



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)

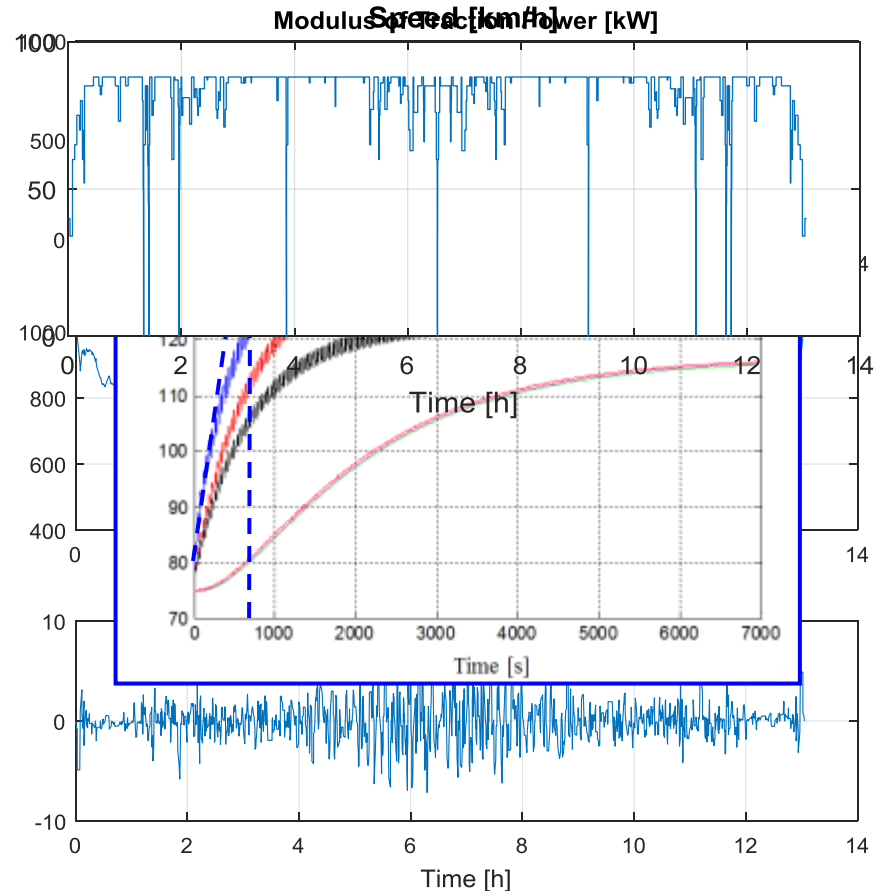
Heavy Duty Trucks

- 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?



