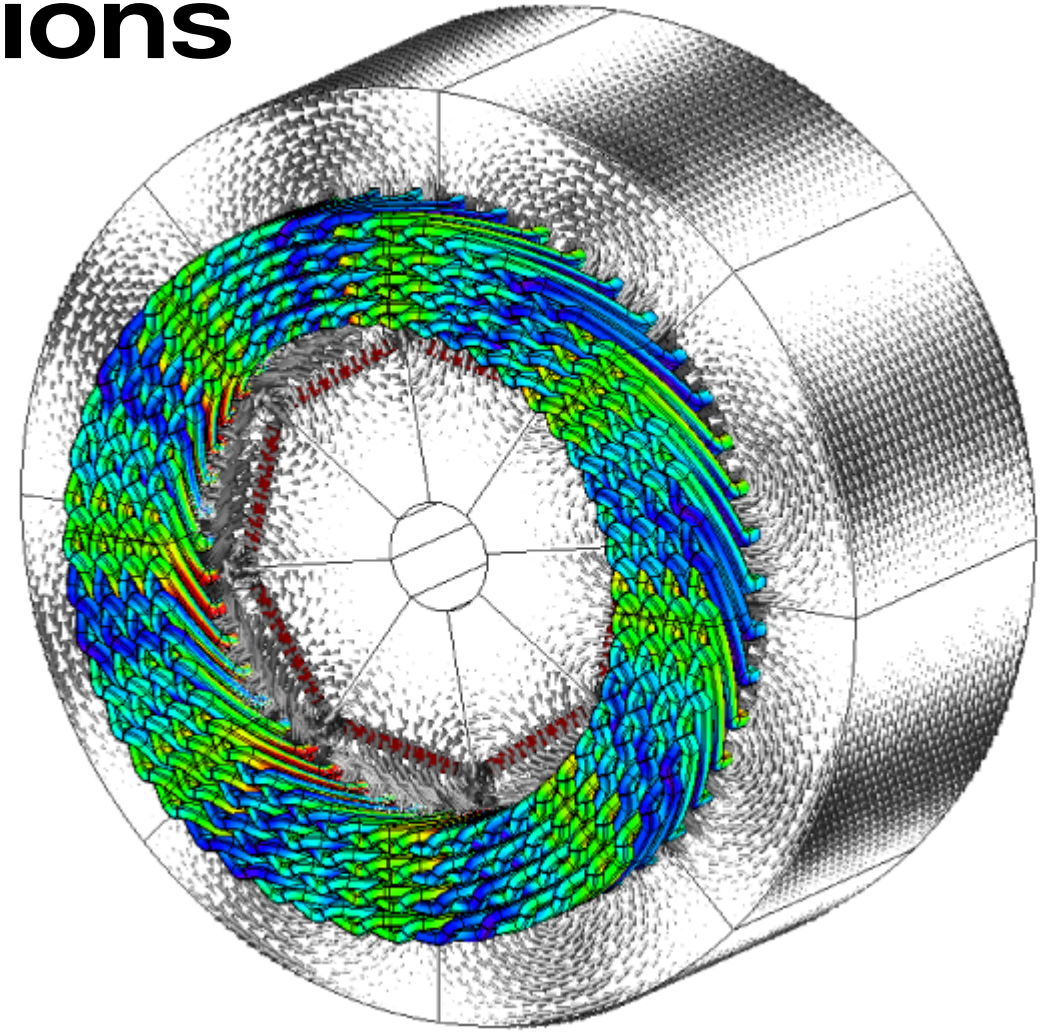
Design of IPM machine with hairpin windings for electric vehicle applications



Webinar

October 15th, 2025

Presented by – Nithara P V, JMAG HPC Engineer

Company - POWERSYS

POWERSYS

CONTENTS

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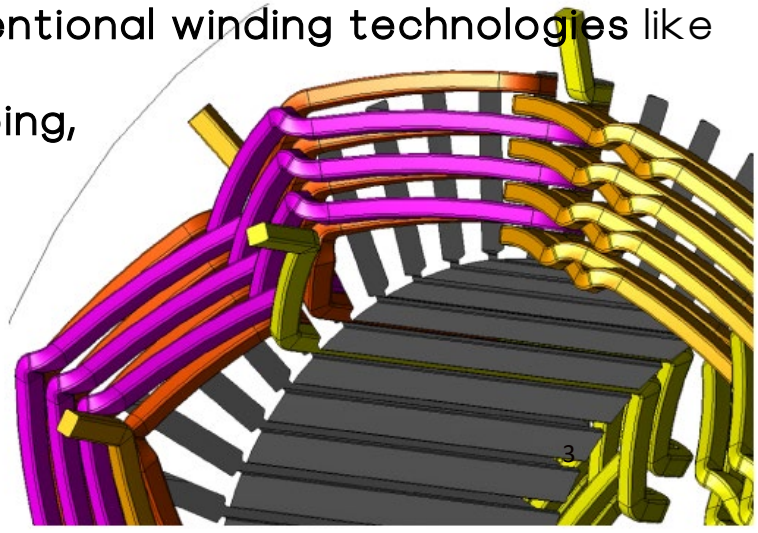
Background of Hairpin Winding

•Emergence in Automotive Industry:
•Hairpin winding has gained **significant prominence in drive-train motors** used in **electric and hybrid vehicles**.
•The **automotive sector** has spurred **innovations in manufacturing** and application of hairpin windings.

•Reasons for Adoption in EV Traction Motors:
•Automotive applications demand **compact design, high efficiency**, and **high-speed operation**.
•Battery voltage limitations in EVs impose **constraints on the number of turns** in the winding.
•Hairpin windings enable a **high slot fill factor**, making better use of available stator space.

