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

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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.
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’ >> 4-wheel passenger cars
  • 2-wheelers: e-bikes, e-motorcycles
  • 3-wheelers; prominent 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.
Windings

Design, Cooling, and Analysis

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Importance of windings

• Power from Lorentz force:
  \[ P = \mathbf{v} \cdot \mathbf{F} = \mathbf{v} \cdot B \cdot l \mathbf{I} = \mathbf{v} \cdot B \cdot l \cdot J A_{\text{copper}} \]

Implications:

• \( B = \text{flux density} \) = cannot be increased much
  • Iron saturation
  • Ironless superconducting machines \textit{might} help in the future

• \( \mathbf{v} = \text{surface speed of rotor} \)
  • \( \sim \)diameter x rpm
  • Can – and continuously is – increased \textit{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 \( \rightarrow \) most scalable way of increasing power
Current density: Being pushed higher

- DC-resistive losses:
  \[ W_{DC} \sim \rho l A_{copper} J^2 \]

- Efficiency
  \[ \eta = \frac{P}{P + \text{losses}} \sim \frac{vJBlA_{copper}}{vJBlA_{copper} + rJ^2 + W_{iron}} \]

  - Iron losses proportional to \sim \text{speed} \ldots \text{speed}^2

\rightarrow 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


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.

\[ J = \sigma E \]
\[ E = -x \frac{dB}{dt} \]
\[ p = \frac{P}{V} = \frac{4}{\pi l d^2} \int_V J E dV = \frac{4\sigma}{\pi l d^2} \int_V \left( x \frac{dB}{dt} \right)^2 dV \]
\[ = \frac{4\sigma}{\pi l d^2} \left( \frac{dB}{dt} \right)^2 \int_{-d/2}^{d/2} x^2 \sqrt{\frac{d}{2} - x^2} dx = \sigma \frac{d^2}{16} \left( \frac{dB}{dt} \right)^2 \]
AC Losses – Advanced Approaches

Point-conductors

- Each strand represented by 2D point = delta functional
  - E.g. mass matrix:
    \[ M_{ij} = \int \sigma(x, y) \varphi_i(x, y) \varphi_j(x, y) dx dy = \sigma A_{\text{strand}} \varphi_i(x_c, y_c) \varphi_j(x_c, y_c) \]
  - 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
    \[
    \begin{bmatrix}
    S_{ff} & S_{fw} \\
    S_{wf} & S_{ff}
    \end{bmatrix}
    \begin{bmatrix}
    a_f \\
    a_w
    \end{bmatrix} =
    \begin{bmatrix}
    f_f \\
    f_w
    \end{bmatrix}
    \]  (1)
  • Solve for
    \[ a_w = S_{ww}^{-1}(f_w - S_{wf}a_f) \]  (2)
  • Substitute back (1), solve for \( a_f \) only
    • Much smaller problem <> denser matrix
    • Obtain \( a_w \) with (1)
  • \( f_w \) changes with time
    • Store LU-factorization of \( S_{ww} \) for speedups (e.g. Matlab’s decomposition class)
    • In case of regular mesh, reuse same factorization for all slots/coils

Conductor vector potentials + voltages

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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
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
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 \( \rightarrow \) 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

- Looooots 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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