Cooling, Ageing and Condition Monitoring of Electric Traction Machines

Prof. Avo Reinap (Lund University)
Dr. Zhe Huang (AB Volvo)
Prof. Mats Alaküla (AB Volvo & Lund University)

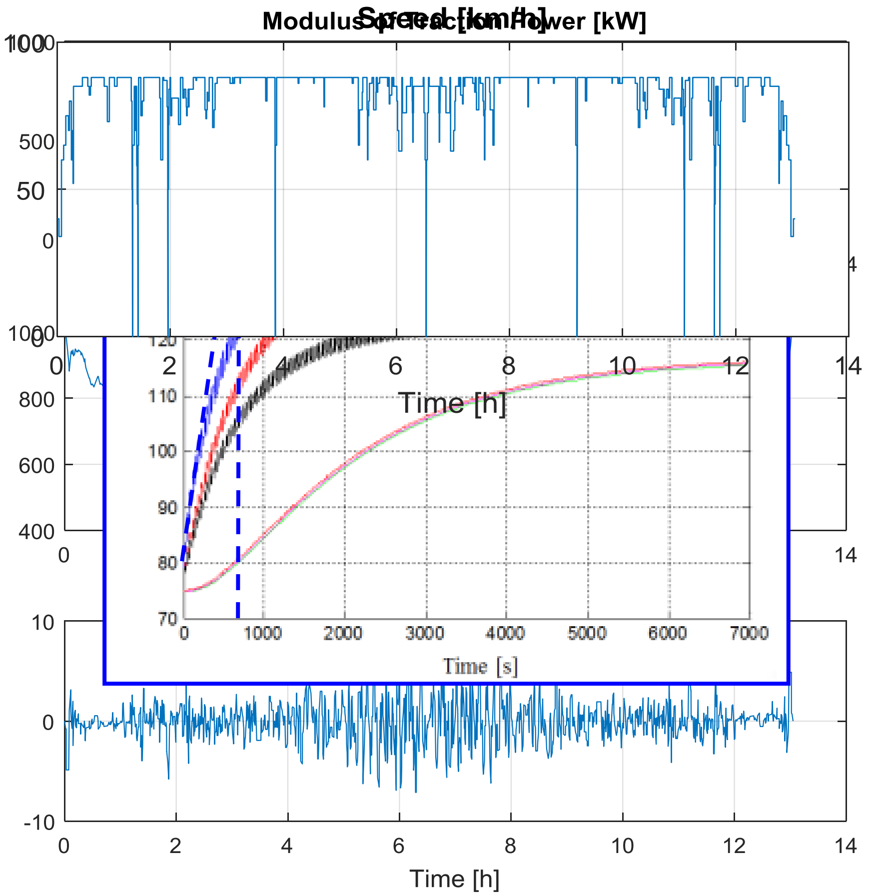
Heavy Duty Trucks

- Daily travel distance > 800 km
- 30..90 tons
- Full Electric now possible
  - On batteries, with ”Mega” Charging
  - On Electric Roads

- What about the electric drive trains?

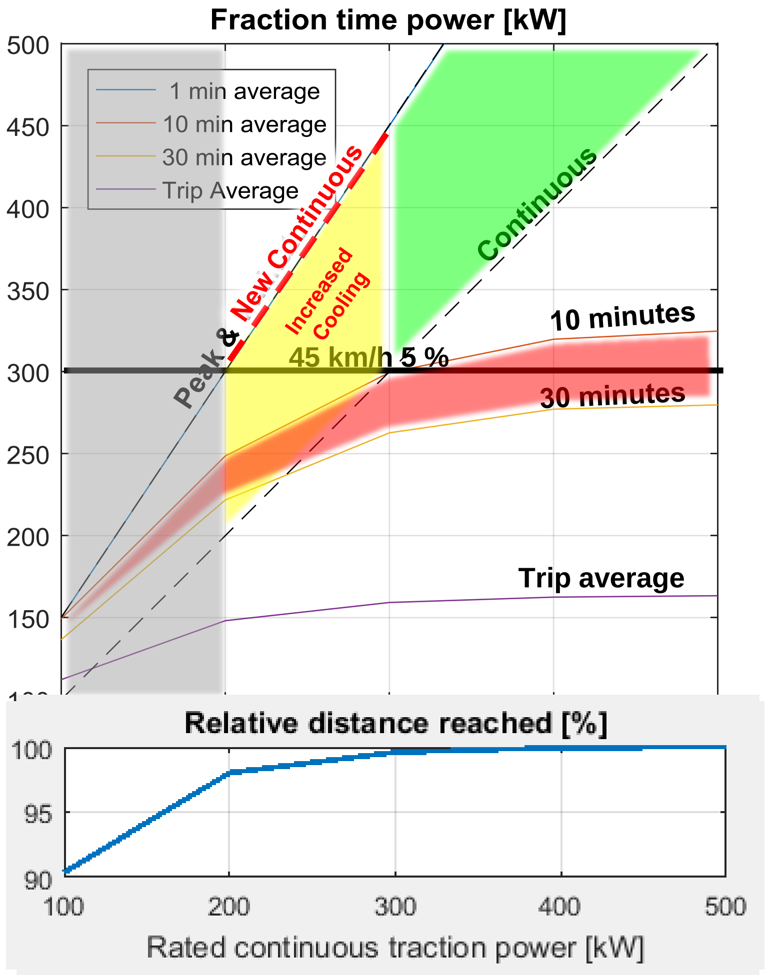
Full Electric Heavy Duty Trucks

- High power levels, during extended periods
  - Significant cooling requirements
- HDT in a tough Long Haul cycle:
  - 44 ton
  - 500/750 kW traction power (cont/peak)
  - 13 h operation roundtrip
  - Max 60 [s] average Power = 651 [kW]
  - Max 600 [s] average Power = **325** [kW]
  - Max 1800 [s] average Power = **280** [kW]
  - Full trip average Power = 163 [kW]
- Is that reasonable?