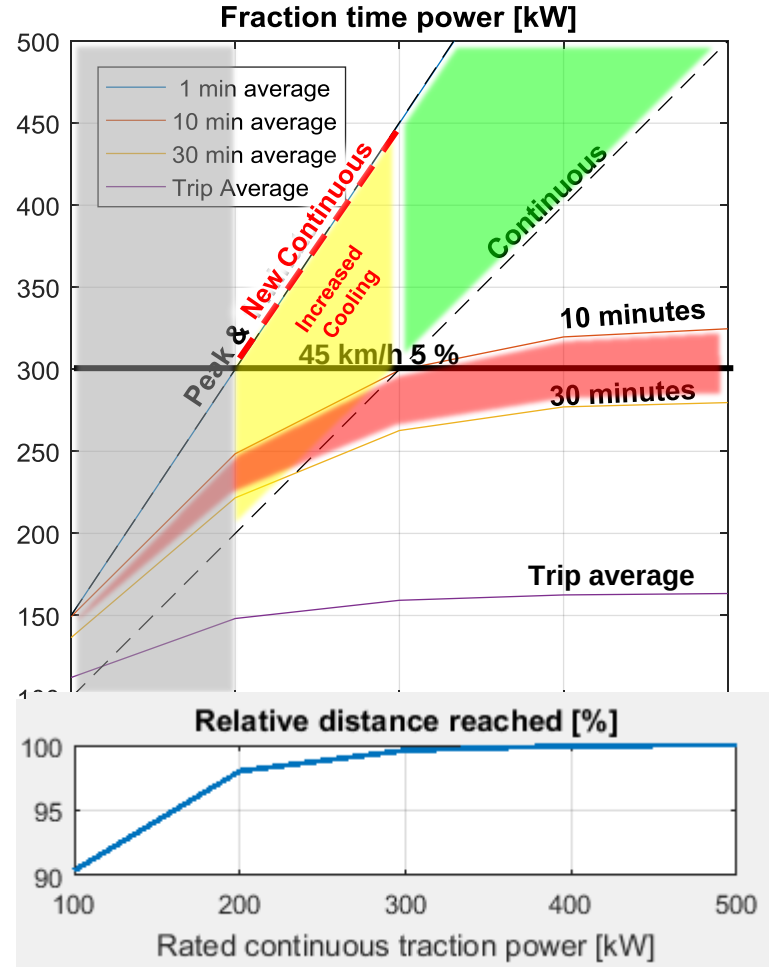
Full Electric Heavy Duty Trucks

- 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

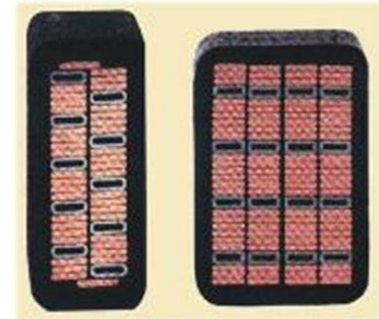
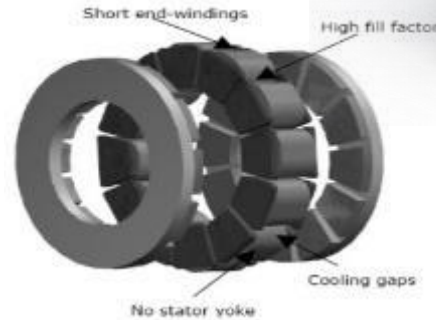


Increased Cooling ...?

- Air cooling outside
- Water sleeve cooling
- Oil cooling, also on end winding and maybe inside rotor
- Oil cooling directly on the windings
- Cooling inside the stator windings
- Cooling inside the stator conductors

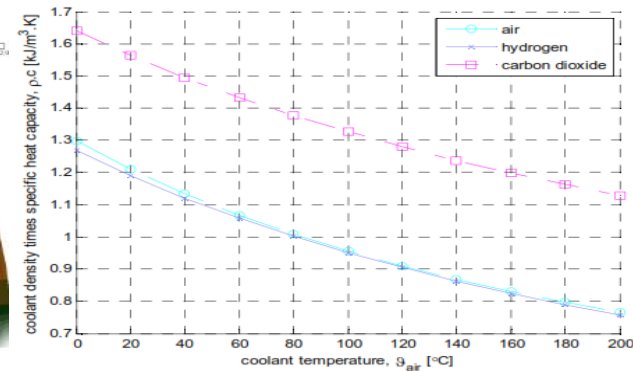
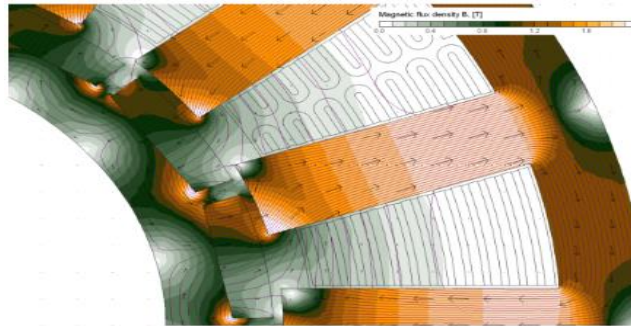
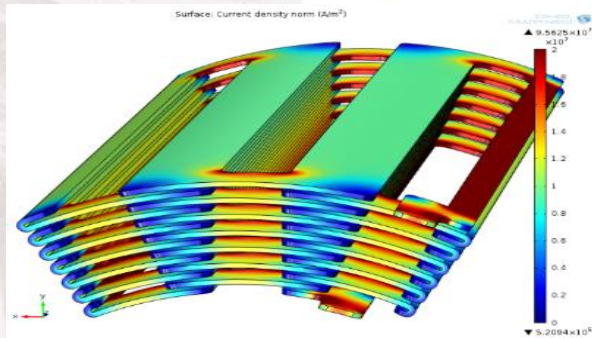
Peak Power determined by
thermal capacitance

