Design of High-Performance Electric Motors

Numerical Modeling of Electrical Machines, Tampere University

Guest lecture, 2.12.

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Contents

- What is ’high performance’?
- Technology landscape
  - Businesses on the field
  - Trends and developments
- Windings
  - Why they are important
  - Losses and modelling
- Optimization
  - Basics

- Will prolly skip some material: plz reach out to antti@smeklab.com

Researcher Background

Antti Lehikoinen

- D.Sc. from Aalto University, 2017
- Consulting engineer & founder at Smeklab Ltd, 2017-
- EV, aviation, and high-speed motors
- FEA software development
  - EMDtool Matlab toolbox, pics →
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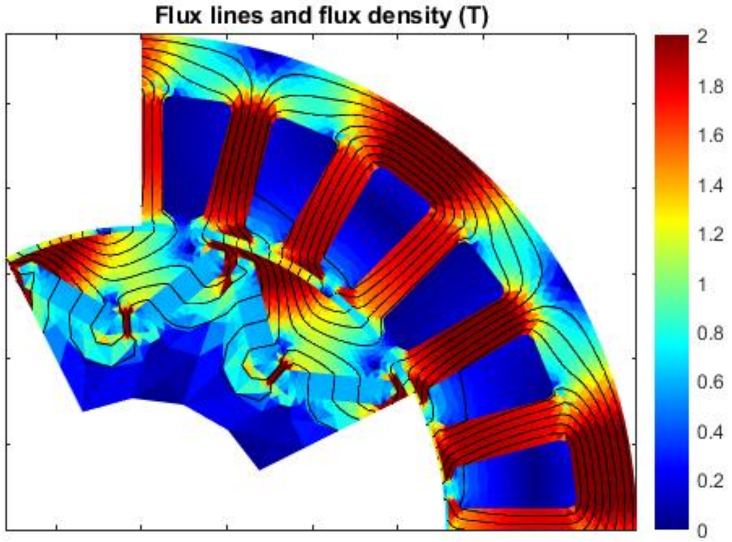
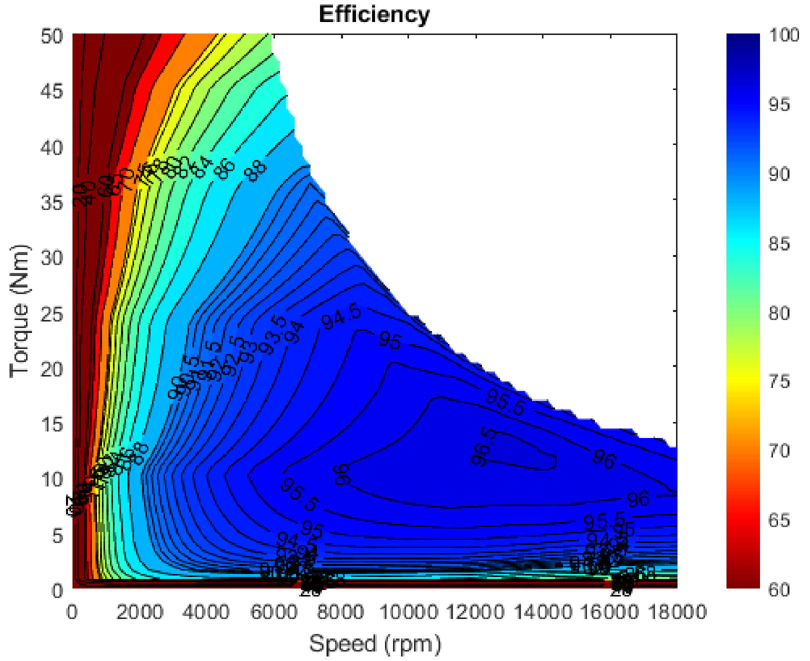




What is ’high performance’?

This lecture POV

High-Performance Motors?

- Subjective term
- Focus on this lecture: motors for electric vehicles (EV) and aviation
- Defining characteristics
  - High power density: kW/kg and kW/l
  - High torque density
  - High efficiency
  - Compact size

High-Performance Motors

Available today:

- Power density: 5-15 kW / kg, nowadays
  - Gasoline engines typically 0.1 – 2 kW / kg or so
- Future targets (for aviation) up to 20-50 kW/kg

- Torque density
  - Up to 110 Nm/l of *rotor/airgap* volume

Technology Landscape

Thoughts and experiences

For informational purposes only, you should not construe any such information or other material as legal, tax, investment, financial, or other advice yada yada ☺

Business landscape

- Motors for electric vehicles and aviation are *not* standardized off-the-shelf components
  - Not like many industrial motors: pumps, blowers, fans, mills, etc.
  - Room for startups and smaller innovators
- Two main development categories:
  - For sales
  - For own products

