

Temperature sensor virtualization to improve cost effectiveness of electric machines

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Electrified Motion

What we do

We provide **low and high-voltage electrified solutions** for **all vehicle classes**:



Low-powered drives and actuators for
**eBikes, two-wheeler and passenger
cars**



E-Mobility for
passenger cars

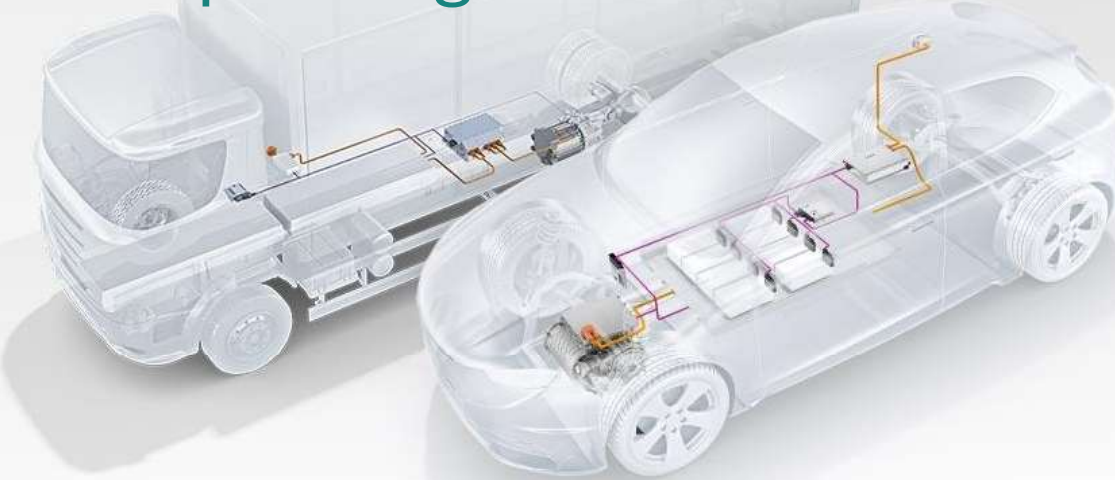


E-Mobility for
commercial vehicles

We enable our customers and partners to successfully drive electrified mobility
– from eBikes to cars up to commercial vehicles – worldwide.

Electrified Motion

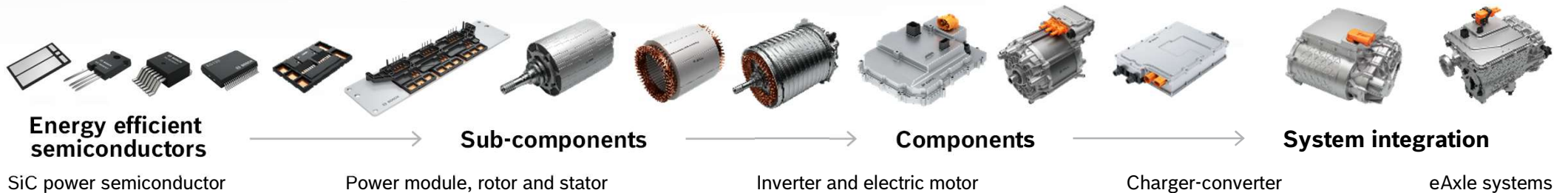
From passenger cars to commercial vehicles



From silicon carbide chips up to drive systems

- Bosch electrifies all vehicle classes and delivers all integration levels
- Inverter: up to 99% efficiency thanks to compact design and SiC
- Electric motor: optimization methods lead to shorter development cycles and require less raw materials and thus contribute to more sustainability

Bosch BEV product portfolio



Standardization and economies-of-scale importance

Integration and customization levels

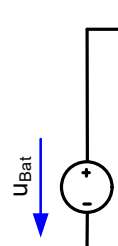
Context

Thermal protection of the electric drive train

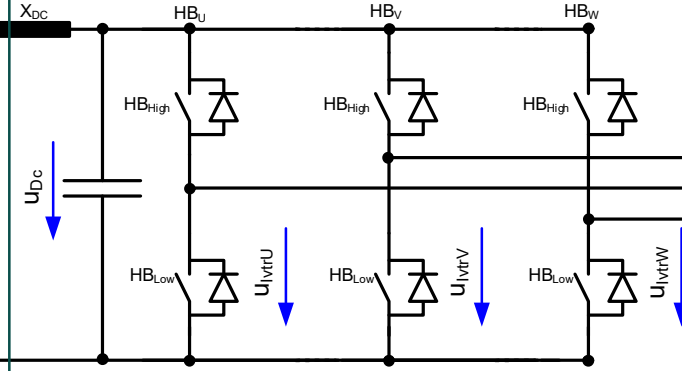
Specification

- $P_{Max} \approx 50-350 \text{ kW}$
- Voltage 400/800 V
- PSM, ASM
- SiC power semiconductors