Less power?

- Try 100...500 kW CONTINUOUS
  - ... with 150...750 kW PEAK
- *Assume thermal time constant* *10...30 minutes*
  - *Assume >300 kW for performance*
  - *< 200 kW underperforms*
  - *200...300 kW enough, but overheating may occur ...*
  - *>> 300 kW overperforms?*
- Lower power with Increased Cooling may be interesting
  - *5...10 % less energy consumption*



What happens at overload?

- Core losses change moderately
- Stator winding losses increase dramatically!
  - $P_{windingloss} = R \times I^2$
- Heat generation > cooling capability

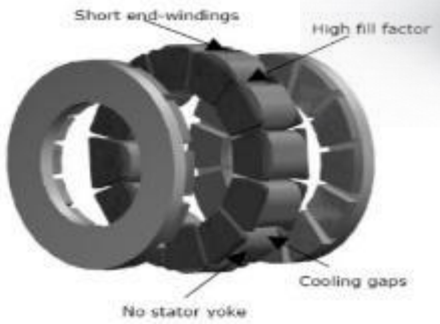
Increased Cooling ...?

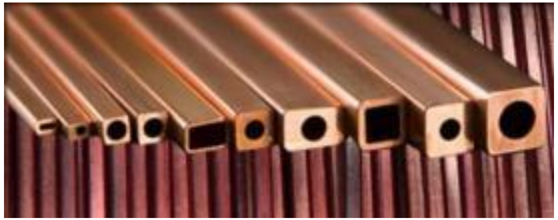
- Air cooling outside
- Water sleeve cooling
- Oil cooling, also on end winding and maybe inside rotor

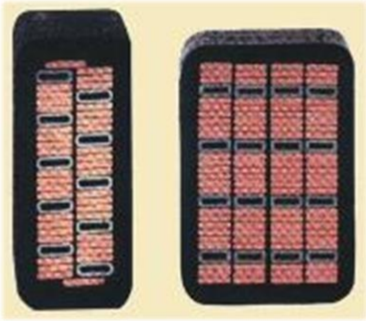
Peak Power determined by **thermal capacitance**

- Oil cooling directly on the windings
- Cooling inside the stator windings
- Cooling inside the stator conductors