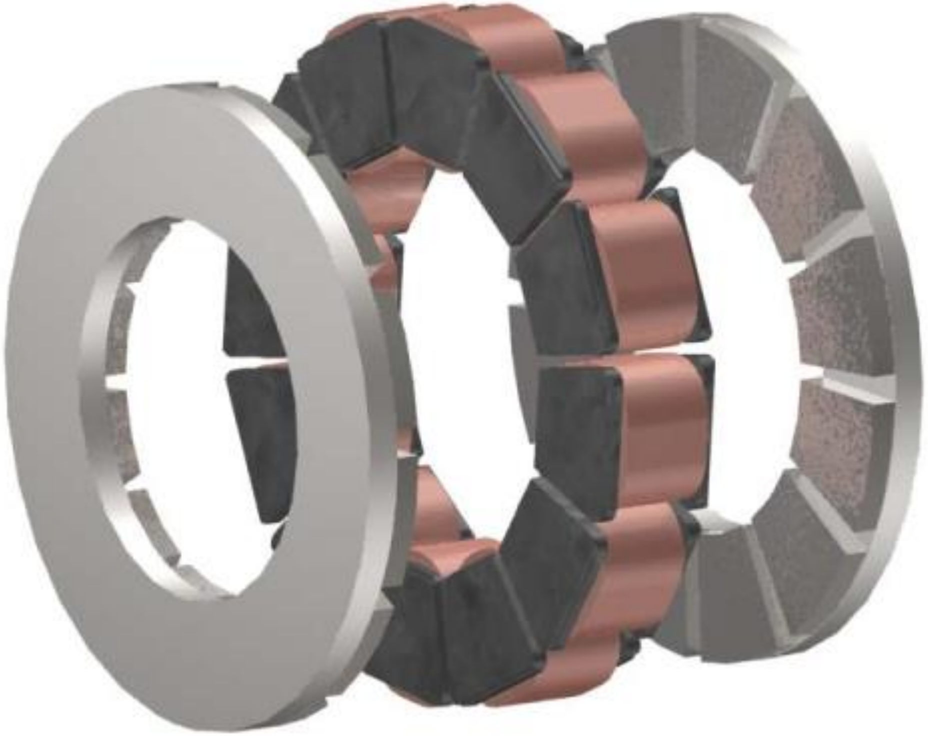
Motor-as-product

EV examples:

- YASA
  - Classic, yokeless and segmented armature axial flux machine
- Magnax
  - Also of YASA-topology

Aviation examples:

- MagniX
- H3X



YASA topology.
https://www.greencarcongress.com/2010/09/oxford-yasa-motors-shows-specific-torque-above-30nmkgyasa-20100928.html

Motor-for-product

- Many EV companies choose to develop their own motors
  - All big players, practically
  - Also many small/niche products
    - Cannot find suitable product on market
    - Want their own IP
- Note: ’EVs’ $\gg$ 4-wheel passenger cars
  - 2-wheelers: e-bikes, e-motorcycles
  - 3-wheelers; prominant in SE Asia
  - Last-mile-delivery vehicles: huge market (apparently), desire for low maintenance
  - Trucks
  - Mining vehicles

Trends

- New semiconductors
  - SiC, GaN
  - Higher switching frequencies
- Increasing rpms and fundamental frequencies
  - Increasing rpm helps increase power density
  - Increasing pole-count helps somewhat with power density

Trends in Aviation

Ambitious programs and goals for electric aviation

- Short-haul fully electric flight (~1000 km) perhaps viable in half a decade
- Hybrid schemes for longer flights
  - Boundary layer ingestion
  - Distributed propulsion
- Technology projections and programs
  - By NASA and similar
  - E.g. ASCEND: MW-level concept @ 12 kW/kg & 97% *combined* motor+inverter+thermal management
- Urban air taxis and similar

Lilium uEV concept.
https://www.electrive.com/2020/03/23/lilium-closes-financing-round-with-240-million/

Windings

Design, Cooling, and Analysis

Importance of windings

- Power from Lorentz force:

$$P = v \cdot F = v \cdot B \cdot lI = v \cdot B \cdot l \cdot J A_{\text{copper}}$$

Implications:

- *B* = flux density = cannot be increased much
  - Iron saturation
  - Ironless superconducting machines *might* help in the future
- *v* = surface speed of rotor
  - ~diameter x rpm
  - Can – and continuously is – increased *somewhat*
  - Space / gearbox requirements
  - Mechanical design difficulties: stresses and resonances

Importance of windings

$$P = v \cdot F \sim v \cdot B \cdot lI = v \cdot B \cdot l \cdot J A_{\text{copper}}$$

- Increasing current density *J* and copper area → most scalable way of increasing power

Current density: Being pushed higher

- DC-resistive losses:

$$W_{DC} \sim \rho l A_{\text{copper}} J^2$$

- Efficiency

$$\eta = \frac{P}{P + \text{losses}} \sim \frac{vJBlA_{\text{copper}}}{vJBlA_{\text{copper}} + rJ^2 + W_{iron}}$$