Peak Power determined by
direct winding cooling
capability



First idéa: - The laminated winding

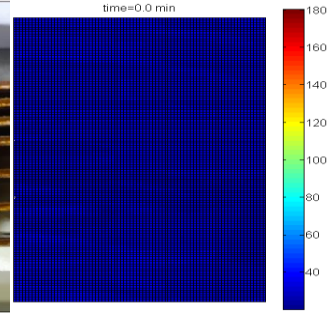
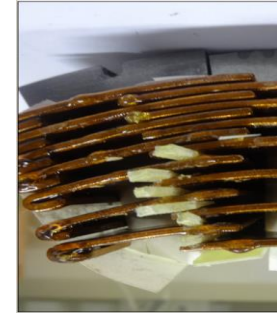
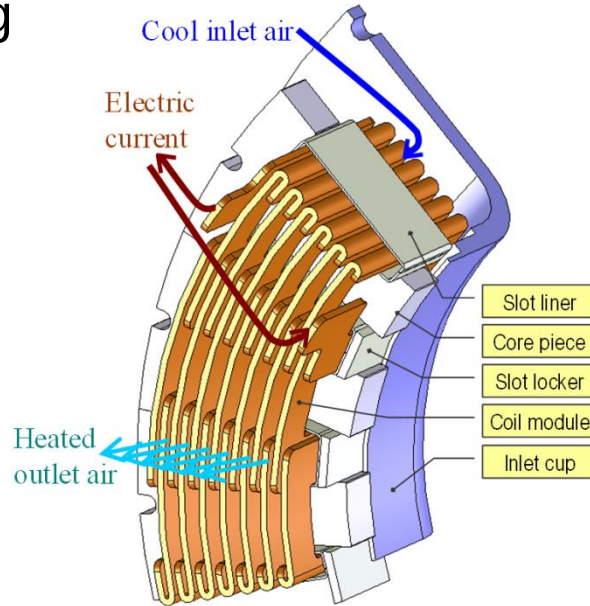
- Suitable cooling media ?
- Air a reasonable compromise



	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	

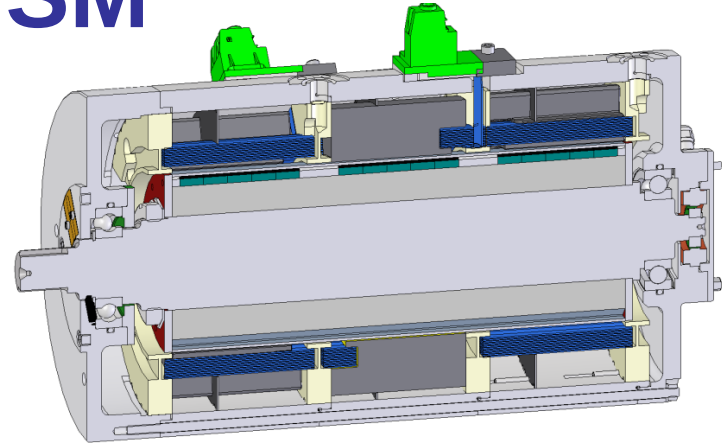
Directly cooled laminated windings

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

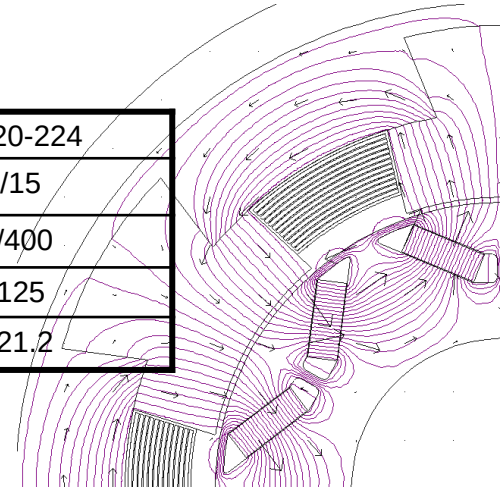


3 ϕ Axially Stacked IPMSM

- 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

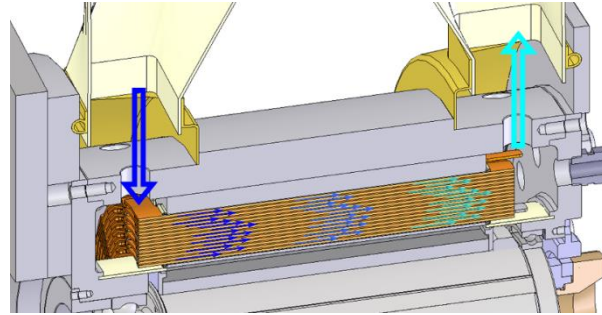


Stator size D_o/D_i-H	mm	200/120-224
Speed n , nom/pk	krpm	7.5/15
Current I_{ph} , nom/pk	A	120/400
<u>Torque</u> T_{em} , nom/pk	Nm	35/125
C density J_{ph} , nm/pk	A/mm ²	7.0/21.2