Peak Power determined by **direct winding cooling** capability

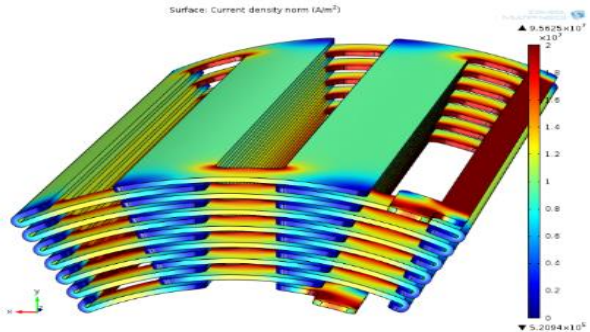


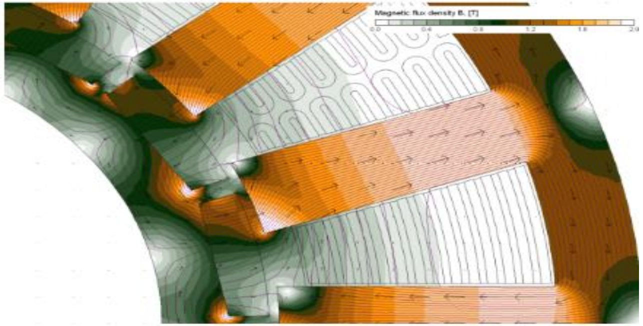


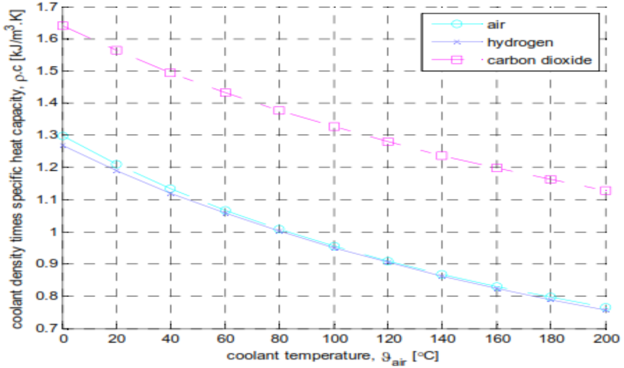


First idéa: - The laminated winding

- Suitable cooling media ?
- Air a reasonable compromise



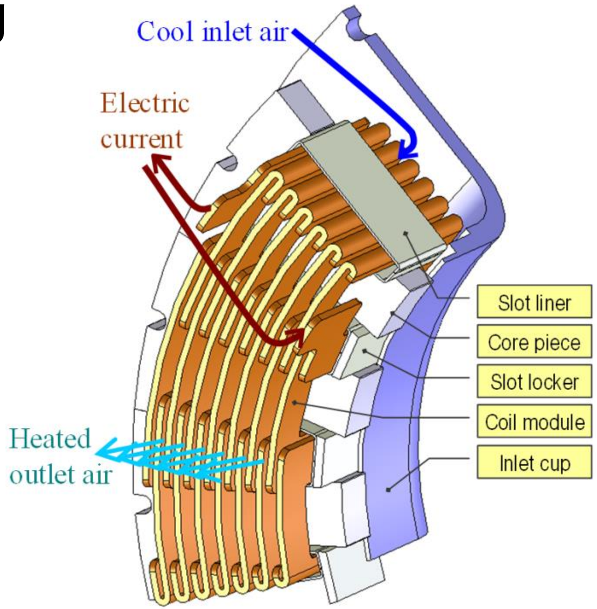


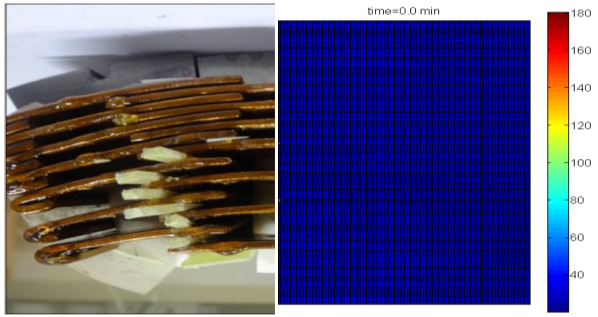


	Air		Hydrogen		Carbon Dioxide		Water		Transformer Oil	
Temperature [C]	20	120	20	120	20	120	20	120	20	120
heat capacity [kJ/kg,K]	1,005	1,014	14,2	14,49	0,854	0,938	4,187	4,25	1,71	2,114
Mass Density [kg/m3]	1,204	0,898	0,084	0,063	1,83	1,364	999,6	942,2	879,1	816,5
Cooling Potential [kJ/m3,K]	*1,21*	*0,91*	*1,19*	*0,91*	*1,56*	*1,28*	*4 185*	*4 004*	*1 503*	*1 726*
Thermal Conductivity [W/m,K]	0,026	0,033	0,178	0,227	0,016	0,024	0,594	0,686	0,111	0,102
Dynamic Viscosity [Pa s]	1,80E-05	2,30E-05	8,00E-06	1,10E-05	1,40E-05	1,90E-05	1,00E-03	2,00E-04	0,052	

Directly cooled laminated windings

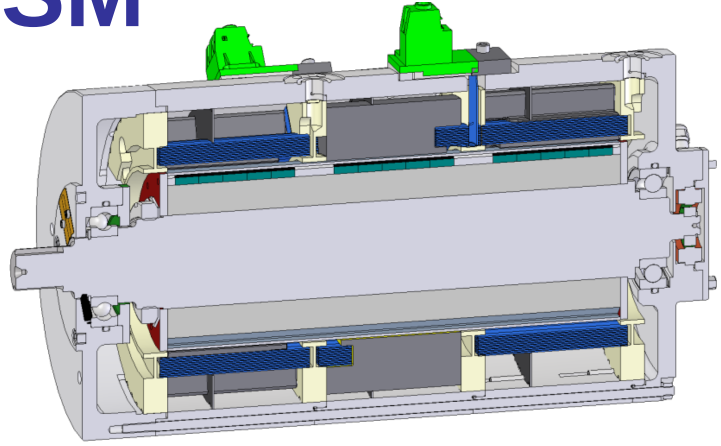
- Provide direct cooling & overloading capability
- Excellent cooling capability
- Manufacturing problems lead to Overheated & undercooled regions



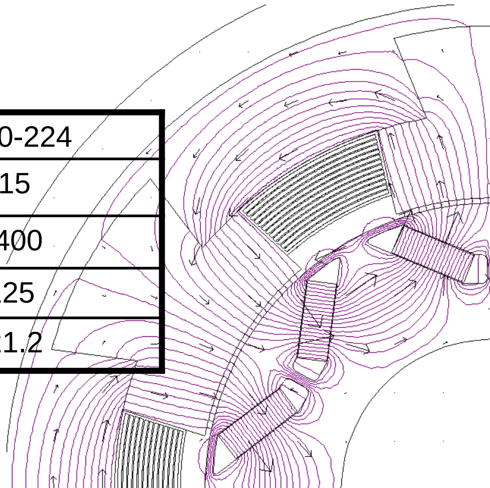


3φ Axially Stacked IPMSM

- Axially displaced laminated windings
- Moulded core facilitates construction BUT limits torque, increases leakage and AC losses in the winding
- Narrow cooling channels, high flow and cooling demand – small geometric differences results large discrepancy in temperature

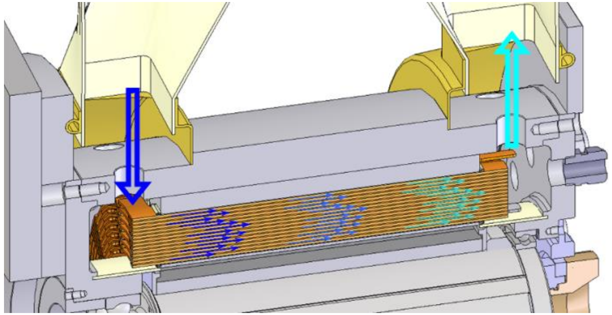


Stator size D_o/D_i-H	mm	200/120-224
Speed n, nom/pk	krpm	7.5/15
Current I_{ph}, nom/pk	A	120/400
Torque T_{em}, nom/pk	Nm	35/125
C density J_{ph},nm/pk	A/mm^2	7.0/21.2

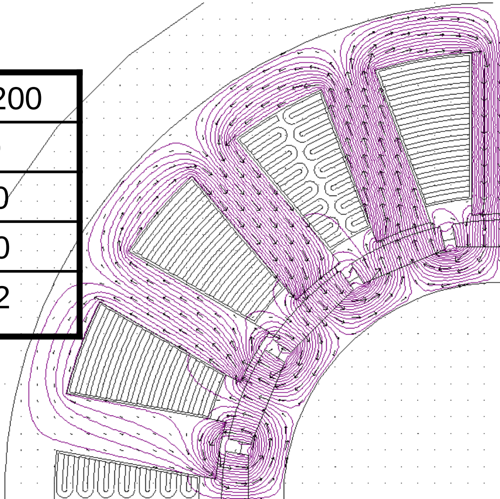


3φ Modular Segmented SPMSM

- Tangentially displaced laminated windings
- Existing machine with redesigned windings - Directly Cooled Laminated Fractional Pitch Windings