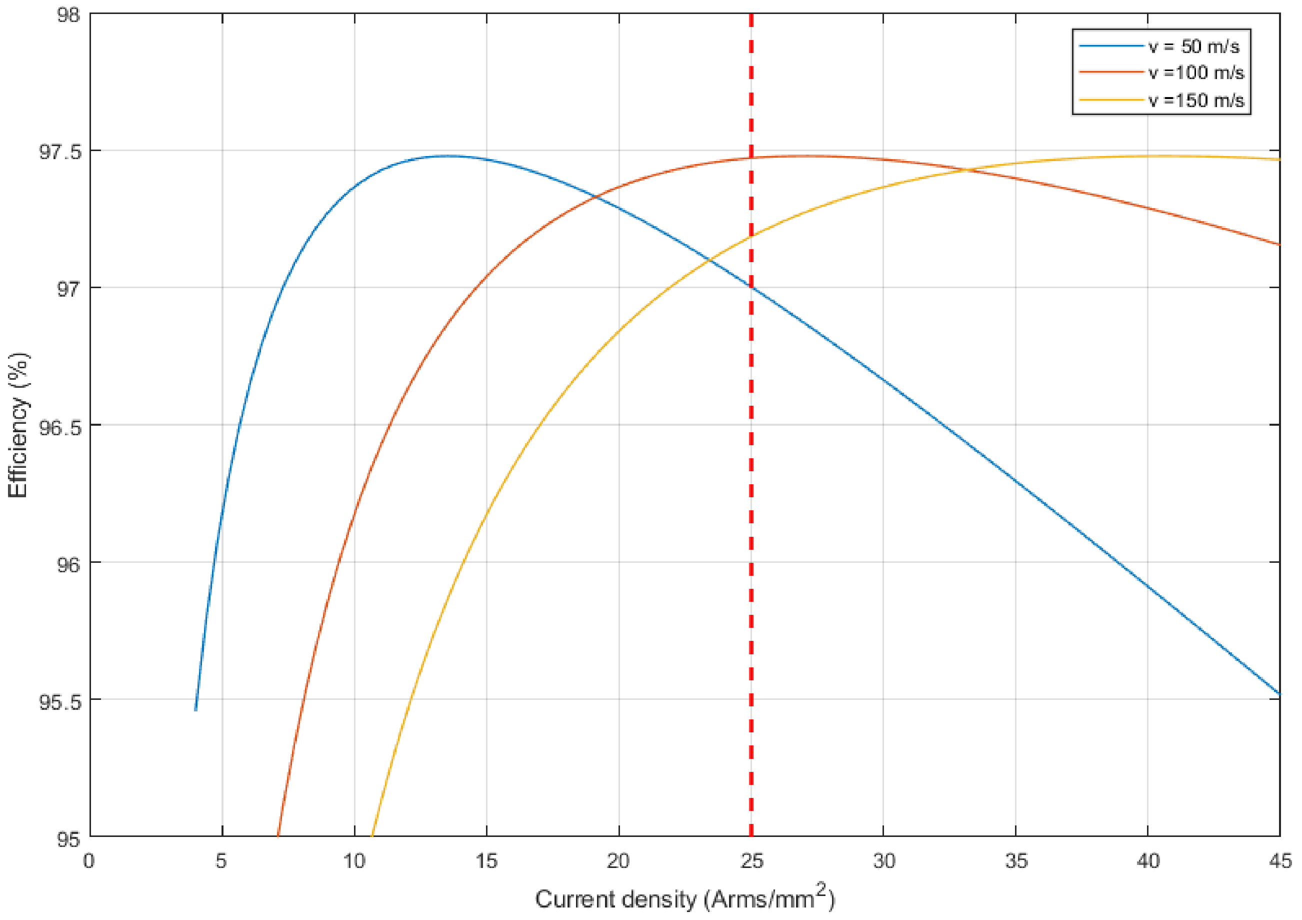
  - Iron losses proportional to ~speed…speed^2

→Increasing surfaces speeds allow higher current densities

  - Without sacrificing efficiency
  - Increased power density, harder cooling

Current density: Being pushed higher

- Pen-and-paper calculation
- Rules-of-thumb:
  - 5 Arms / mm^2 : air-cooled motors
  - 15 Arms / mm^2 : water jacket
  - 25 Arms / mm^2 : 1-3 cooling channels per slot
  - 30-100 Arms / mm^2 : direct wire-to-coolant contact



Windings: AC losses

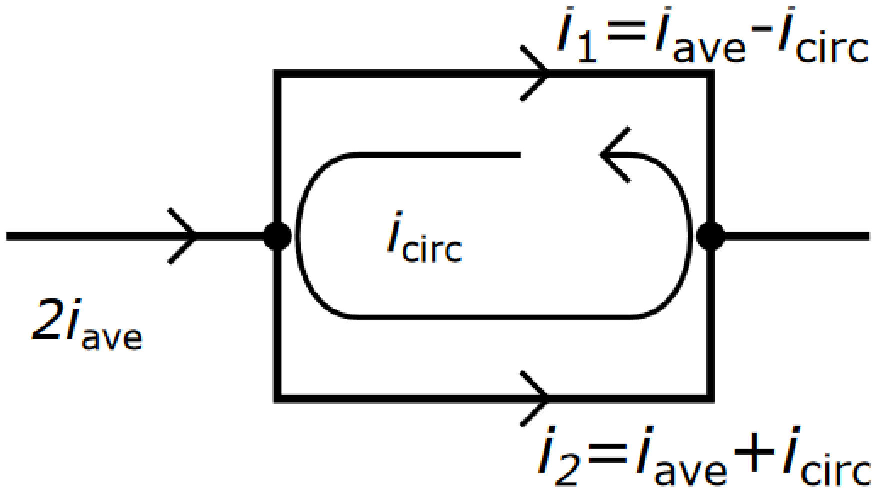
- Increasing frequencies:
  - Increased surface speeds
  - Increased pole count → reduces yoke mass, increases airgap diameter
  - New semiconductors (SiC, GaN) an enabling tech
  - ~ 1 kHz in traction motors, tops
  - 2-4 kHz researched for aviation

→ AC losses in windings become important

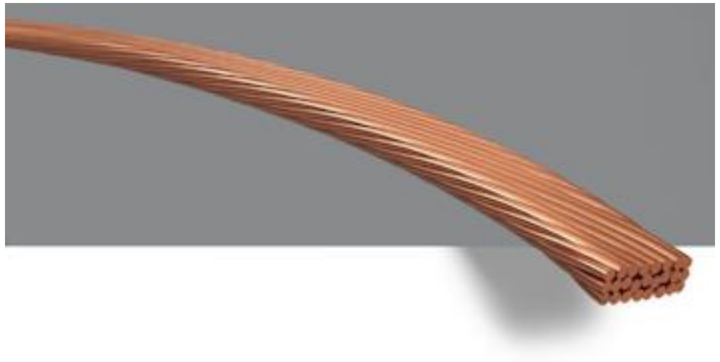
Windings: AC losses

Two components:

- Eddy-current effects
  - Non-uniform *J* inside each conductor
  - Mitigation: thin strands in parallel
- Circulating currents
  - Un-equal total currents in parallel strands
    - Different leakage flux seen by each strand
  - Mitigation:
    - Litz wire
    - Continuously transposed conductors
    - ’Braided’ end-windings