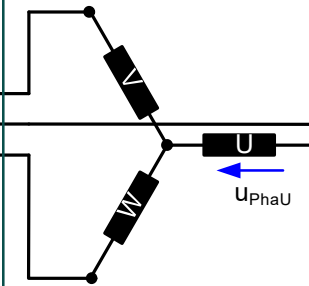
HV-battery



Inverter

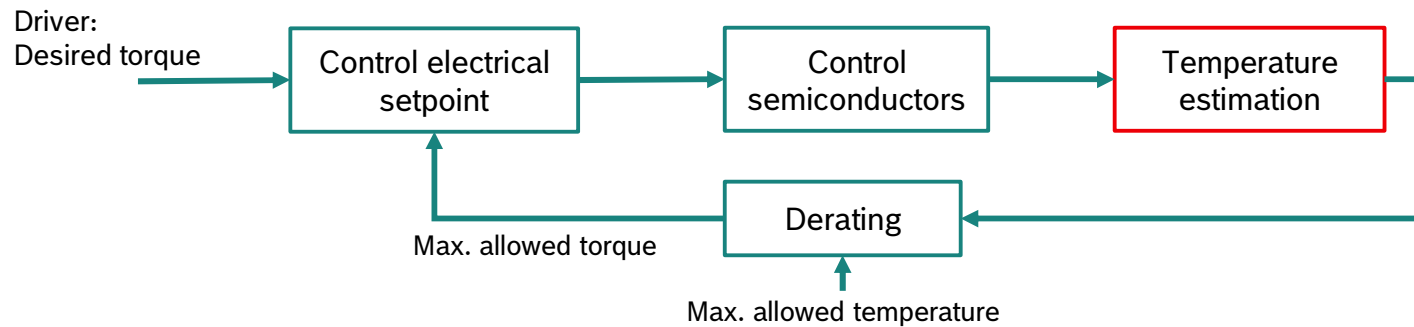


Electric machine



Need for thermal protection

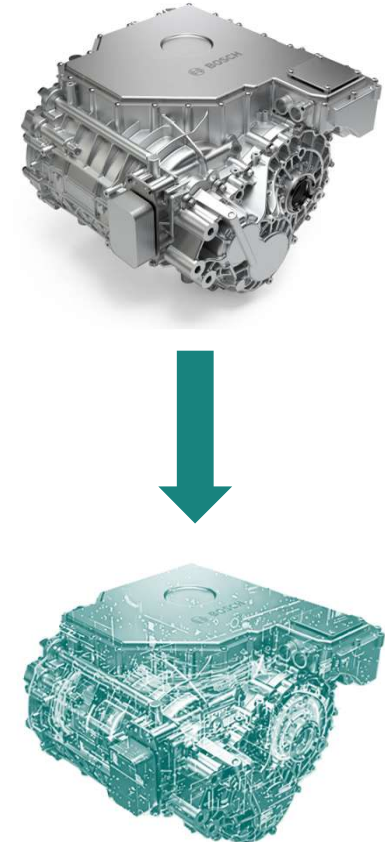
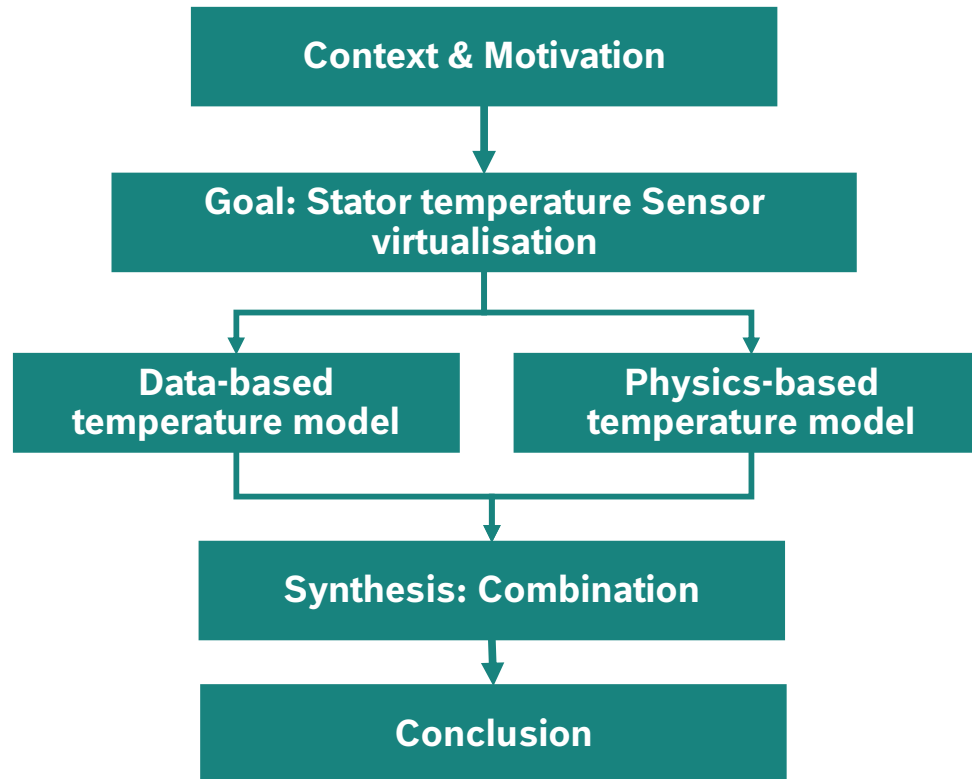
- Fast changing high loads
- Components have individual thermal limits
- Thermal HW overdesign & abundance of temperature sensors not economically reasonable



Thermal protection of electric drive train requires real-time accurate temperature estimation

