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Robust Thermal Model for the Estimation of Rotor Cage and Stator Winding Temperatures of Induction Machines

Christian Kral, Anton Haumer, Sang Bin Lee

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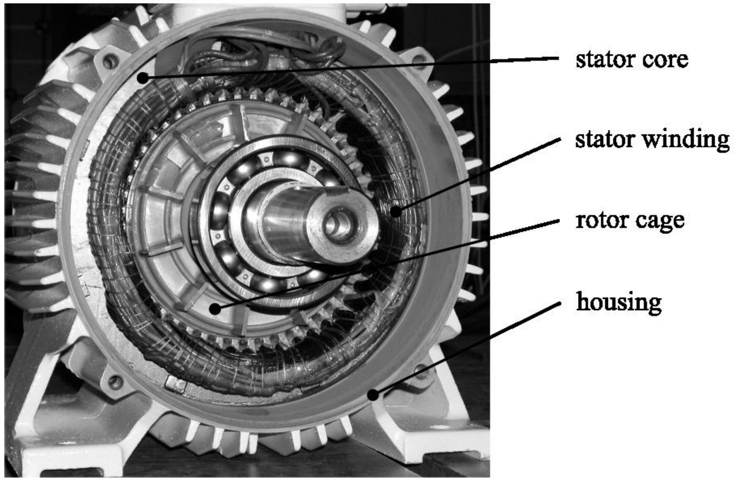
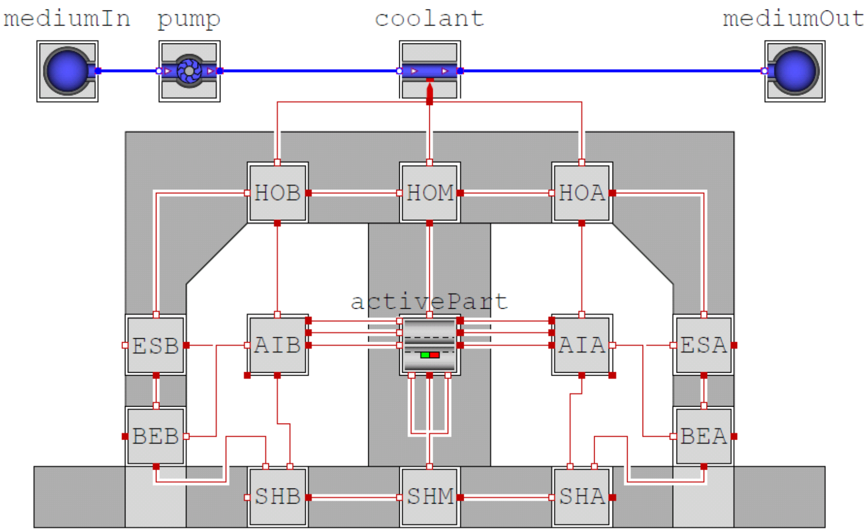
Outline

- Introduction
- Thermal Model
- Determination of Reference Temperatures
- Parametrization
- Experimental Results
- Discussion
- Conclusions