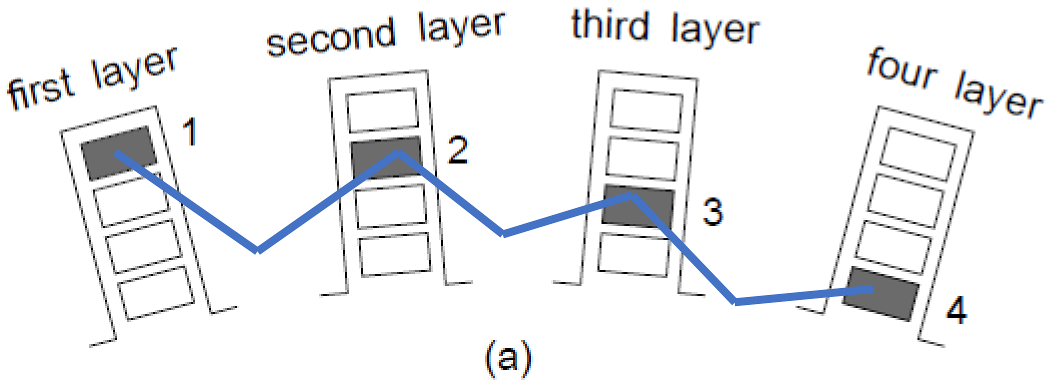


Windings: AC losses



Litz wire. https://www.elektrisola.com/hf-litz-wire-litz/products/profiling.html

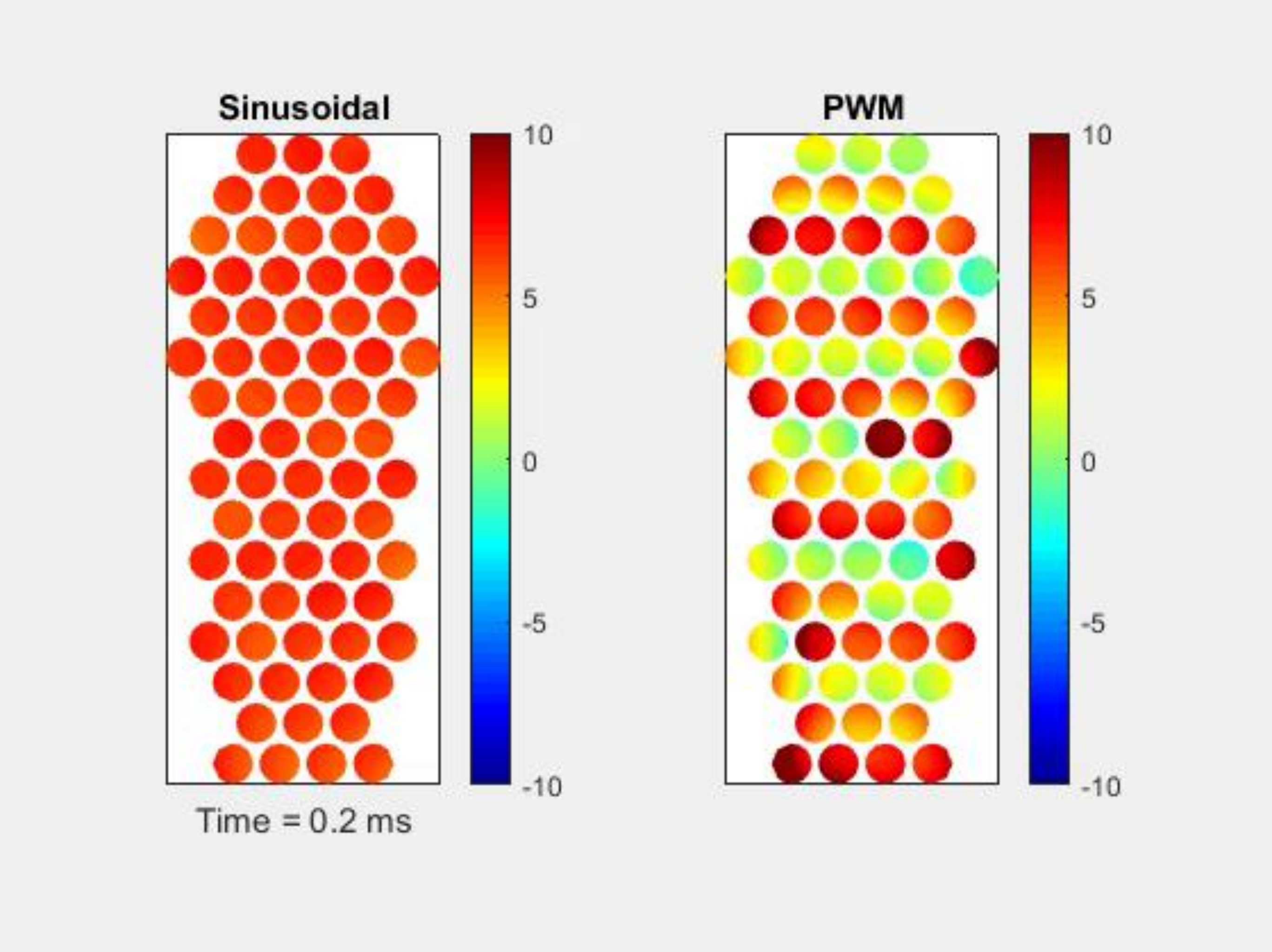
Continuously transposed conductor.
https://static1.squarespace.com/static/5bb2324501232ca58974d603/t/5c6a9a3e6e9a7f0b4e3b6e8a/1550490177542/Continuously+Transposed+Conductor+CTC+catalogue.pdf



End-winding transpositions in hairpin winding, modified.
Analytical Approach to Design Hairpin Windings in High Performance Electric Vehicle Motors

Current density in slot

- Poorly-designed induction motor
- 6 turns per slot
    - ~ 12 parallel strands
- Obvious differences in current density *and* total current in each strand
- Losses compounded by PWM supply