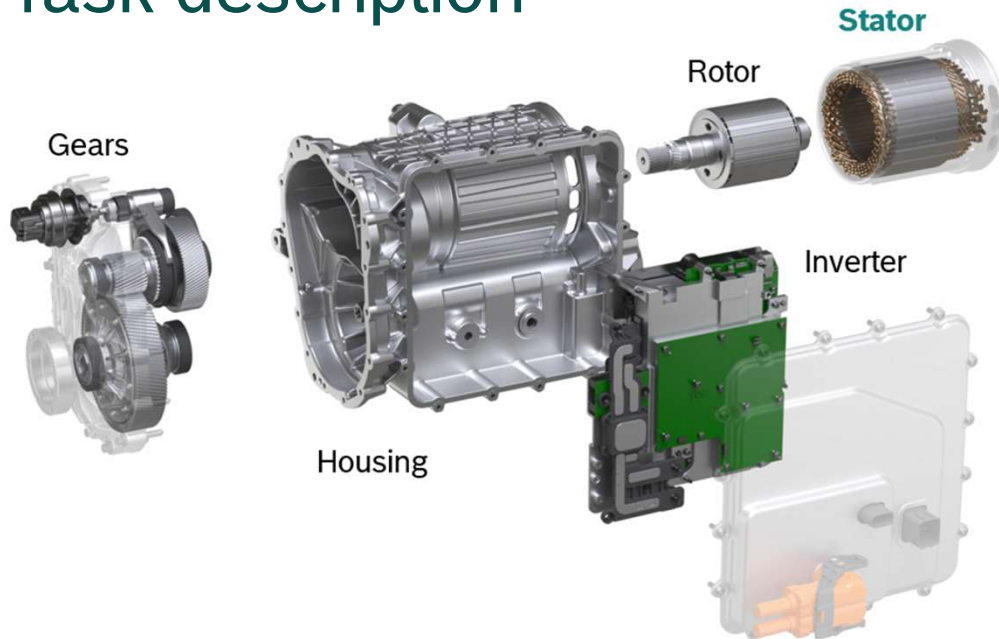
Introduction

Agenda

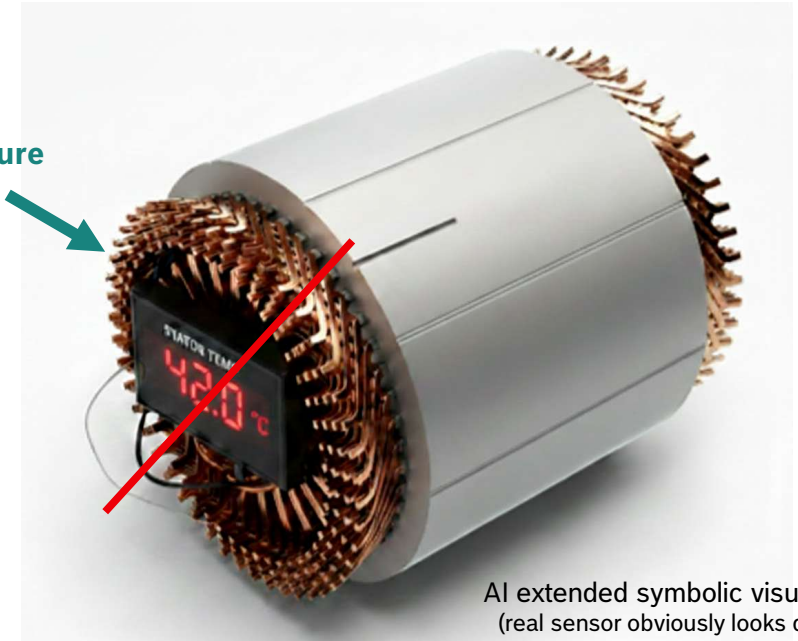


Motivation

Task description



Stator temperature sensor to be removed



AI extended symbolic visualization
(real sensor obviously looks different)

Challenge

- High product costs of stator temperature sensor and high assembly costs
- Accessibility difficult for sensor maintenance
- Sensor removal opens up new design spaces

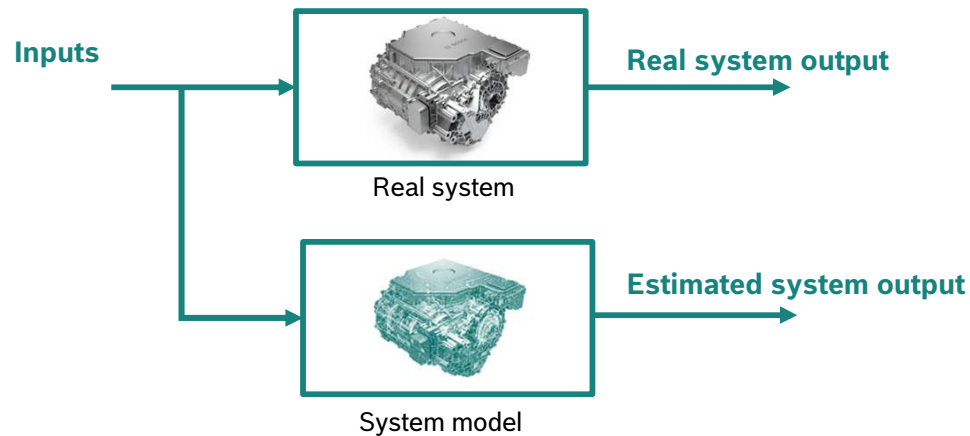
Virtual sensor for stator temperature to enable cost reduction

Motivation

Virtual sensor

A virtual sensor is a model / algorithm that...

- Uses known input signals to estimate an unknown output signal
- For calibration usually a testbench with additional sensors measuring the unknown variable is required
- Real-time deployment on ECU or in the cloud