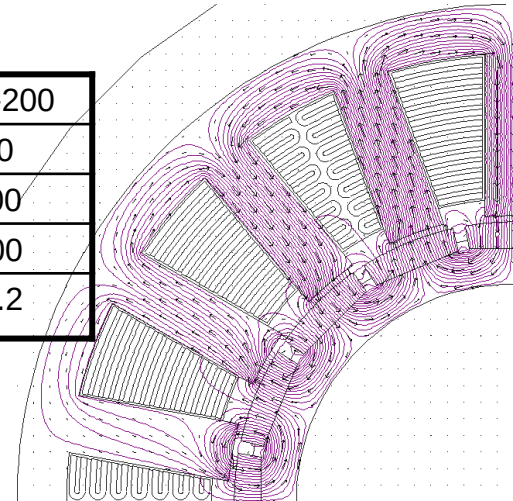


3 ϕ Modular Segmented SPMSM

- **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
<u>Current</u> I_{ph} , nom/pk	A	116/300
<u>Torque</u> T_{em} , nom/pk	Nm	250/500
C density J_{ph} , nm/pk	A/mm ²	7.0/18.2

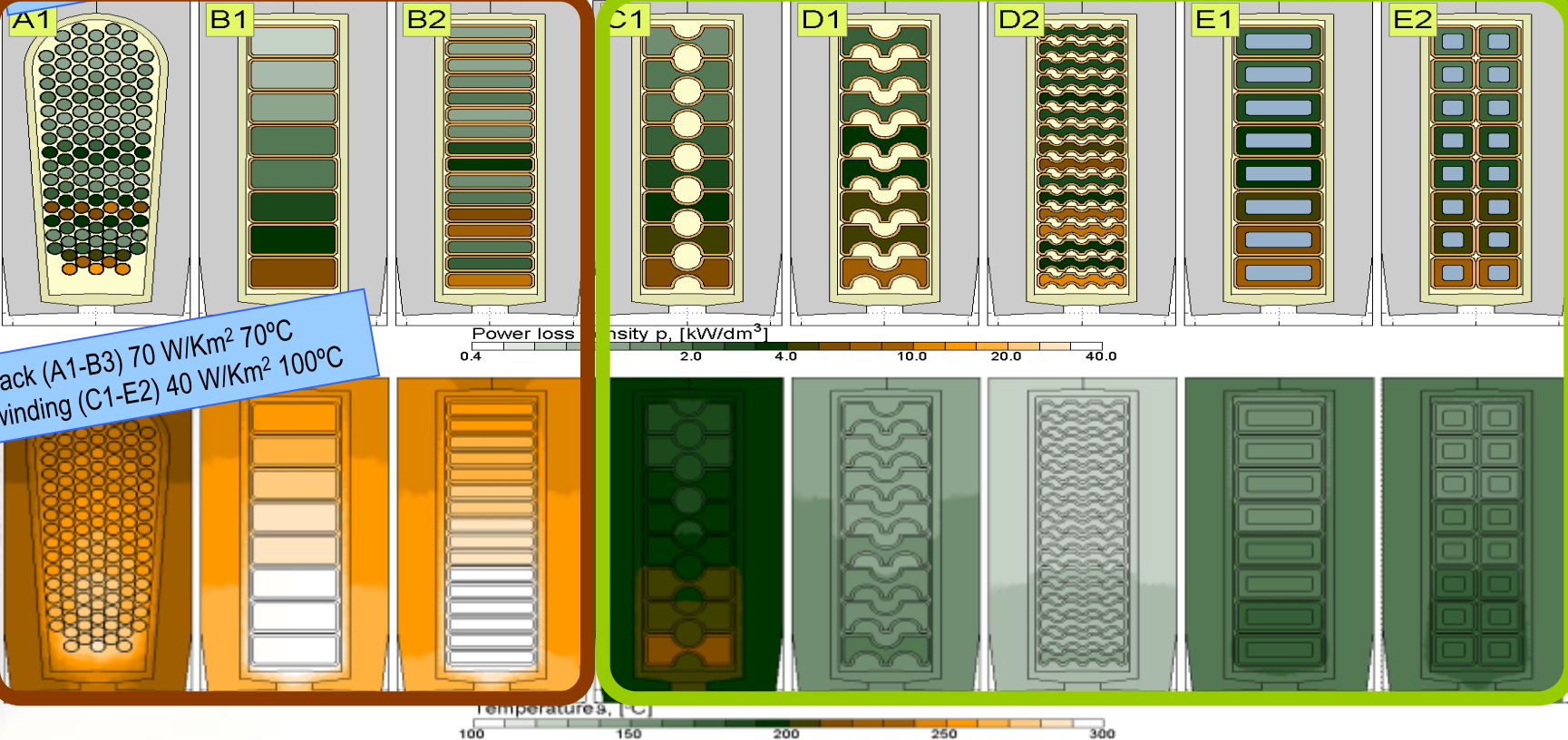


What we learned this far ...