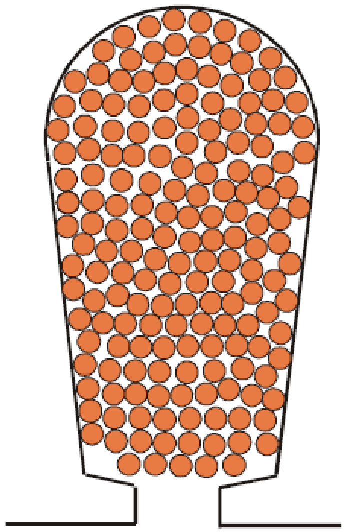
AC loss computation

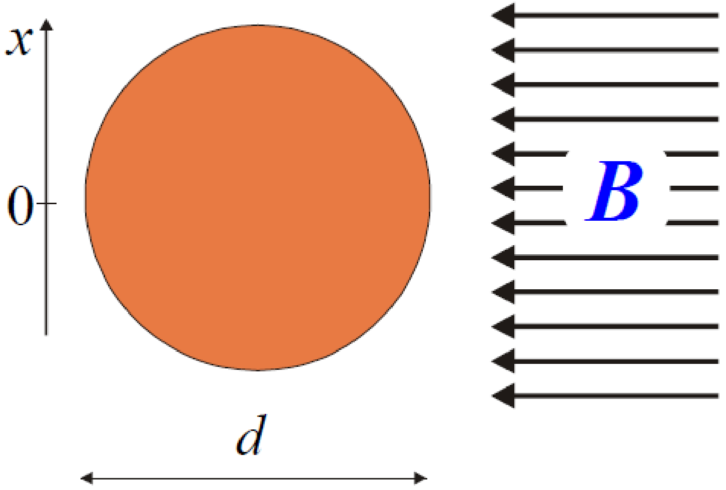
Options:

- Full finite-element solution
  - Each conductor a solid meshed body
  - AVI formulation
  - Accurate but time-consuming
- Post-processing approaches
  - Conductors simulated as uniform current density sources
  - Eddy-effects estimated in post-processing, circulating currents ignored
- Advanced approaches
  - Homogenization (see papers from Gyselinck)
  - Point-conductor models for circulating currents (yours truly)
  - Macro-element model
    - Full AVI model, but x10s faster
    - Yours truly

AC loss - Postprocessing

- Post-processing: squared-field derivative approach
- Source: Special Course on Electromechanics 2016, Aalto University, Arkkio et al.





$$J = \sigma E$$

$$E = -x \frac{dB}{dt}$$

$$p = \frac{P}{V} = \frac{4}{\pi l d^2} \int_V J E \, dV = \frac{4\sigma}{\pi l d^2} \int_V \left(x \frac{dB}{dt} \right)^2 dV$$

$$= \frac{4\sigma}{\pi l d^2} \left(\frac{dB}{dt} \right)^2 \int_{-\frac{d}{2}}^{\frac{d}{2}} x^2 l 2 \sqrt{\left(\frac{d}{2} \right)^2 - x^2} \, dx = \sigma \frac{d^2}{16} \left(\frac{dB}{dt} \right)^2$$

AC Losses – Advanced Approaches

Point-conductors

- Each strand represented by 2D point = delta functional
  - E.g. mass matrix:
  $M_{ij} = \int \sigma(x,y)\varphi_i(x,y)\varphi_j(x,y)dxdy = \sigma A_{\mathrm{strand}}\varphi_i(x_c,y_c)\varphi_j(x_c,y_c)$
  - Accounts for circulating currents, eddies with post-processing

AC Losses – Advanced Approaches

Macro-element approach

- Goes by many names: Schur complement, iterative substructuring etc.
- Idea:
  - Eliminate winding nodes & voltages with simple matrix algebra

$$\begin{bmatrix} \mathbf{S}_{\mathrm{ff}} & \mathbf{S}_{\mathrm{fw}} \\ \mathbf{S}_{\mathrm{wf}} & \mathbf{S}_{\mathrm{ff}} \end{bmatrix} \begin{bmatrix} \mathbf{a}_{\mathrm{f}} \\ \mathbf{a}_{\mathrm{w}} \end{bmatrix} = \begin{bmatrix} \mathbf{f}_{\mathrm{f}} \\ \mathbf{f}_{\mathrm{w}} \end{bmatrix} \quad (1)$$

  - Solve for

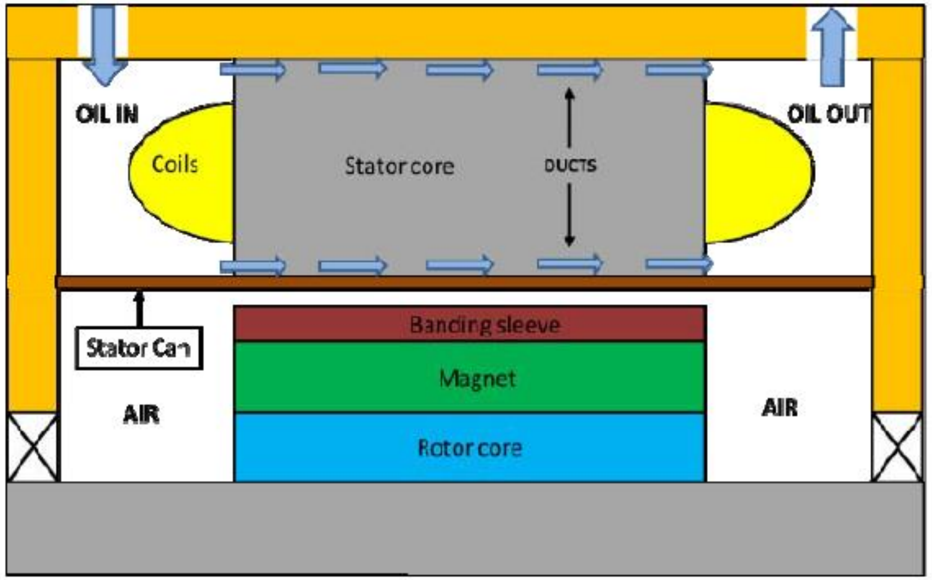
$$\mathbf{a}_{\mathrm{w}} = \mathbf{S}_{\mathrm{ww}}^{-1}(\mathbf{f}_{\mathrm{w}} - \mathbf{S}_{\mathrm{wf}}\mathbf{a}_{\mathrm{f}}) \quad (2)$$