Business Cases

Replace physical sensor by model

Increase accuracy of existing sensor

Enable „virtual measurement“ at inaccessible positions

Monitoring of physical sensor

Benefits

Cost reduction

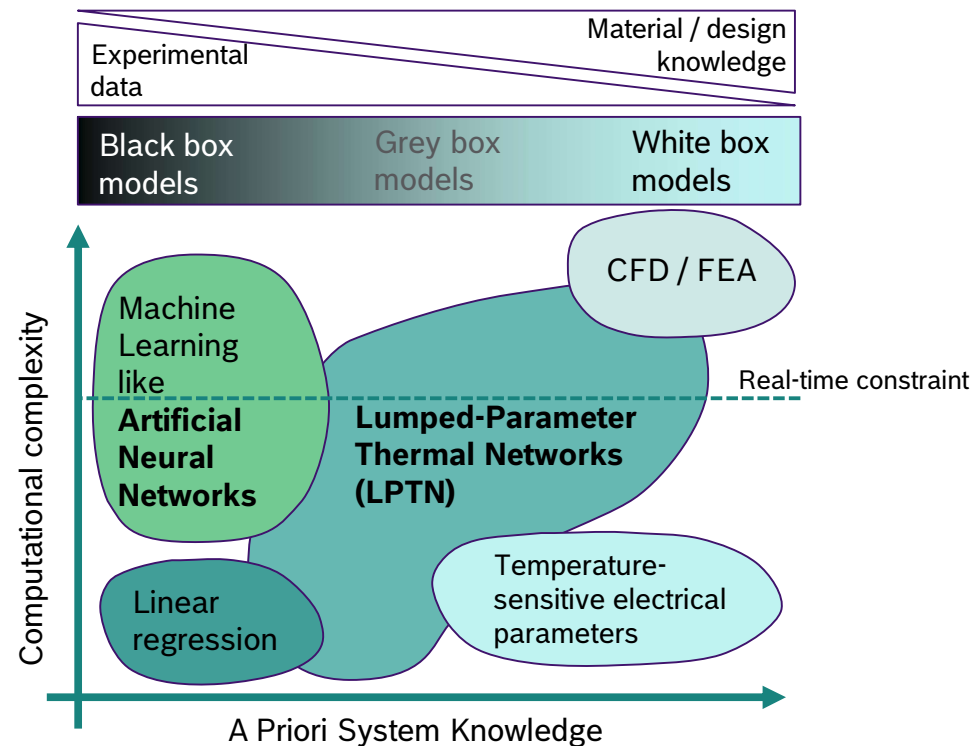
Performance

Re-positioning of sensors

Failure detection

Sensorless stator temperature model

Modeling options

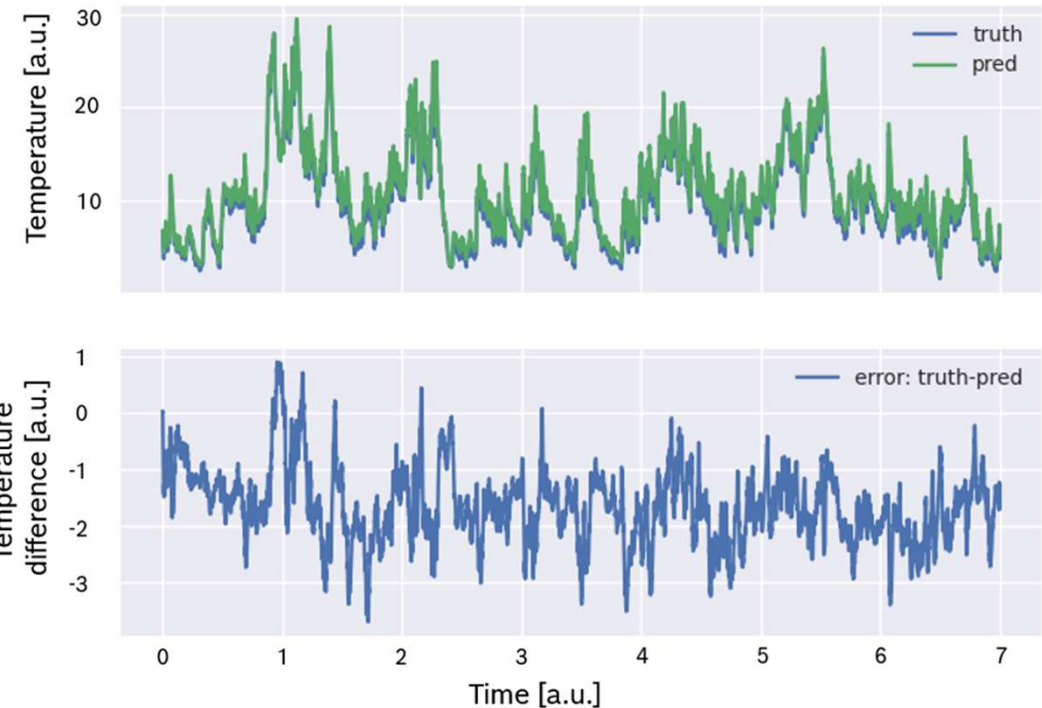
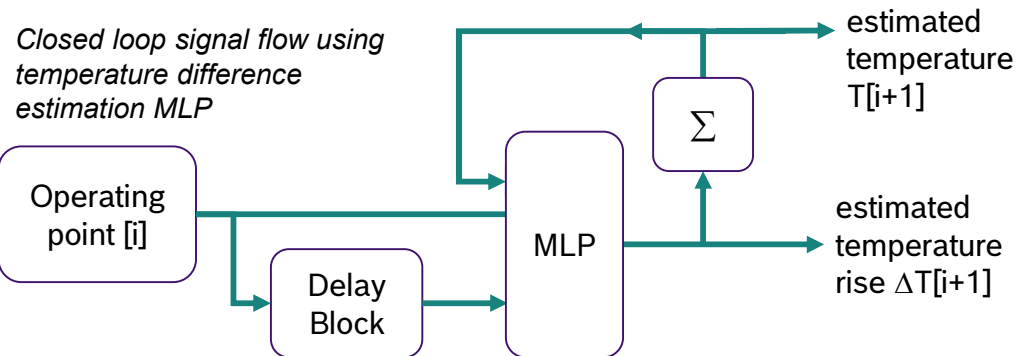
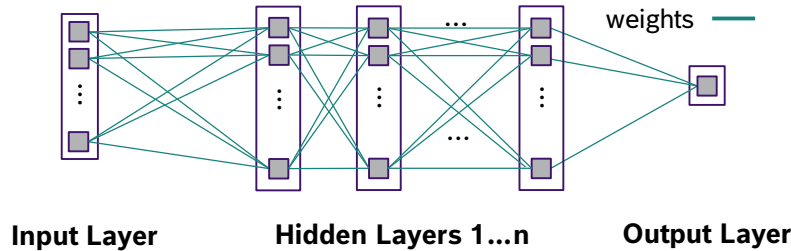