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

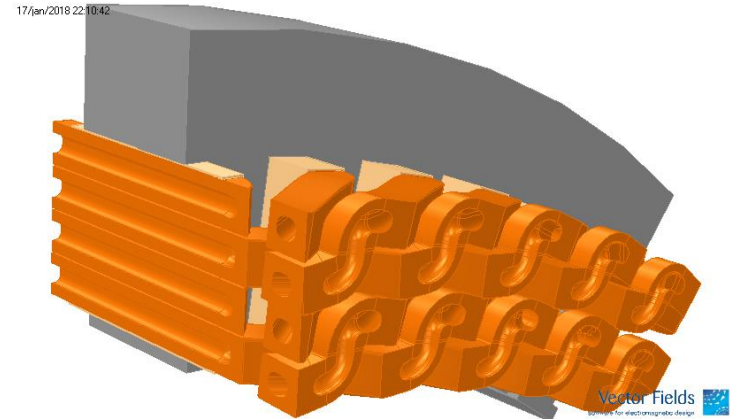
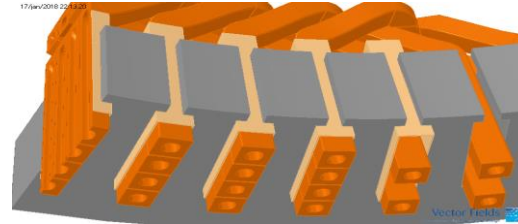
Alternative designs

Nominal
200Apk, 300Hz



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



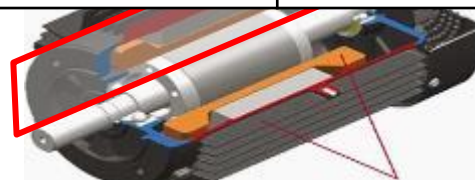
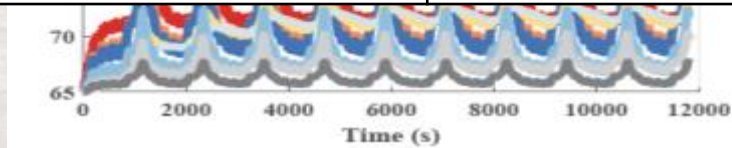
Degradation



- 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)

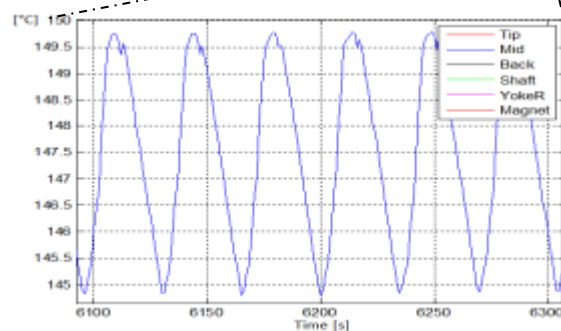
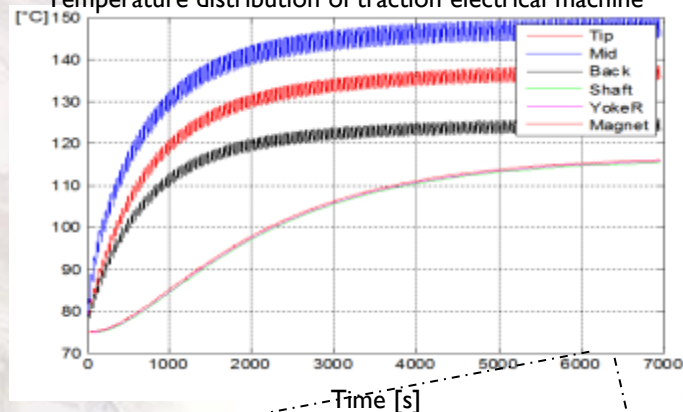
Application example – Wheel Loader