Conductor vector potentials + voltages

  - Substitute back (1), solve for $\mathbf{a}_{\mathrm{f}}$ only
    - Much smaller problem <> denser matrix
    - Obtain $\mathbf{a}_{\mathrm{w}}$ with (1)
  - $\mathbf{f}_{\mathrm{w}}$ changes with time
    - Store LU-factorization of $\mathbf{S}_{\mathrm{ww}}$ for speedups (e.g. Matlab's *decomposition* class)
    - In case of regular mesh, reuse same factorization for all slots/coils

Windings – Cooling

- Increasing current densities → increased loss densities
  - The heat still has to go somewhere
- New insulation materials help somewhat
  - Higher temperature → easier heat extraction
- Current approaches
  - Flooded stator, 1-2 cooling channels per slot
  - Separate cooling pipes
  - Current densities up to 25-27 Arms/mm^2

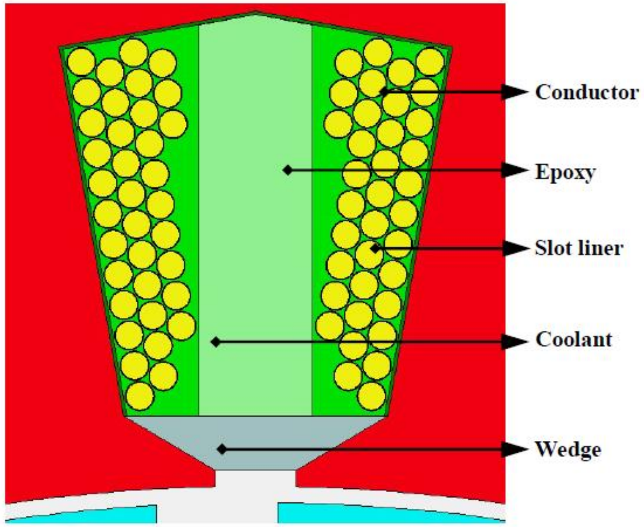


A semi-flooded cooling for a high speed machine: Concept, design and practice of an oil sleeve

Windings – Cooling

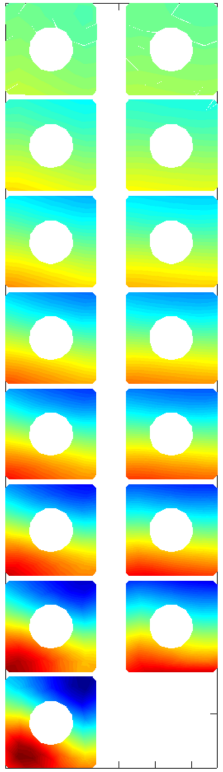
How to get to 35-60 Arms/mm^2?

- Winding resin becomes the limiting factor
  - Low thermal conductivity, ~0.2-0.4 W/mK
  - Conductors furthest from cooling channel overheat
- Need to minimize the distance each wire to nearest heat sink
  - Or greatly improved resins

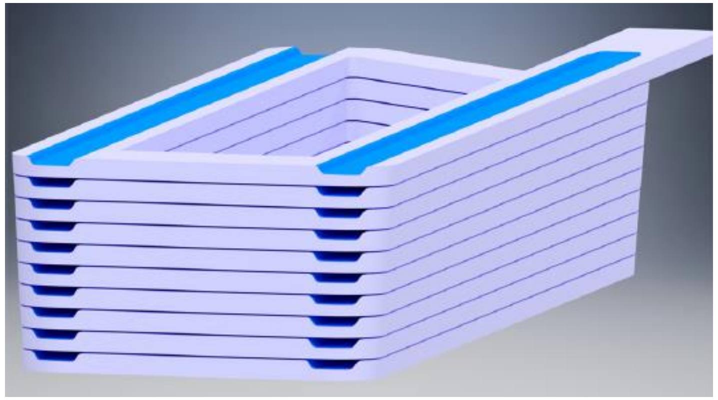


Thermal Management of a Racing E-Machine

Winding – Direct cooling approaches



- Hollow conductors with coolant
  - Great cooling performance
  - Good up to 1 kHz or so
  - Would need smaller conductors to go higher → assembly difficult
- Additive manufacturing?
  - Shaped conductors with internal and/or external flow
  - Printing tech getting there, slowly



Optimization

Electric Motors POV

Optimization?