Overview of thermal motor modeling and monitoring techniques based on [Wallscheid, 2021]

- Model selection criteria: Accuracy, robustness, memory & runtime demand, amount of measurement data needed, calibration effort, explainability of results
- Boundary conditions: Real-time capability; limited ECU resources (memory, μ C speed)
- Both data-based and physics-based modelling approaches will be presented

Data-based sensorless stator temperature model

Setup and results of MLP model

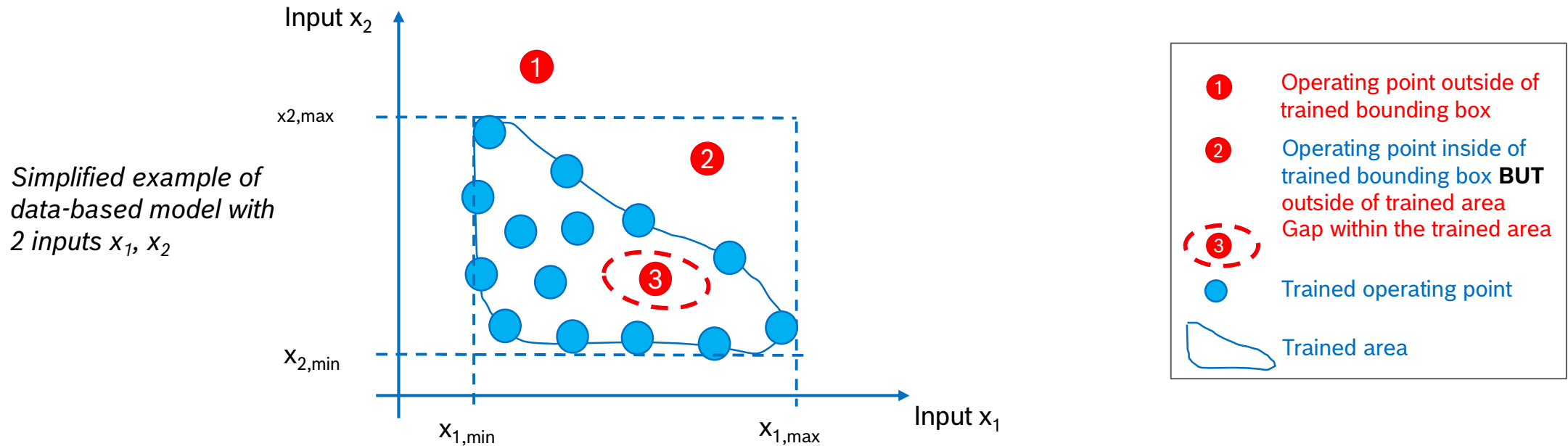


- MLP model is trained to estimate the stator temperature gradient using input data of operating point
- Stator hotspot temperature is derived by integration of temperature gradient

High accuracy achievable with MLP model

Data-based sensorless stator temperature model

Data gaps

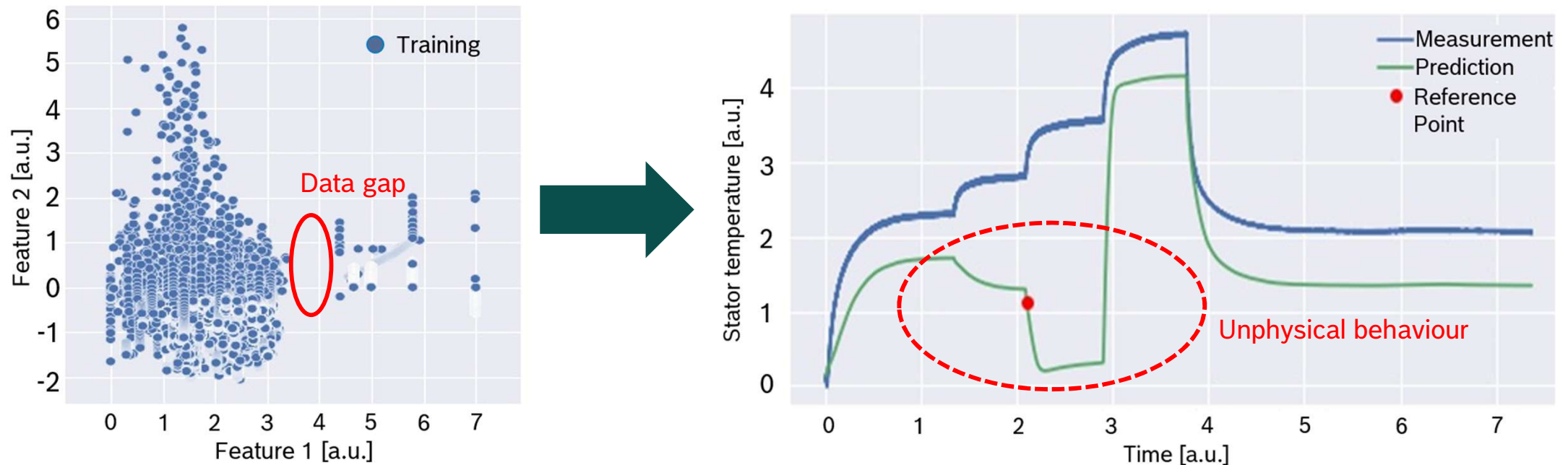


- Operating point 1 outside of trained bounding box can easily be spotted
- Points 2 & 3 within the trained bounding box but still outside the trained region are harder to locate
- Detection becomes more difficult with increasing number of input dimensions → Risk of hallucinations