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

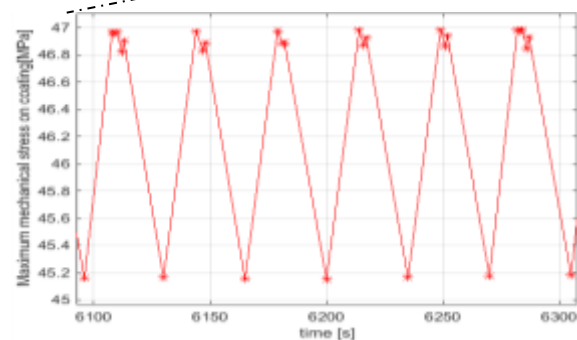
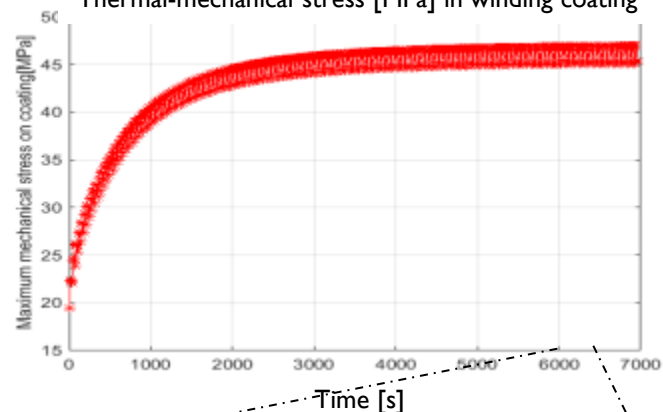
Traction Electrical machines temperatures after 200 Short Loading cycle (SLC)

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

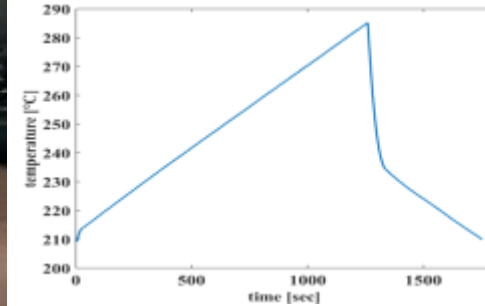


Other examples – thermal cycling

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



- 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.

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%

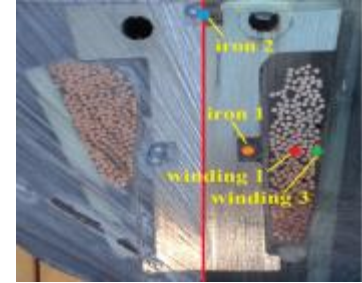
Motorrette/stator segment



Full stator



Motorrette/
Stator segment

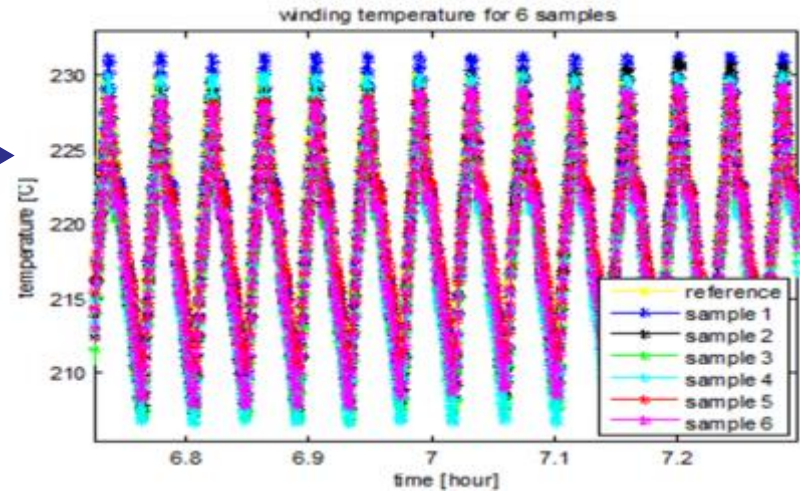


Impregnation,
Thermal sensors

Thermal cycles – tested

- Table shows three tested cycles with 20° C depth
- Plot of measured hot spot temperatures (cycle #1)