Stator size D_o/D_i-H	mm	240/136-200
Speed n, nom/pk	krpm	1.5/6.0
Current I_{ph}, nom/pk	A	116/300
Torque T_{em}, nom/pk	Nm	250/500
C density J_{ph},nm/pk	A/mm^2	7.0/18.2

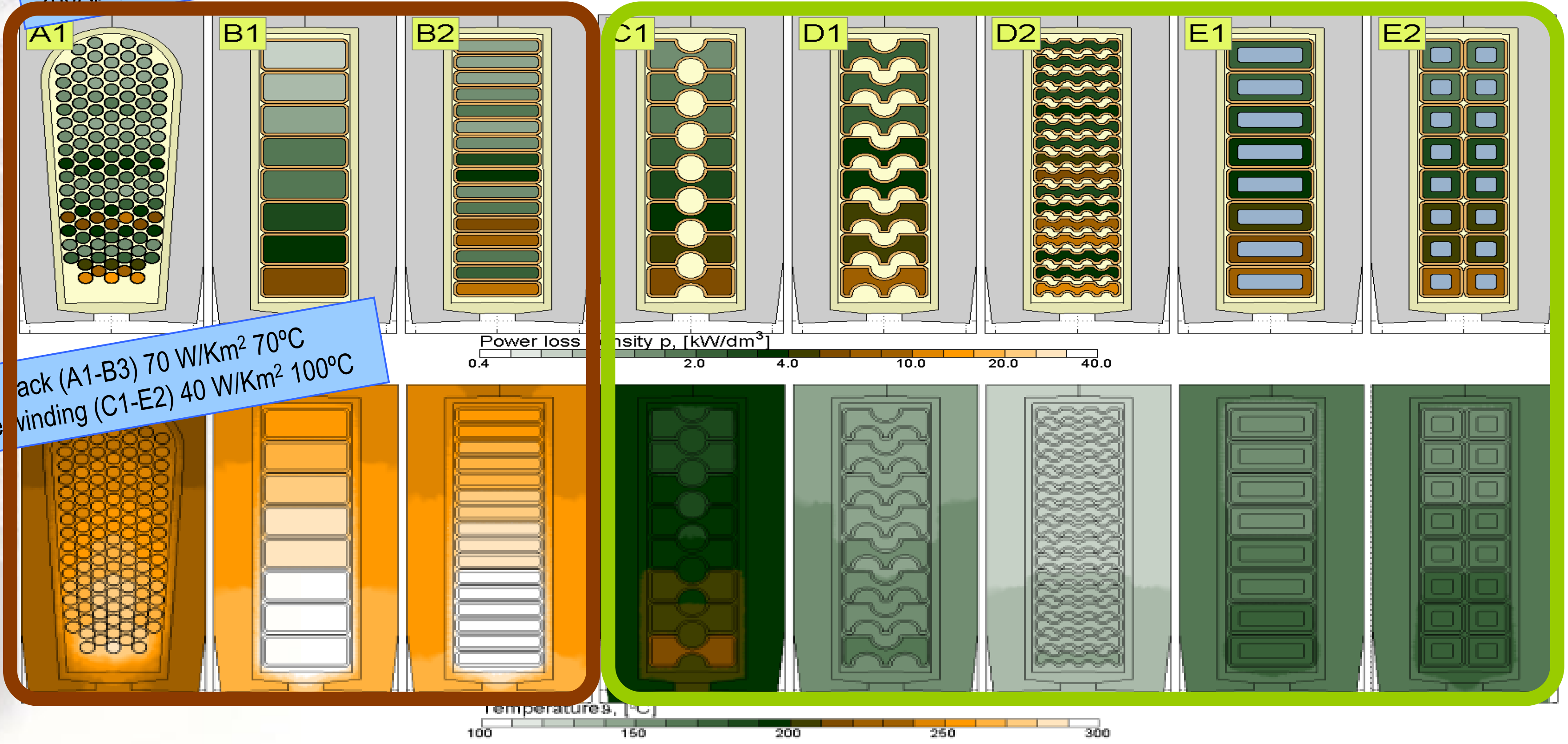


What we learned this far ...

- High current densities (>30 A/mm^2) can be balanced by forced air velocity (20-25 m/s) with hot-spot temperature limits (150-180 ºC).
- It is VERY hard to manufacture with maintained physical integrity.
- Additional losses due to stray fields near the air gap occur.

Alternative designs

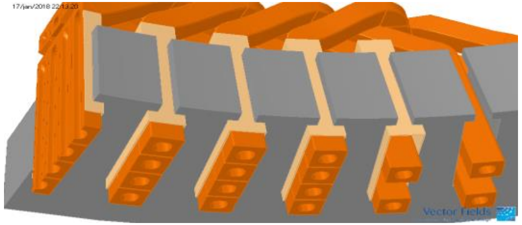
Nominal
200Apk, 300Hz

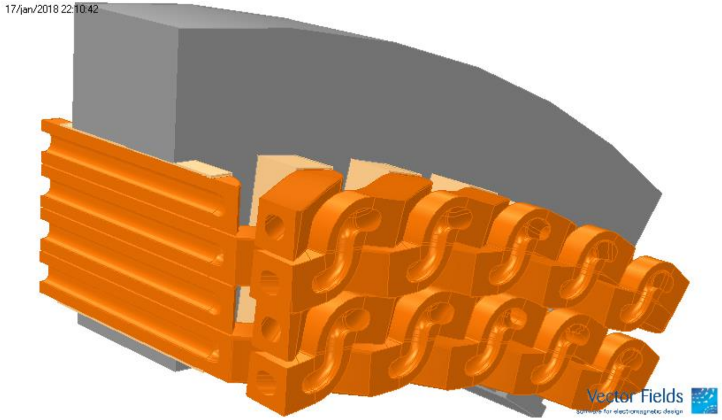


Stator back (A1-B3) 70 W/Km² 70°C
Inside winding (C1-E2) 40 W/Km² 100°C

Directly cooled hollow conductors

- Cooling integration in the machine conductors
- Less challenge with production tolerances and physical integrity
- Mechanical integration: end regions, inlet and outlet