Introduction

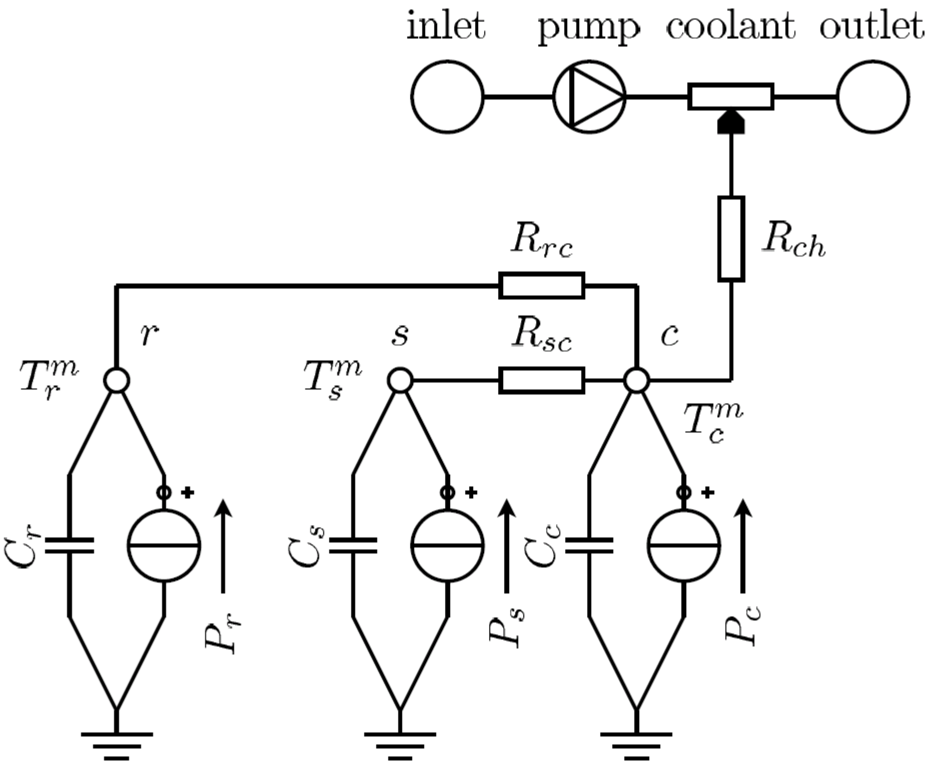
- Local temperature is determined by
  - losses (heat sources)
  - conductive and convective heat transfer
  - heat storage effects
  - cooling concept
  - ambient conditions
- Comprehensive thermal network model
  - used in design stage
  - transient behavior (load cycle)
  - challenge: heat convection
    - heat transfer from air to
      - winding head
      - housing
      - end shield





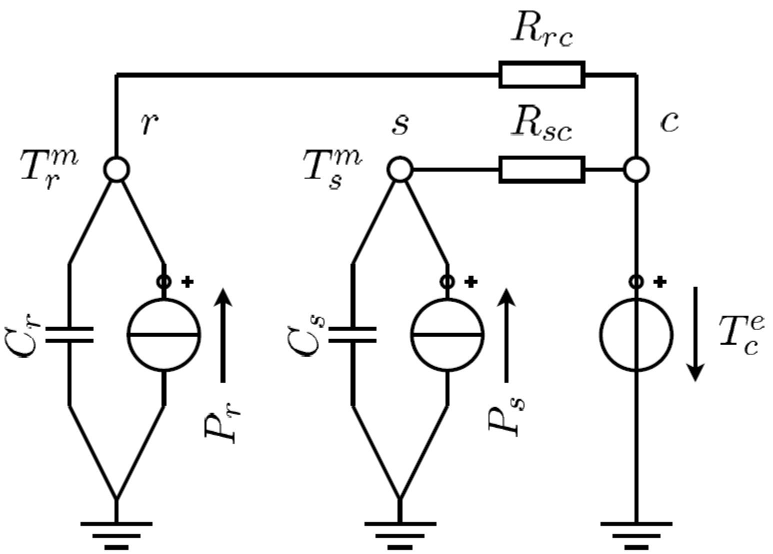
Thermal Model 1/2

- Simplified thermal model with three time constants
- Thermal nodes
  - rotor cage
  - stator winding
  - stator core
- Cooling circuit
  - physical model with coolant
  - pump / cooling fan
  - ambient conditions
- On-line application
  - thermal parameters
  - loss model
    (operating condition)
  - cooling model
    (including ambient conditions – congested cooling vents ?)