Main challenge of data-based models: Detection & handling of untrained operating points

Data-based sensorless stator temperature model

Consequences of gaps in training data

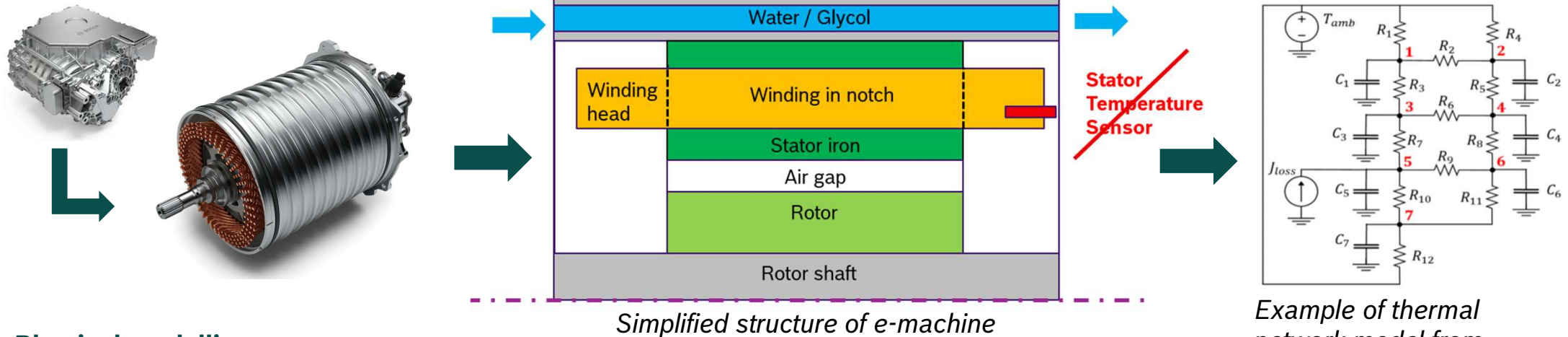


- Model operation in **untrained area** resulted in **unphysical behavior**: Estimated stator temperature dropped despite increased load
- Gaps in training data difficult to spot in case of higher input dimensions (only 2 input dimensions of model visualized here)

Unphysical behaviour and hallucinations of data-based model in case of data gaps during operation

Physics-based sensorless stator temperature model

Modeling concept



Physical modelling:

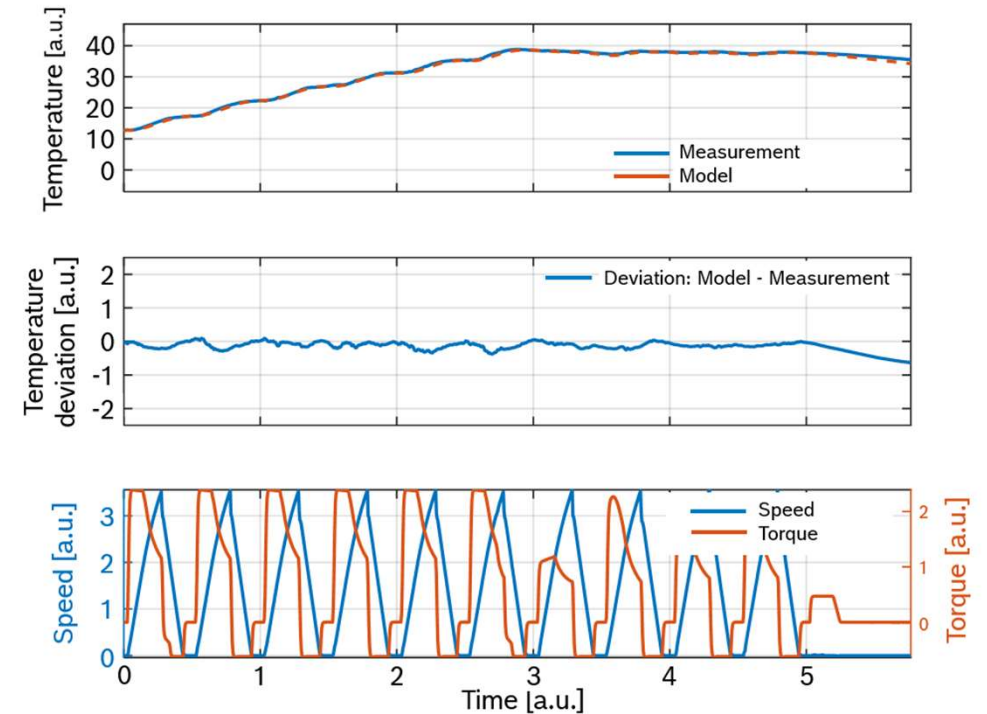
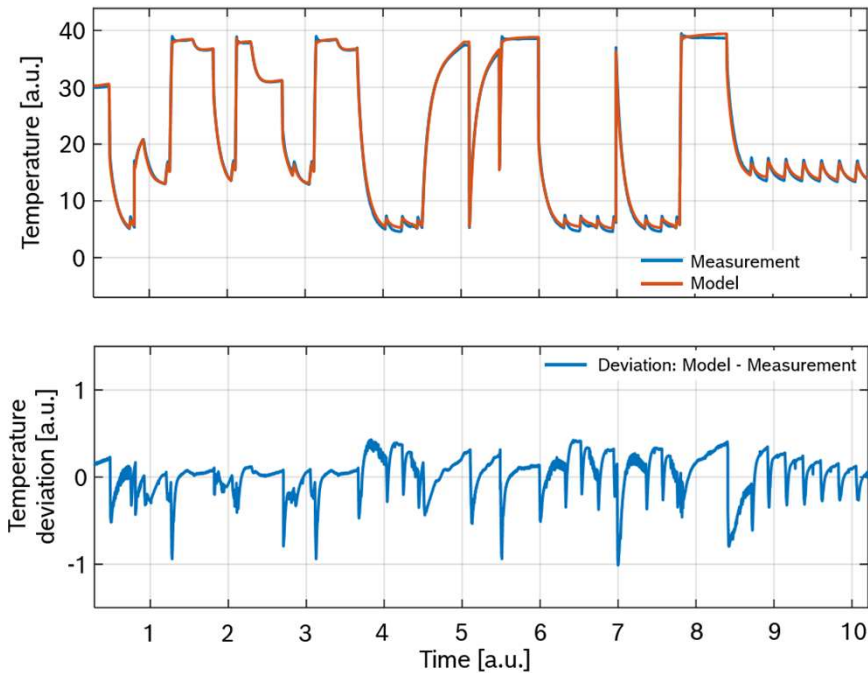
- Heat generation within and heat flows between individual components are considered
- Number of degrees of freedom in thermal network is several magnitudes smaller than in FEM / CFD
- Significant simplifications required but interactions between components still covered
- Small ECU footprint regarding memory and runtime
- Parameters like thermal resistances & capacities are explainable → easier debugging in comparison to pure data-based models
- Existing domain knowledge is put to use