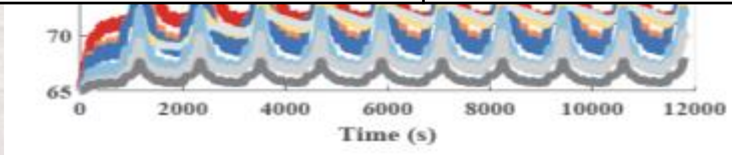


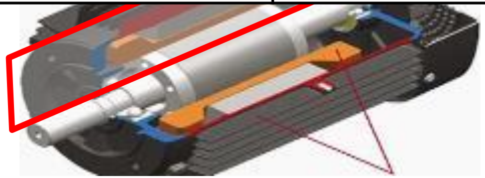
Degradation

- Degradation of the EIS
  - Degradation and failure of **electrical machine**
  - Degradation and failure of **electrified vehicle**
- TEAM stresses
  - Thermal
  - Electrical
  - Ambient
  - Mechanical

Dynamic temperatures

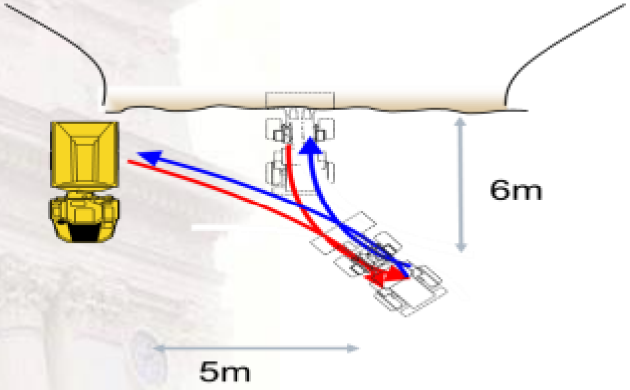
	Grid Fed **Industrial** Electrical Machine (EM)	**Industrial** EM on variable speed control	**Traction electrical machine**
Loading profile			
Temperatures			
Life expectancy			





(Plot above from Emma Arfa Grunditz, PhD thesis)

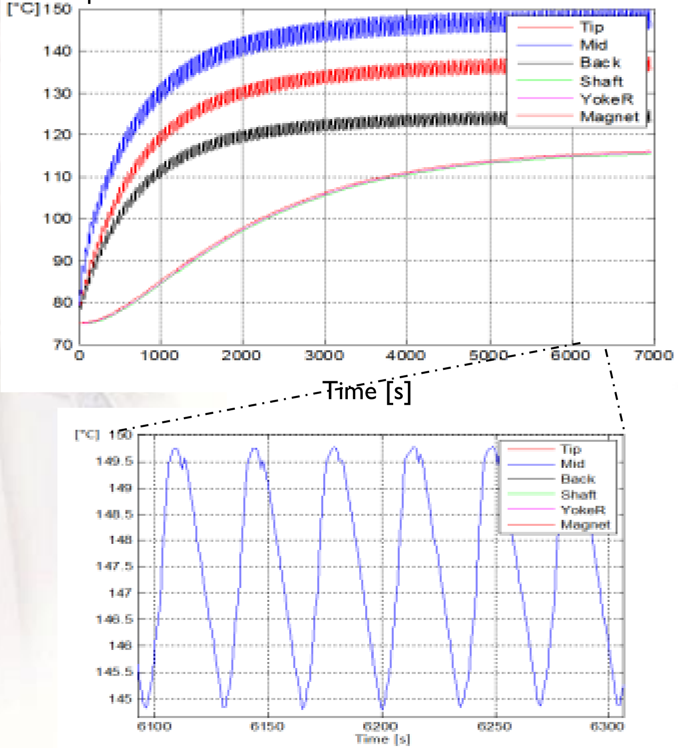
Application example – Wheel Loader



- Four wheel driven by electrical machines
- Short loading cycle (SLC)
  - Filling bucket
  - Leaving pile
  - Towards truck
  - Emptying bucket
  - Leaving truck
  - Toward pile

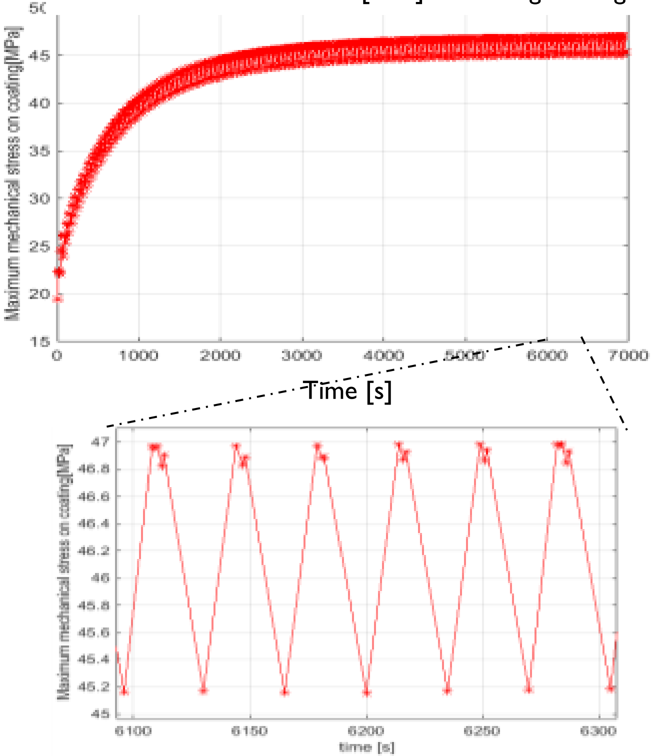
Traction Electrical machines temperatures after 200 Short Loading cycle (SLC)