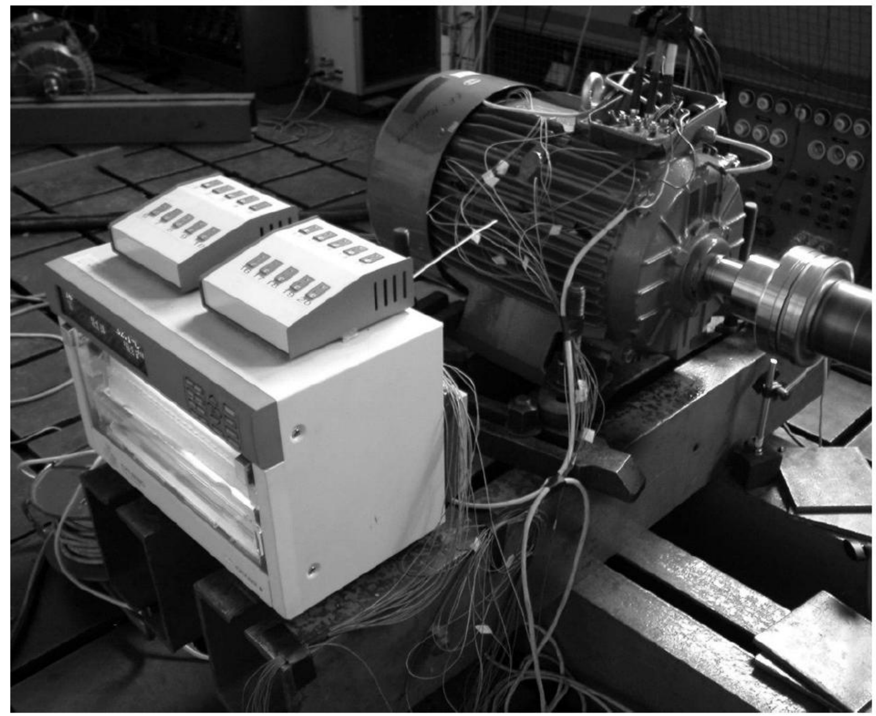
Thermal Model 2/2

- Simplified thermal model with two time constants
- Thermal nodes
  - rotor cage
  - stator winding
- Temperature source
  - stator core
- Cooling circuit
  - inherently model by using core temperature as input
- On-line application
  - thermal parameters
  - loss model
  - measuring stator core temperature
  - no cooling model required
  - ambient conditions have not to be considered



Determination of Reference Temperatures 1/3

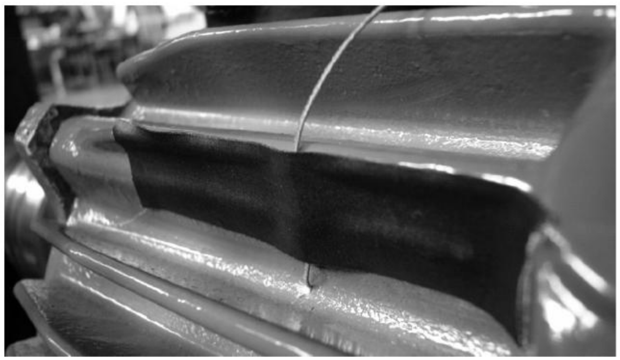
- Calibration of simplified thermal model with two time constants
- Reference measurement of temperatures
  - stator core
  - stator winding (average)
  - rotor cage (average)
- Stator core sensor
- Stator winding (and winding head) sensor(s)
- Rotor cage sensor or on-line method



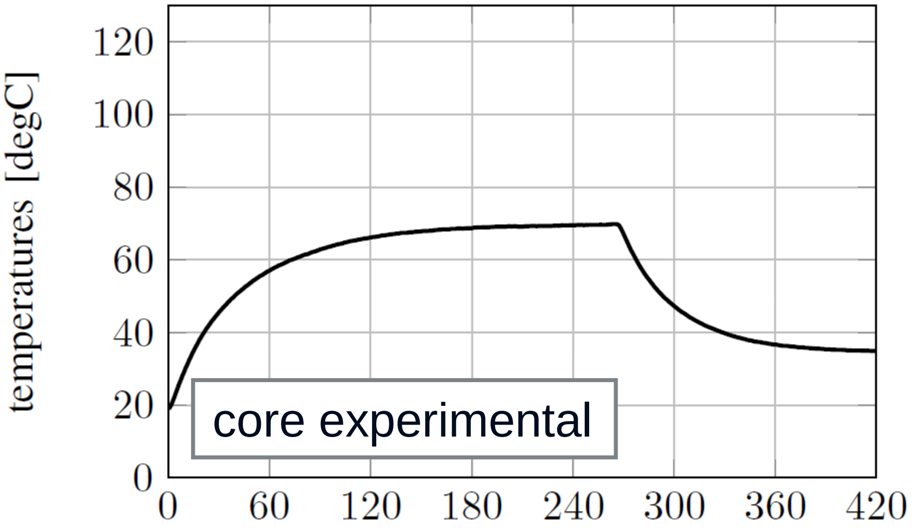
- Heating up and cooling down (transient)

