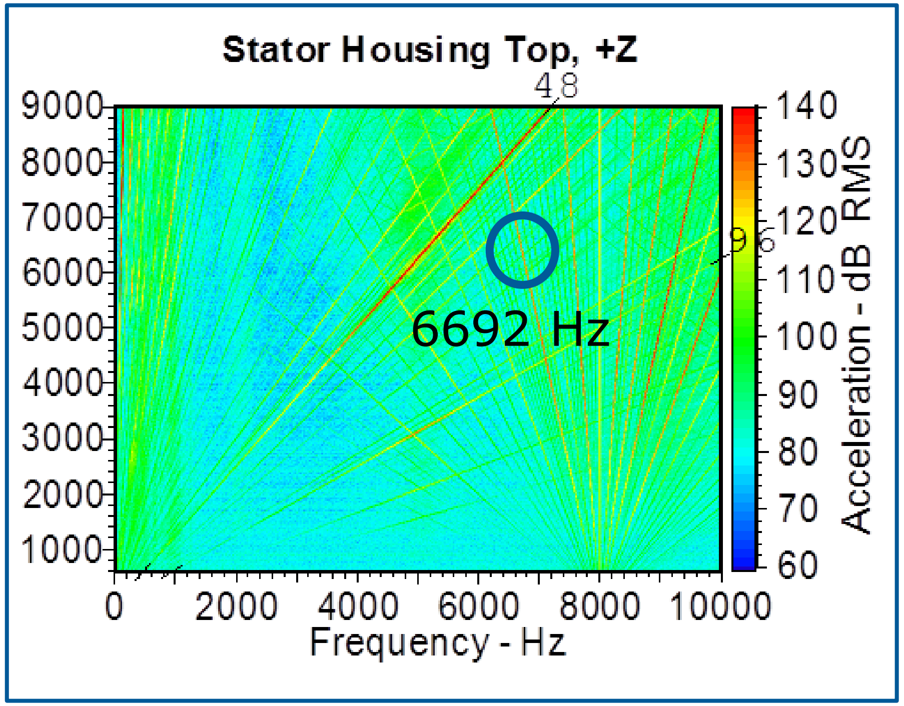


REFERENCE PROJECT

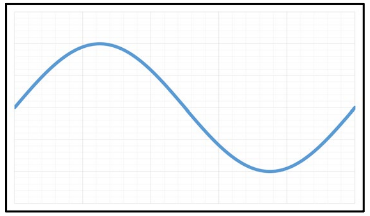
High torque electric machine– PWM harmonic correlation

NVH due to PWM harmonics measured. NVH comparison between sinusoidal, measured and simulated current

ACCELEROMETER

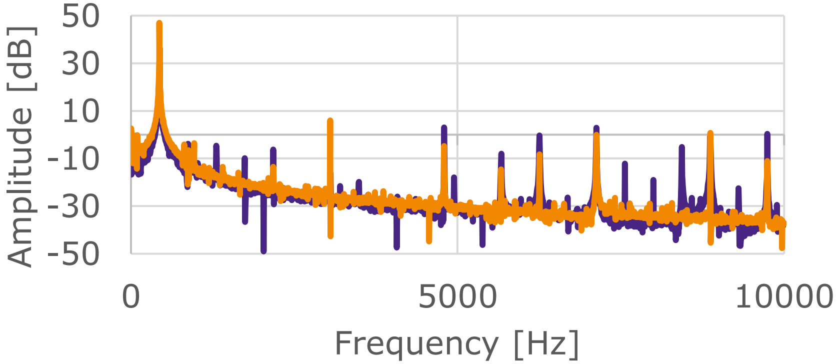


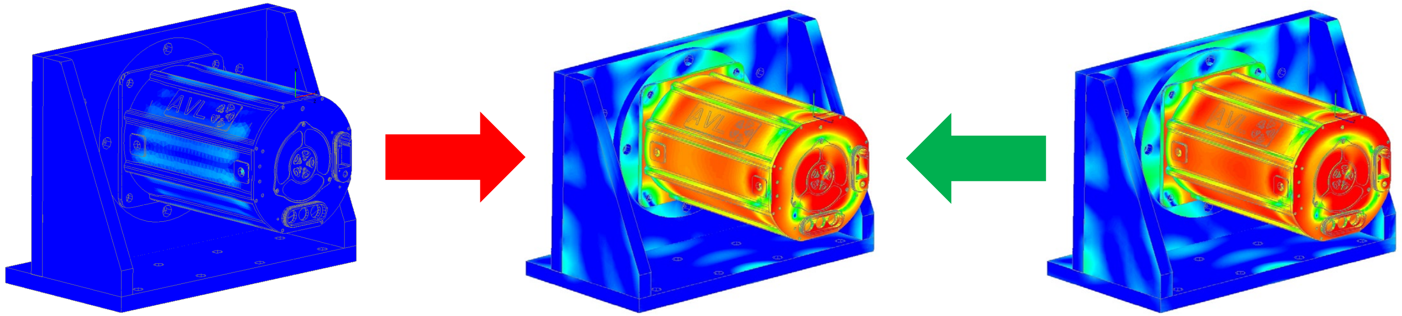
Ideal Current Signal



Measured inverter current

Simulated inverter current





Sinusoidal model not OK for PWM harmonic NVH simulation

Simulated inverter model OK for PWM harmonic NVH simulation

Thank you

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