Temperature distribution of traction electrical machine



Traction Electrical machines thermal-mechanical stress after 200 Short Loading cycle (SLC)

Thermal-mechanical stress [MPa] in winding coating

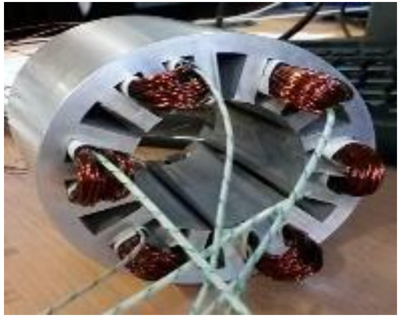


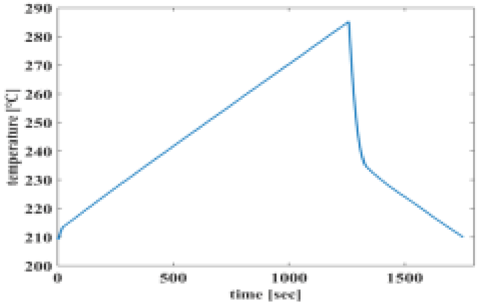
Other examples – thermal cycling

- Voitto Kokko, Fortum, ’Aging Due to Thermal Cycling by Power Regulation Cycles in Lifetime Estimation of Hydroelectric Generator Stator Windings’

Root cause	Distribution
Ageing by number of operation hours	15%
Ageing by thermal cycling	38%
Internal PD & defective corona protection	27%
Mechanical condition	8%
Vibration	8%
Contamination	4%

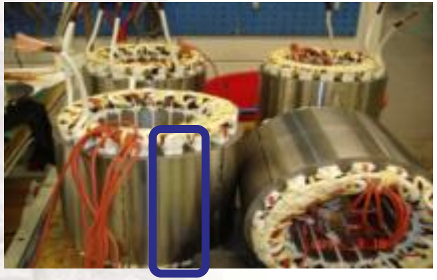
- C. Sciascera, University of Nottingham, ‘Lifetime Consumption and Degradation Analysis of the Winding Insulation of Electrical Machines’

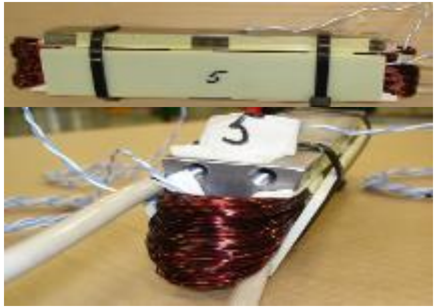


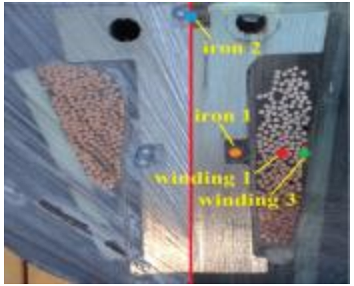


Expected lifetime: 713 hours,
Actual lifetime: 90 hours.

Motorrette/stator segment







Full stator

Motorrette/

Stator segment

Impregnation,

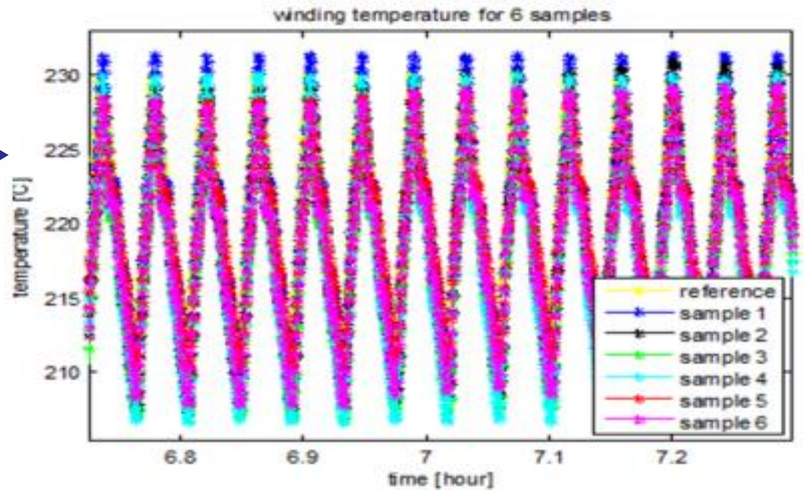
Thermal sensors

Thermal cycles – tested

- Table shows three tested cycles with 20˚C depth

Cycle No.	θ_{min} [°C]	θ_{max} [°C]	τ [s]
# 1	210	230	150
# 2	190	210	250
# 3	180	200	250

- Plot of measured hot spot temperatures (cycle #1)