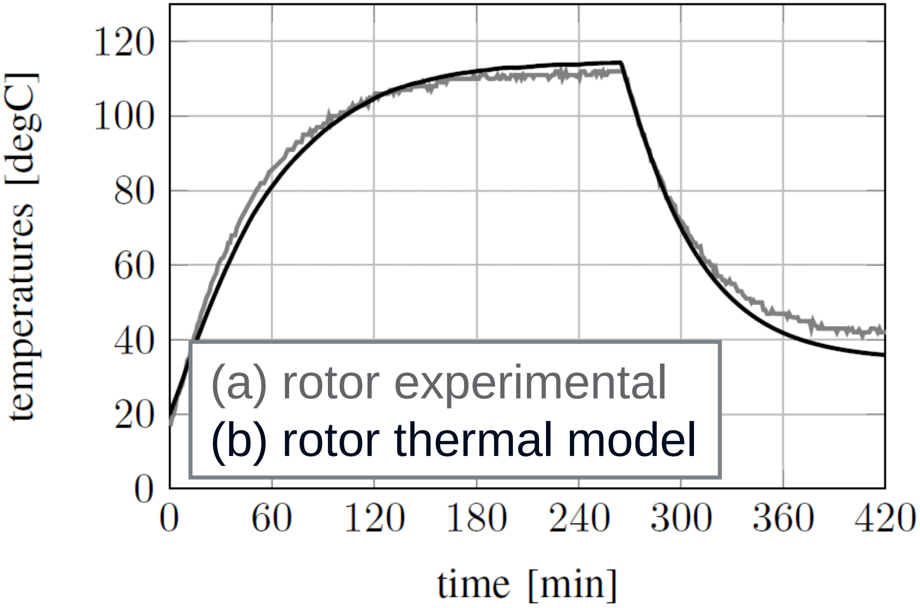
Determination of Reference Temperatures 2/3