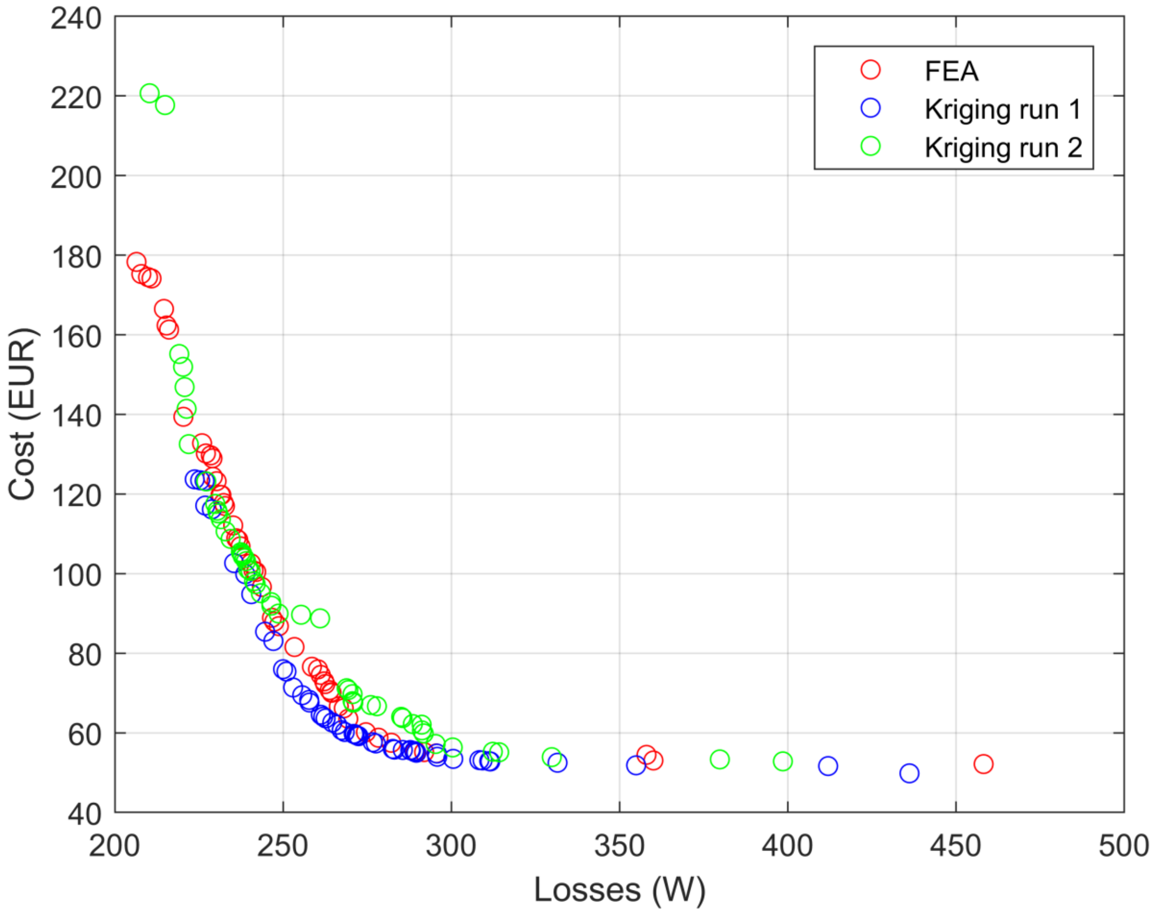
- Want ’the best’ motor, in some sense
  - Usually several senses: size, efficiency, price, etc.

→ Motor optimization is

- Multi-objective
  - Study e.g. tradeoffs between size and efficiency
- ’Black-box’ : based on FEA simulations
  - No simple equation to play with
- Derivative-free : no access to gradients
  - See above

Multi-Objective Optimization

- No single best design
- Pareto front
  - ’Best you can get’
  - Can’t improve one characteristic without worsening other(s)



Genetic algorithms

- Genetic algorithms are common
  - And other heuristic optimizers
- Simple principle
  - Each design characterized by a few (2-15 usually) dimensions to be optimized
    - Inner diameter, magnet thickness, slot depth, etc.
  - Maintain a set of independent, different designs : a population
  - Improve population over time : generations

- Quite easy in reality; don’t be afraid to code your own ☺

Genetic Algorithms

- A few typical steps

1. Create initial population
2. Select individuals for ’breeding’
3. Create new individuals
4. Select best ones for new generation
5. Go to 2.

1. Initial Population

- Often created purely randomly
- Latin Hypercubes and similar may help in getting more diverse population
  - Good for exploring entire design space

- Smarter approaches welcome
  - Initial Pareto front often within 20 % of the final, or so

2. Select individuals for breeding

- Loooooots of approaches
- Binary tournament(?) is simple:
  - Randomly pick two candidates
  - Select the better(*) one

(*) Discussed later

3. Generate offspring

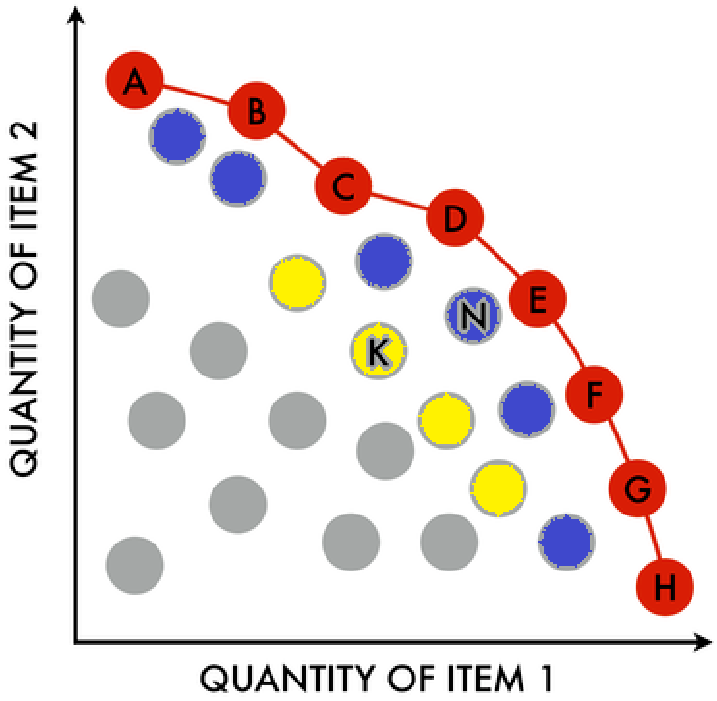
- Again, lots of approaches
- A simple one:

1. Pick two parents (see previous slide)
2. Offspring dimensions = randomly weighted mean of parents
    - Example: parent one has an inner radius of 100 mm, parent 2 has 110 m
    - Offspring radius is within 98 mm and 112 mm
    - Called ’cross-over’
3. Occasionally (e.g. 10 % of time) add ’mutation’: random variations independent of parents