Lifetime – simulated VS measured

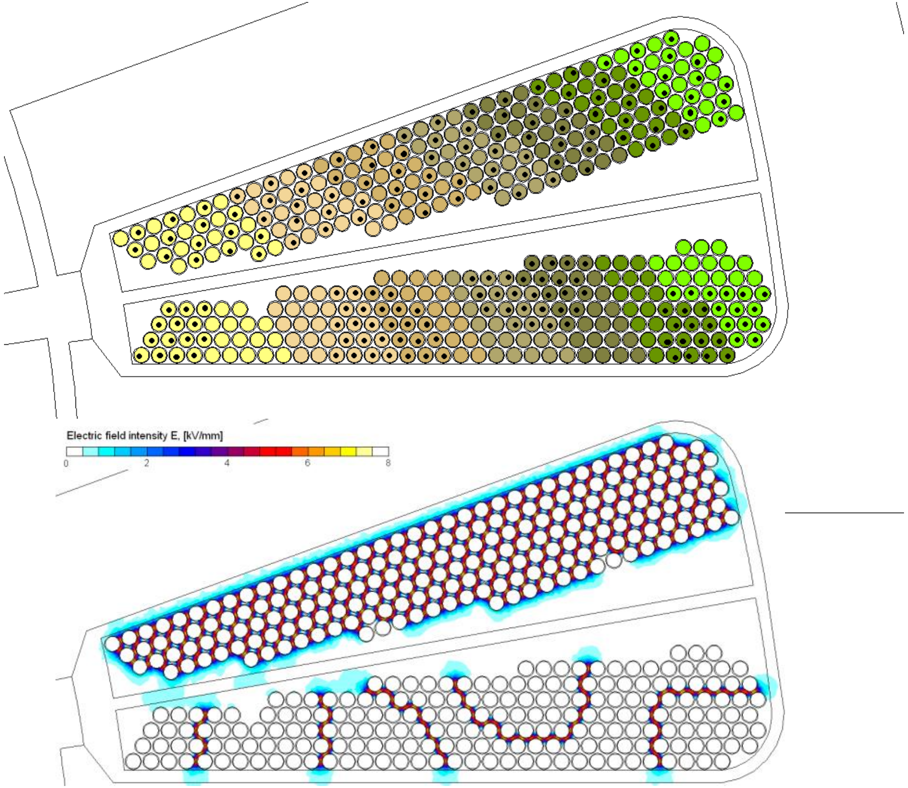
Thermal cycles and corresponding lifetime

Test No.	θ_{cycle} [°C]	LT 1 [hour]	LT 2 [hour]	LT 3 [hour]	tested [hour]
#1	210-230	4255	949	30	<47
#2	190-210	24999	4256	119	150-180
#3	180-200	64172	9456	192	250-290

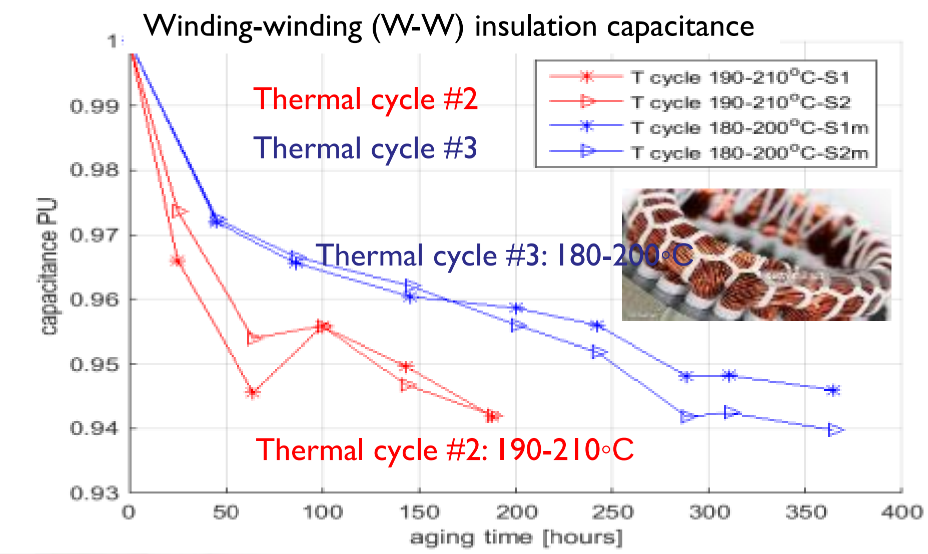
- Arrhenius law model over-estimates the lifetime.
- High fatigue model can more accurately predict the lifetime of EIS, when they are exposed to these thermal cycles.
- The high temperature oxidation is not the only degradation mechanism.
- Thermal-mechanical fatigue is one of the degradation mechanisms, which cannot be overlooked.

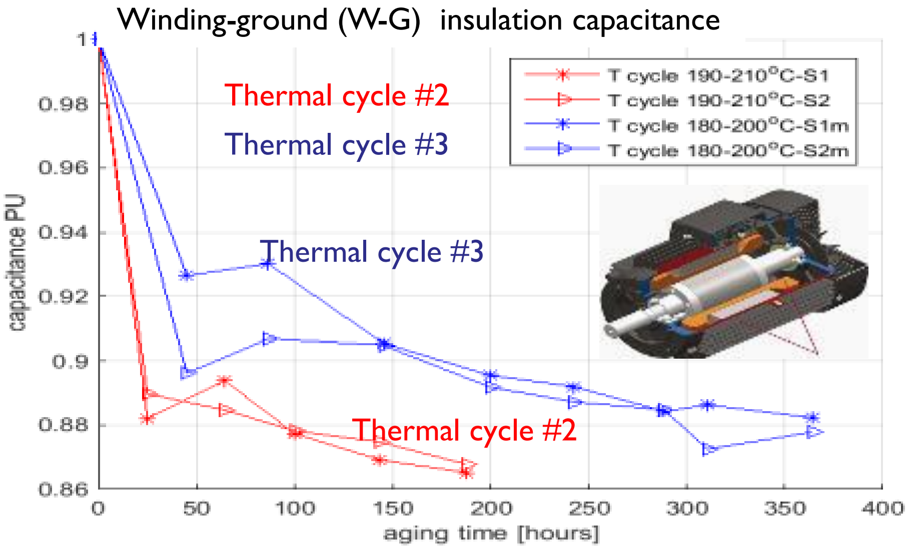
Condition monitoring – concept

- 7 turns with two groups of parallel strands, kept separate or mixed
- Winding-Winding and Winding-Core capacitance measured as a function of thermal cycle ageing