- Stator core temperature
  - Type K thermocouple



- Rotor cage temperature

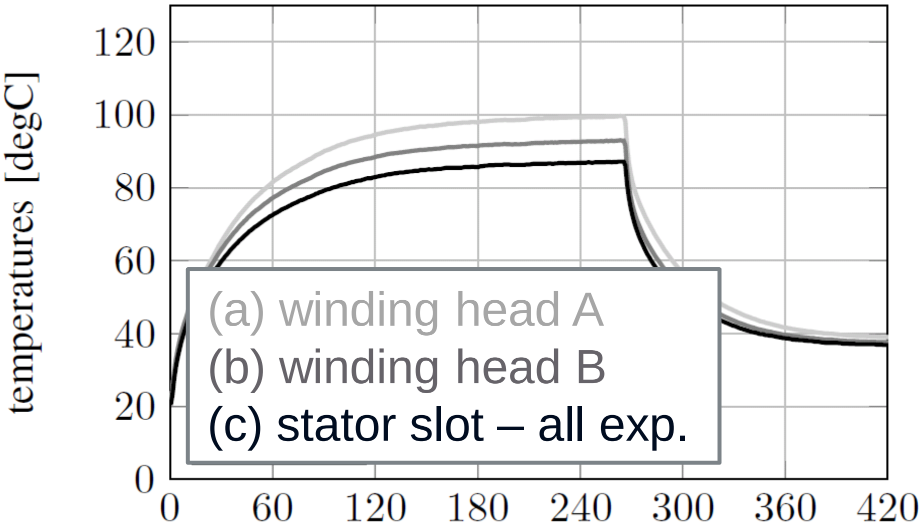


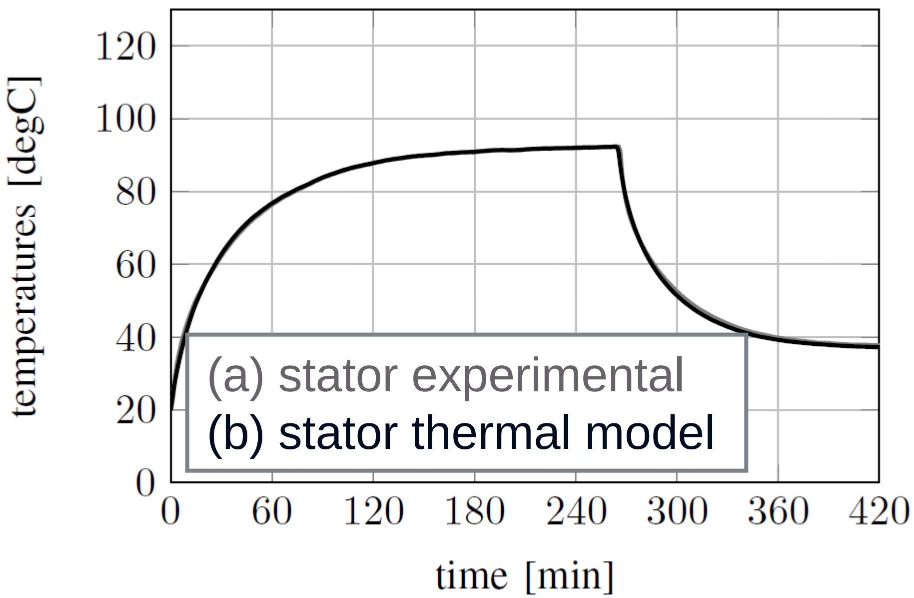


Determination of Reference Temperatures 3/3

- Stator temperatures
  - Type K thermocouples
  - averaged over several sensors
  - averaged over several regions

$$T_s^e = c_\ell T_\ell^e + \frac{1-c_\ell}{2}(T_a^e + T_b^e)$$





Parameterization 1/2

- Power balance
- Losse model
  - stator winding losses

    $$P_s = 3R_{s,20}(1 + \alpha_{s,20}(T_s^m - 20°\mathrm{C}))I^2$$
  - stator core losses

    $$P_c = P_{c,\mathrm{ref}}\left(1 - h + h\frac{f_n}{f}\right)\left(\frac{V}{V_n}\right)$$

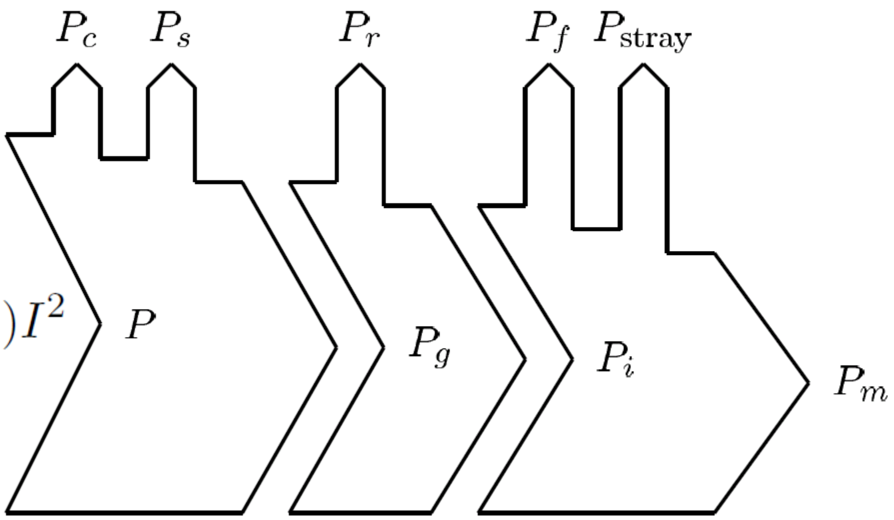
    including fraction of hysteresis losses, *h*
  - air gap power

    $$P_g = P - P_s - P_c$$
  - rotor losses

    $$P_r = sP_g$$

    depending on slip

    $$s = \frac{f - pn}{f}$$



Parameterization 2/2

- Experimental data (superscript *e*)
- Modeled data (superscript *m*)
- Determination of parameters

quantity	value	unit	comment
G_{rc}	33.91	W/K	thermal conductance between rotor cage and stator core
G_{sc}	10.10	W/K	thermal conductance between stator winding and stator core
C_r	8512	Ws/K	thermal rotor cage capacitance
C_s	15550	Ws/K	thermal stator winding capacitance