Example of thermal network model from literature [Sciascera, 2017]

Physical cause-effect relationships considered

Physics-based sensorless stator temperature model

Measurement results



- Driving cycles and high transient load changes covered well
- Model shows robust and consistent physical behaviour

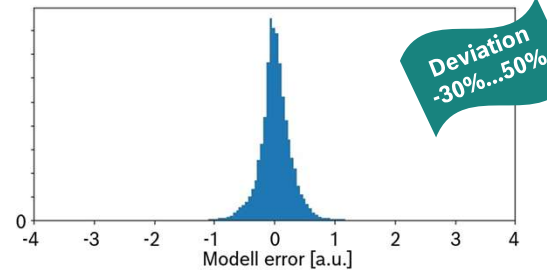
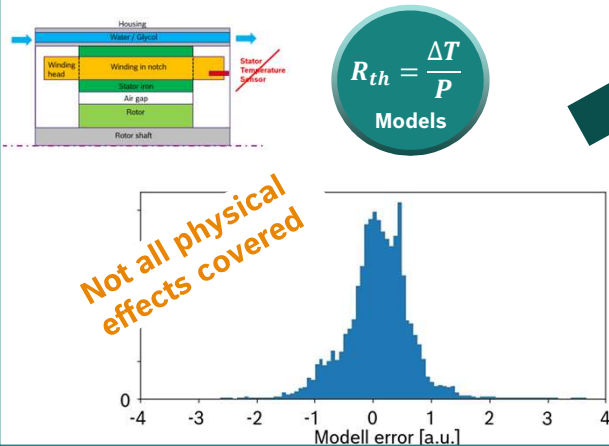
Physical model capable of achieving good accuracy as well

Combined Modeling

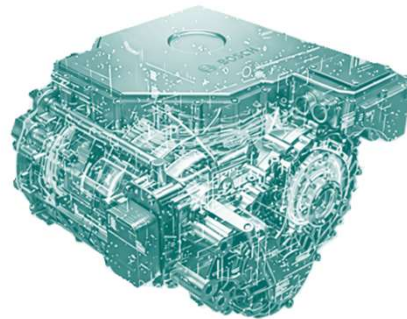
Benefit of combined models

Purely physical model

- ☺ Good extrapolation capabilities
- ☺ Good explainability
- ☹ Not all physical effects covered

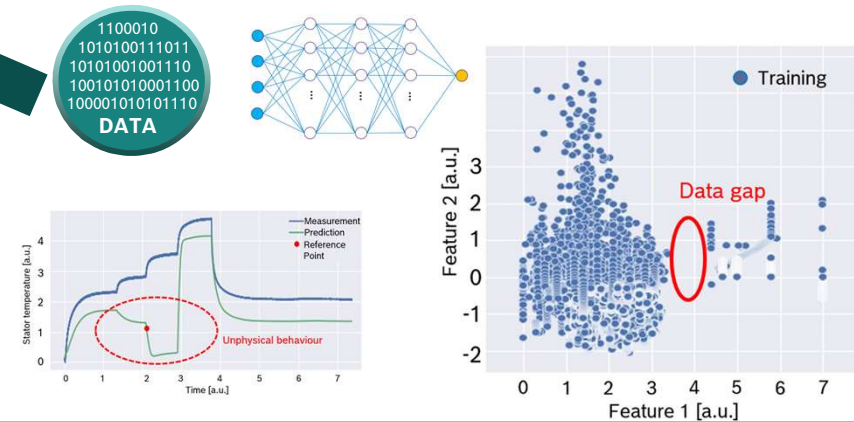


Combined Model



Purely data-based model:

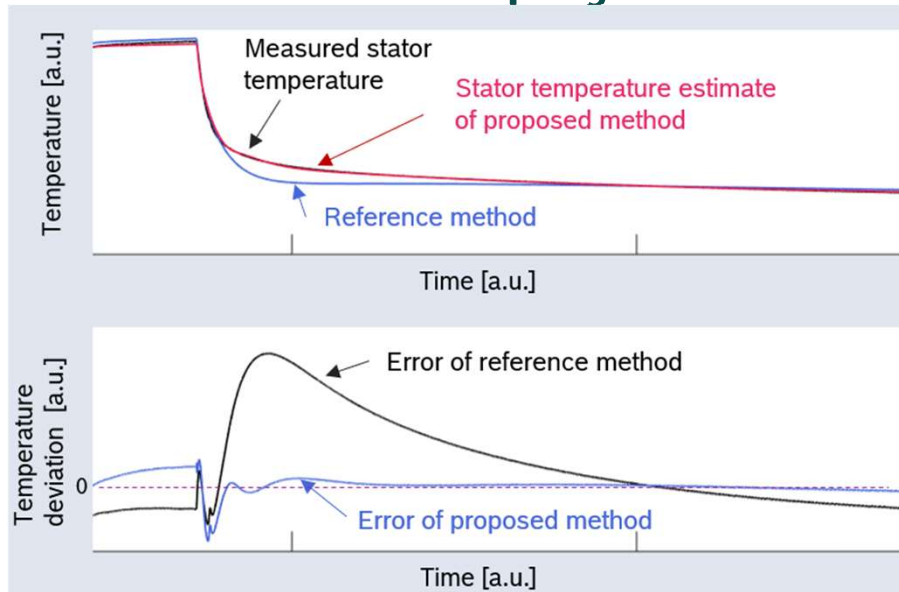
- ☺ Potential for high accuracy (if enough data is available)
- ☹ Bad extrapolation capabilities



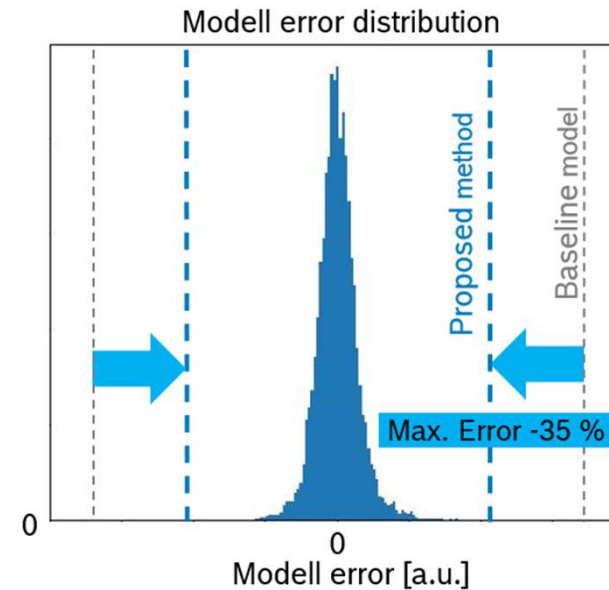
Combination of the best of both worlds (physics & data)
Good extrapolation capability & increased accuracy

Sensorless stator temperature model

Combination of physics-based and data-based models



Results of combined model for water-cooled e-machine



Results of combined model for oil-cooled e-machine

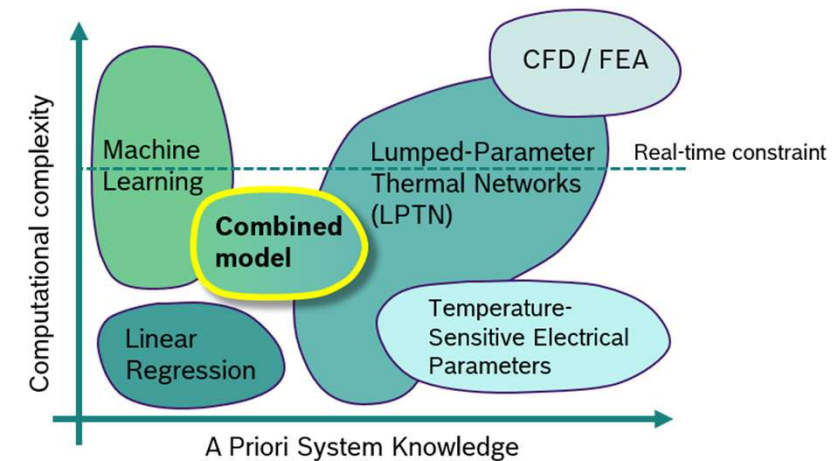
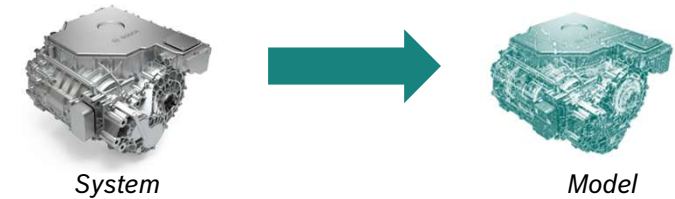
- Combined model (physics & AI) is capable to improve on the results of the pure physical model. Max. error reduced by ~35%
- Safe fallback: In case of untrained operating points the combined model falls back to the physics-based model
- No additional oversight model needed

Combination of physics- and data based provides robust and highly accurate stator temperature estimation

Sensorless stator temperature model

Summary

- Virtual sensors allow for cost-savings by reducing HW and assembly costs
- Pure data-based models suffer from risk of hallucination and non-physical behaviour
- Pure physics-based models show robust and consistent behaviour but have limited accuracy
- Combination of Physics + AI opens path for highly accurate and robust models



Sensorless stator temperature model

References

- **[Wallscheid, 2021]:** O. Wallscheid, "Thermal Monitoring of Electric Motors: State-of-the-Art Review and Future Challenges," in *IEEE Open Journal of Industry Applications*, vol. 2, pp. 204-223, 2021, doi: 10.1109/OJIA.2021.3091870
- **[Sciascera, 2017]:** C. Sciascera, P. Giangrande, L. Papini, C. Gerada and M. Galea, "Analytical Thermal Model for Fast Stator Winding Temperature Prediction," in *IEEE Transactions on Industrial Electronics*, vol. 64, no. 8, pp. 6116-6126, Aug. 2017, doi: 10.1109/TIE.2017.2682010