Insulation capacitance

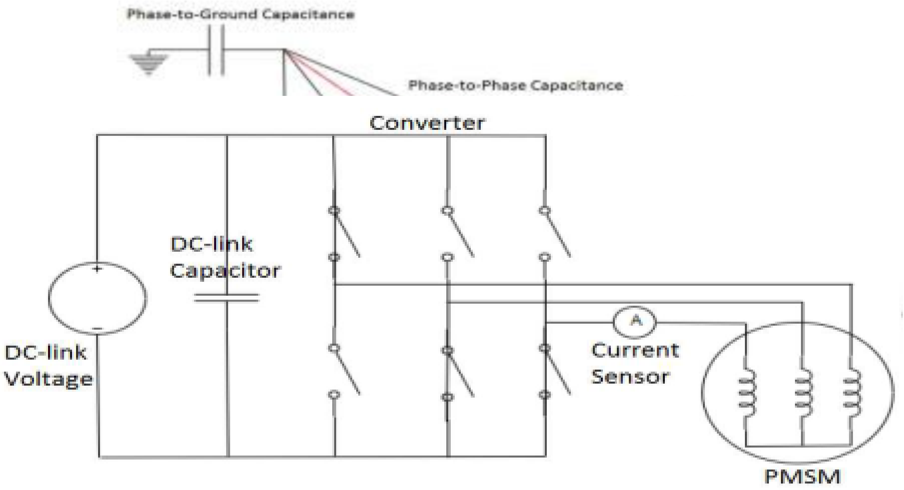


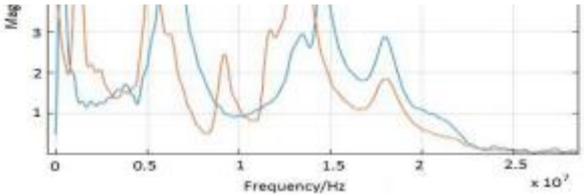


- Thermal cycle #2 190~210° C: **5% to 6% (W-W)** and **12 to 14% (W-G)** drop
- Thermal cycle #3 180~200° C : **4% to 6% (W-W)** and **11 to 12% (W-G)** drop

On board condition monitoring

- Use the clear changes of insulation capacitance during aging
- Measure e.g. the winding-core capacitances development over time
- Use the power electronic controller on a vehicle;
- By changing between two switching patterns, a voltage pulse over windings is formed;
- High frequency current is measured;
- Migration of amplitude and frequency of the current → parasitic capacitance → the state of health of machine





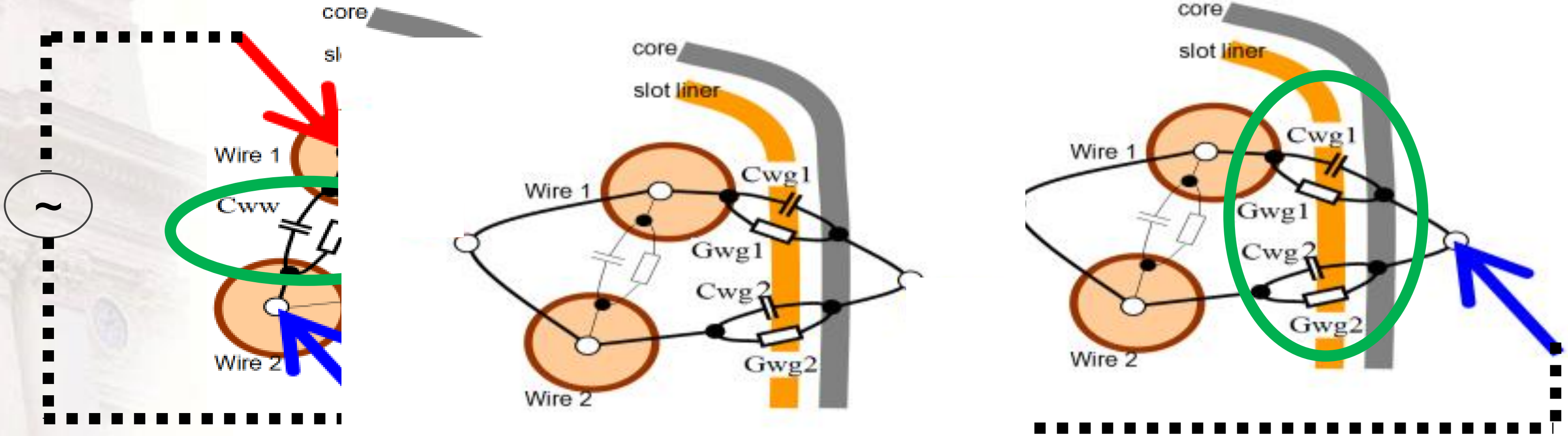
Conclusions

- Traction machines generally sized for a certain overloading
- Efficient direct winding cooling may change overloading conditions and thus sizing

- Thermal cycling drives ageing
- Efficient direct winding cooling may limit thermal cycling and thus extend lifetime

- Parameter measurement for condition monitoring promising technology

Condition monitoring – concept



Winding-winding

Winding-core