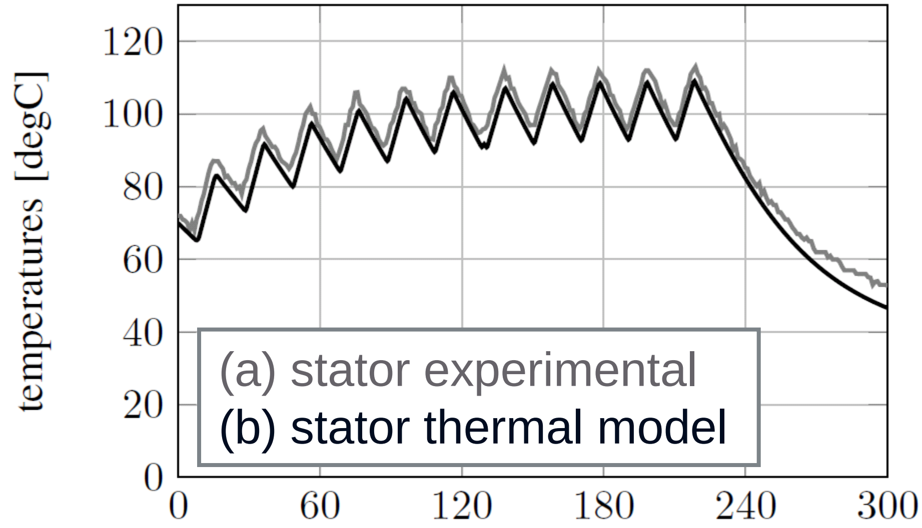
by minimizing the integral of the squared temperature differences

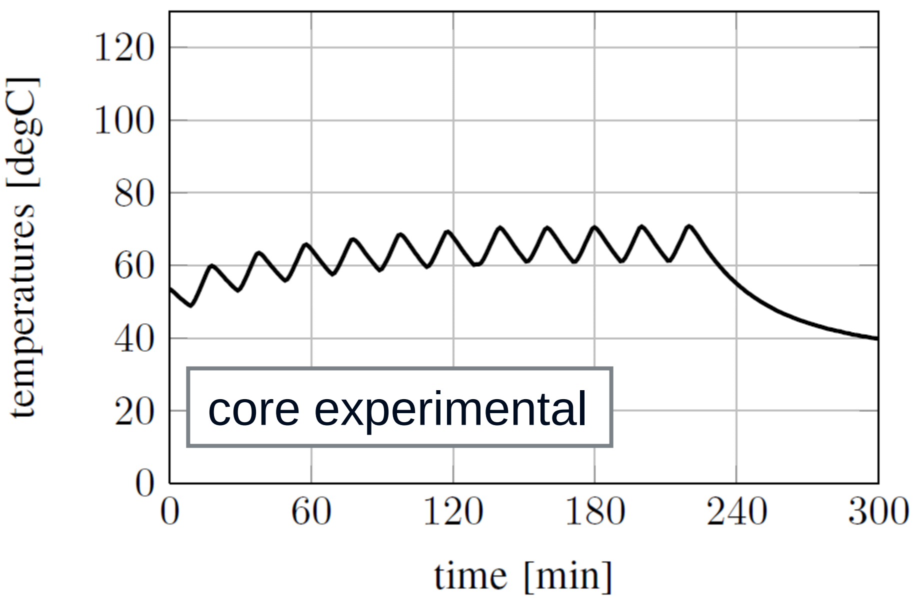
$$\Delta T^2 = \frac{1}{T} \int_0^T \left((T_r^e - T_r^m)^2 + (T_s^e - T_s^m)^2 \right) \mathrm{d}t$$