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



Lifetime – simulated VS measured

Thermal cycles and corresponding lifetime

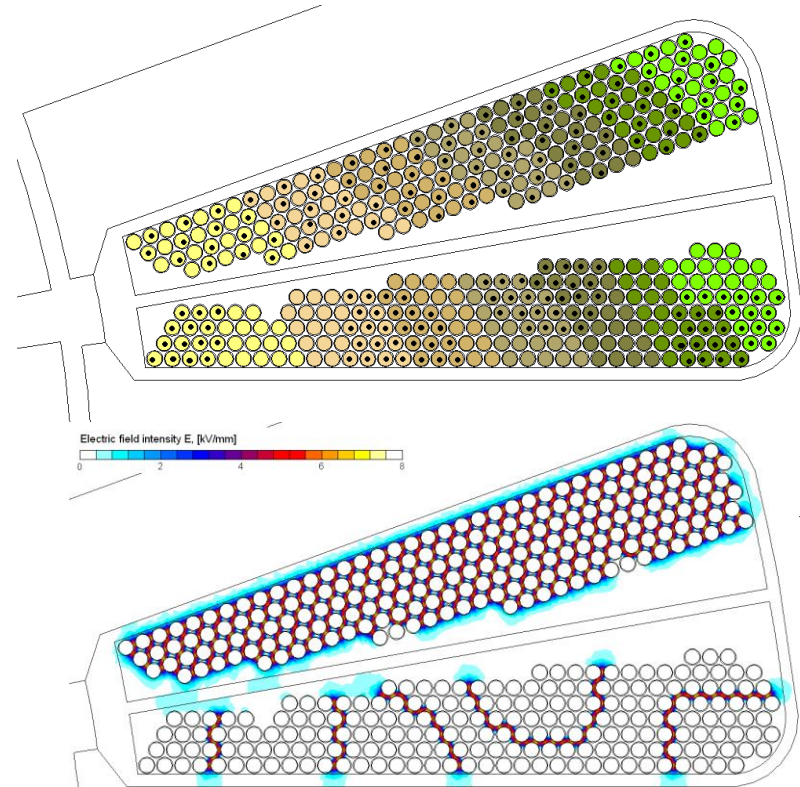
Test No.	θ_{cycle} [°C]	LT 1 [hour]	LT 2 [hour]	LT 3 [hour]	tested [hour]
#1	210-230	4255	949	30	<47
#2	190-210	24999	4256	119	150-180
#3	180-200	64172	9456	192	250-290

- 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

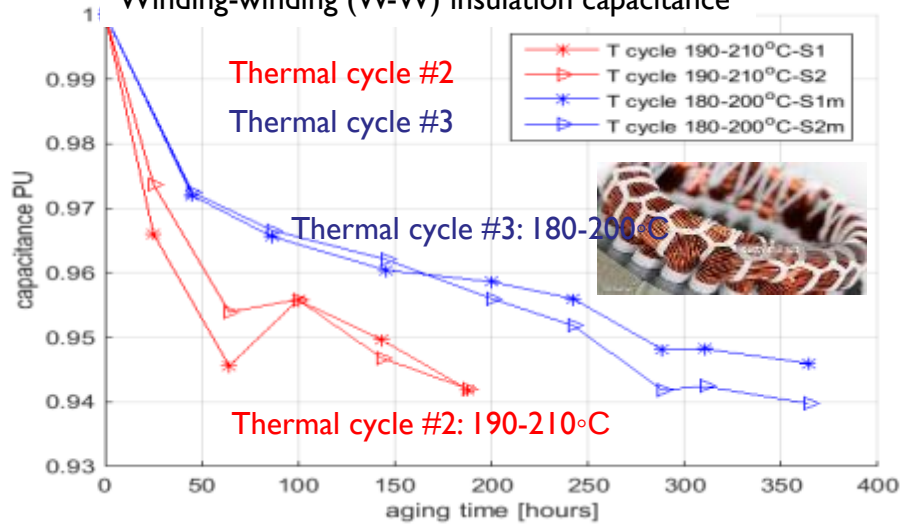


- 7 turns with two groups of parallel strands, kept separate or mixed
- Winding-Winding and Winding-Core capacitance measured as a function of thermal cycle ageing