4a. Select best individuals for new generation

- Easy in single-objective optimization: just pick the *N* best ones
- Multi-objective: several approaches
- NSGA-style is quite easy:

1. Order designs in fronts
   - Red: actual Pareto front, best
   - Blue: front after red is removed
   - Yellow: etc
2. Additionally: compute distance score for each design
   - To avoid lumps of designs close together

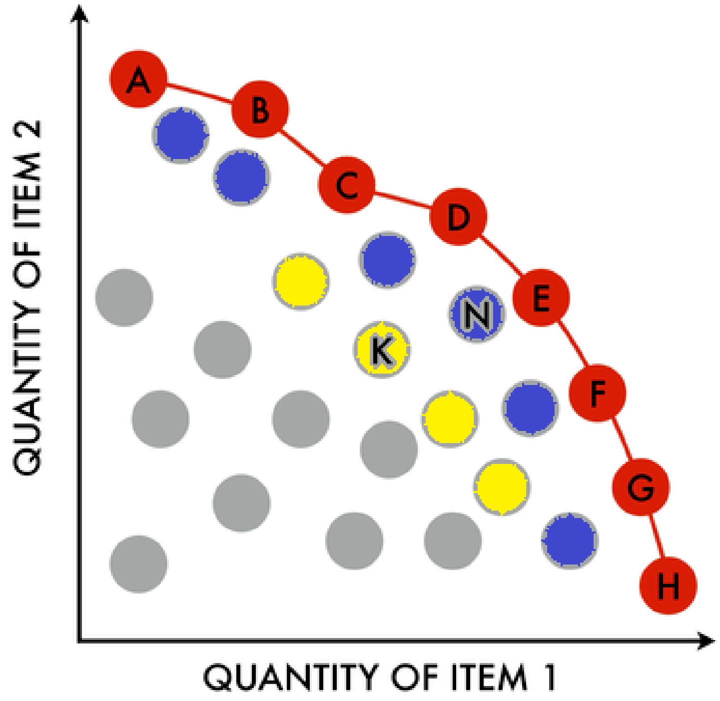


Modified:
https://en.wikipedia.org/wiki/Pareto_efficiency

4b. Select best individuals for new generation

Pick designs for new generation:

- First from red front, ordered by distance score
- Then from second front
- …
  Continue until have *N* designs



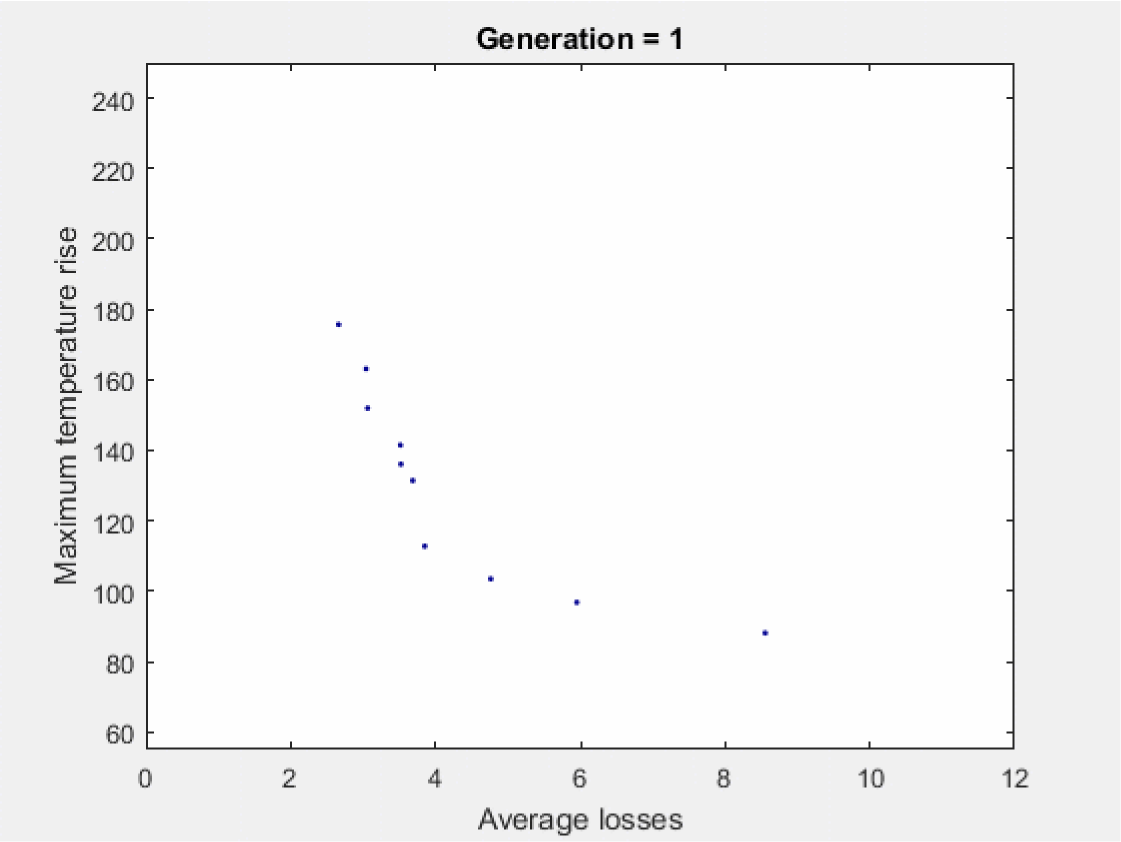
4c. Archiving

- Usually: good idea to select best designs from combined parent and offspring populations
  - Good parents outlive bad offspring
  - Never discards optimal designs

- Called *archiving*

Genetic algorithms: Result

- Population gets better with generations



Conclusions

Conclusions

Overview on high-performance motors:

- Landscape and trends
- Windings: one critical component
- Optimization and genetic algorithms: general-purpose tool

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