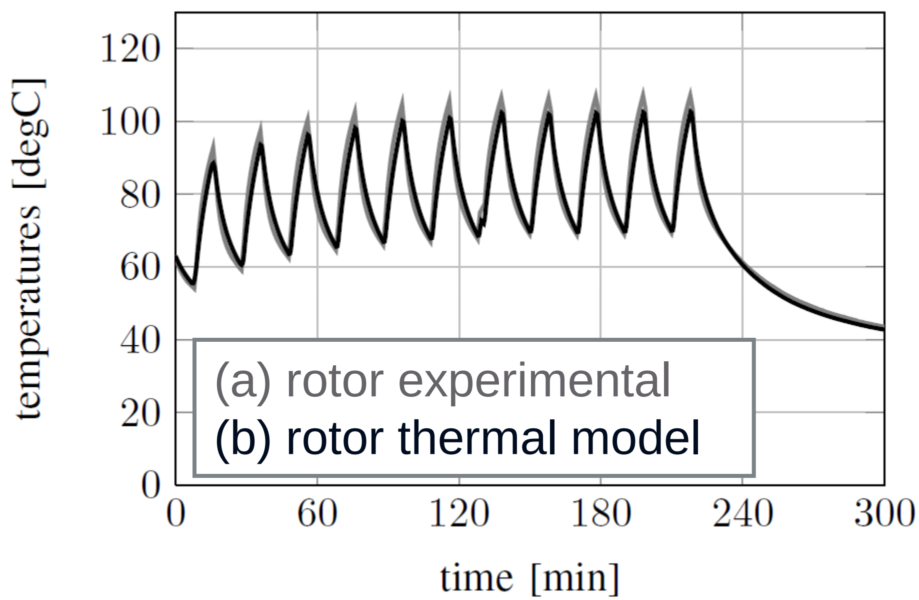
- Calibration / optimization method (

Experimental Results

- Continuous duty with intermittent load
- Thermal model with two time constants slightly underestimates temperatures

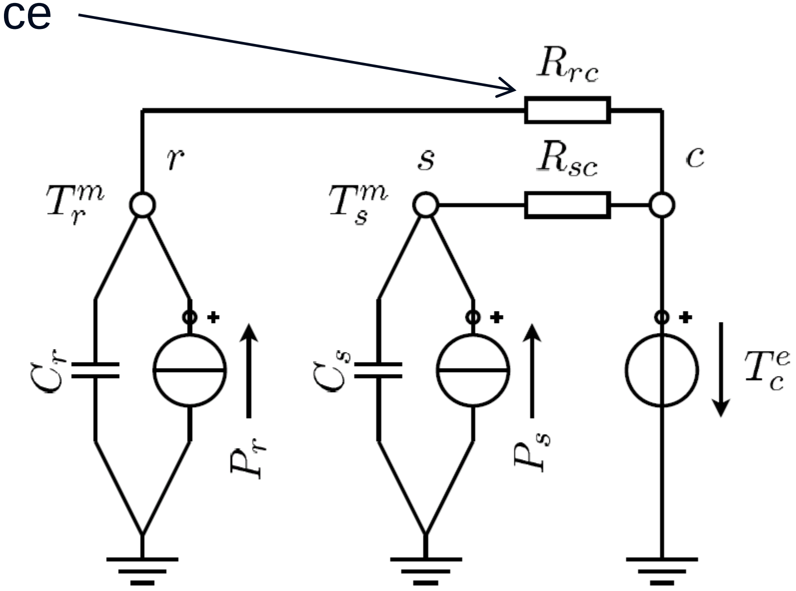






Discussion

- Measurement: local temperature – hot or cold spot?
- Thermal model: averaged over region
- Two time constants
  - significant simpifcation
  - temperature deviation < 5 degC
- Speed dependency could be considered by
  - frequency dependent thermal conductance
- Higher order thermal model allows
  - higher level detailization
  - asymmetry of machine or cooling
- Impact on model quality
  - quality of loss estimation (slip)
- Differnt locations of stator core sensor
  - low impact of about 1 degC
- Alternatively comprehensive thermal model in stead of experimental reference data



Conclusions

- Thermal model with three and two time constants
- Loss model
- Temperature sensor in the stator core
  - Inherently covers ambient conditions
  - Very robust and simple
- Model calibration
- Experimental results

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