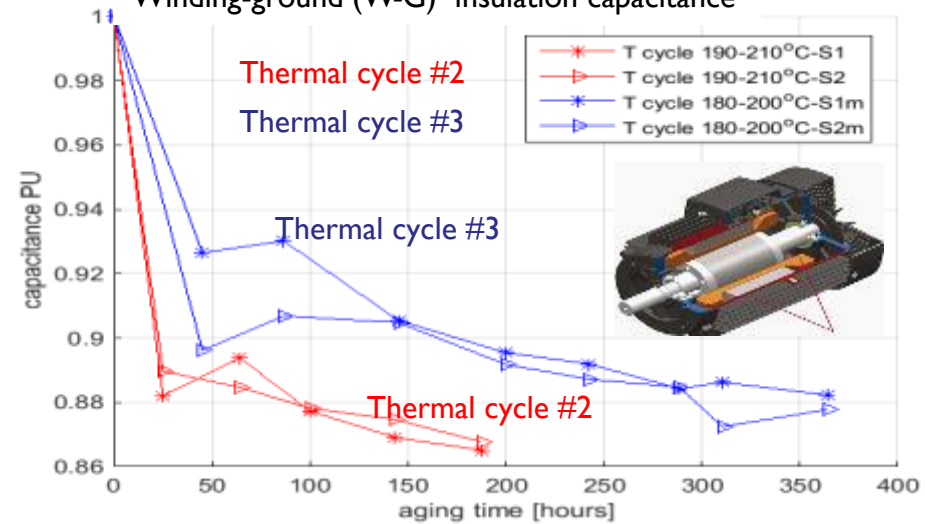


Insulation capacitance

Winding-winding (W-W) insulation capacitance



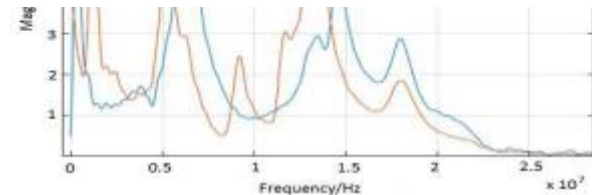
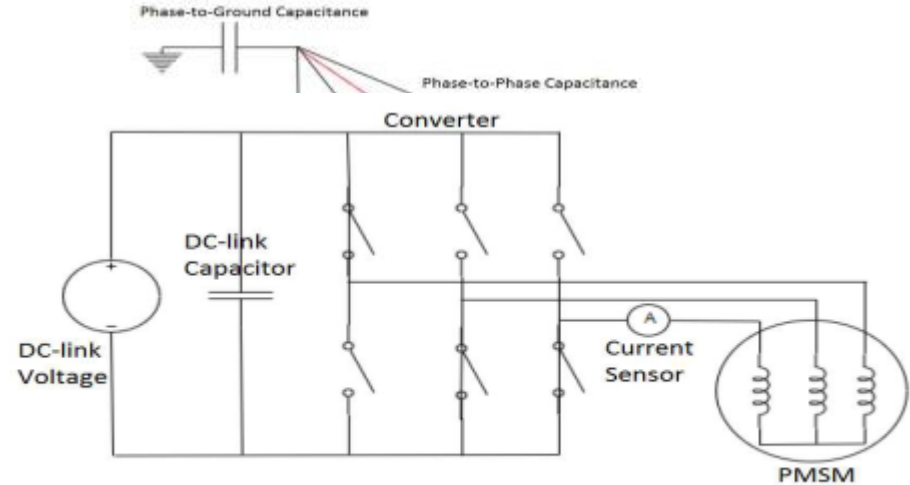
Winding-ground (W-G) insulation capacitance



- 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 $\rightarrow$ parasitic capacitance $\rightarrow$ the state of health of machine

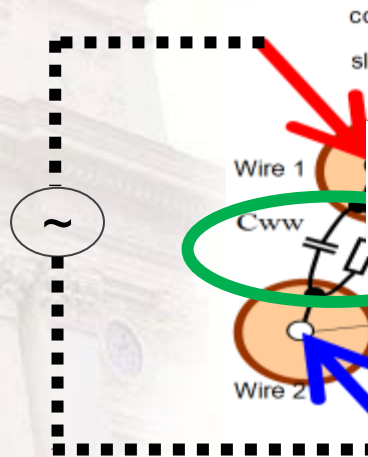


Conclusions

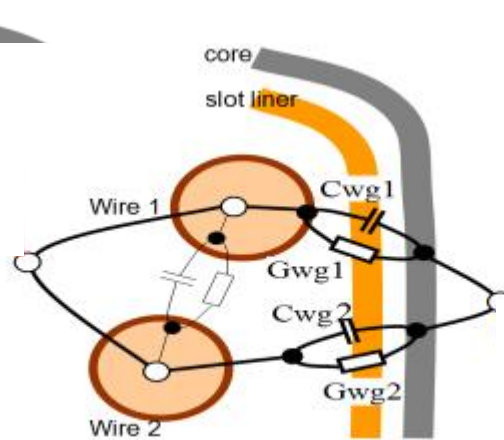
- Traction machines generally sized for a certain overloading
- Efficient direct winding cooling may change overloading conditions and thus sizing
- Thermal cycling drives ageing
- Efficient direct winding cooling may limit thermal cycling and thus extend lifetime
- Parameter measurement for condition monitoring promising technology



Condition monitoring – concept



Winding-winding



Winding-core