•Advantages of Hairpin Winding in Automotive Context:
•Supports **high power density** due to efficient copper usage.
•Enhances **thermal performance** and **mechanical stability**.
•Better suited to **automated manufacturing**, aligning with mass production needs.

•Industry Impact:
•The transition to hairpin winding in EV motors represents a **shift from conventional winding technologies** like random or distributed windings.
•Automotive demand has led to **innovative developments in insulation, shaping, and joining techniques** for hairpin coils.



About the webinar

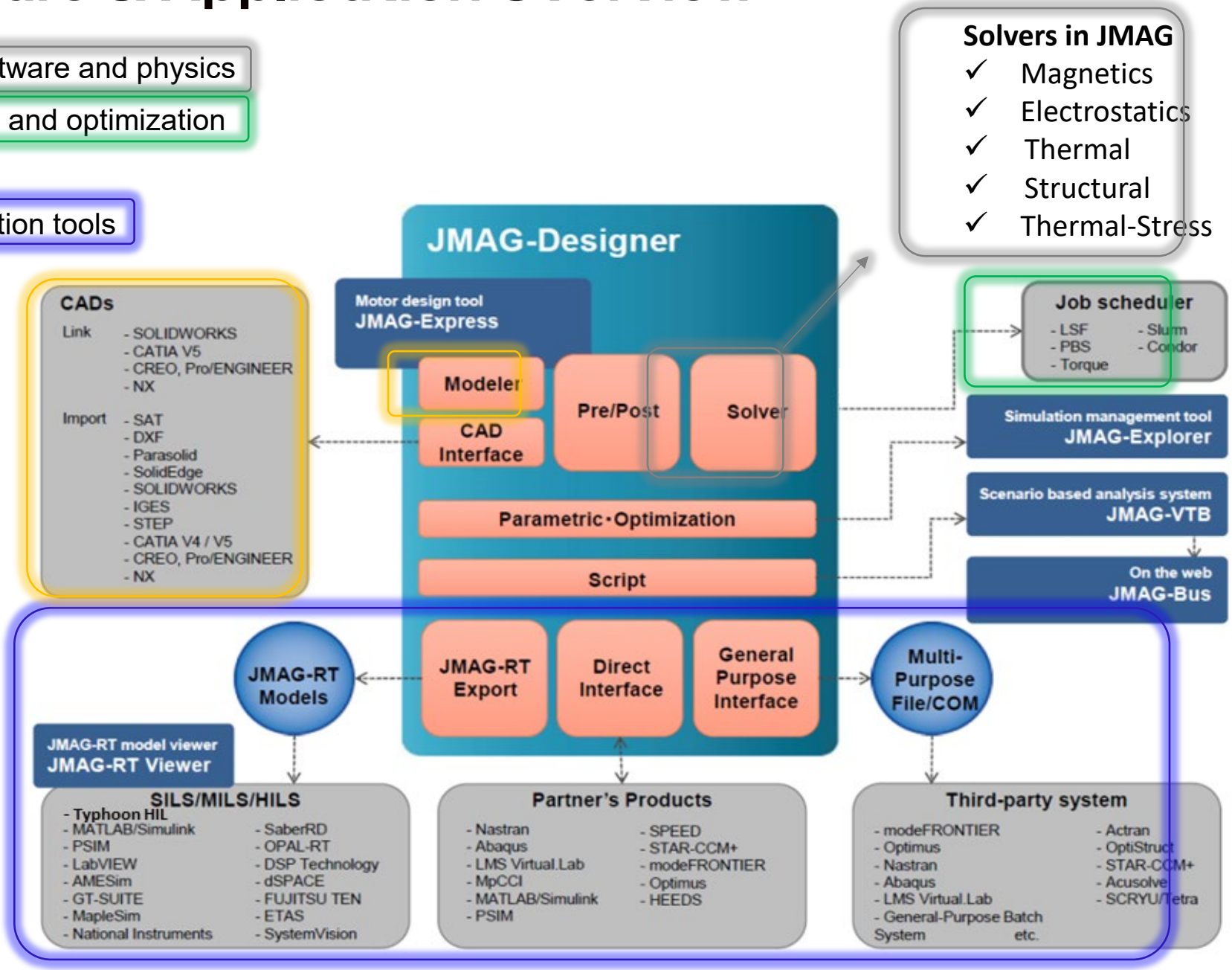
- This webinar explains to find and optimize solutions for a good winding design that can be produced easily in high volumes and keep a good compromise between cost and performance.

Overview of JMAG Designer

JMAG's structure, strengths and motor design workflow

JMAG Structure & Application Overview

1. Data connection between software and physics
2. Efficient HPC implementation and optimization
3. Common CAD for FEA
4. Integration of different simulation tools



Motor Design Workflow using JMAG (V Cycle)

Concept Technology Selection

Predefined CAD Templates

JMAG Express Classic

Large Scale Parameter Sensitivity

Optimization with global parameter set

System level requirement verification

JMAG-RT

JMAG Express

Integrated Motor Control

Focused Optimization (including Multiphysics)

System model verification, Controller Design (MILS)

JMAG-RT

JMAG Designer

Loss Analysis:
- ✓ AC Copper losses,
- ✓ Iron losses,
- ✓ Magnet losses,
- ✓ ...

Current Density (A/m^2)

High-fidelity Component definition (3D modeling)

JMAG Designer

Component validation (including Multiphysics)

System Characterization (Efficiency Map, Control, SIL...)

JMAG-RT

Motor speed target value
Motor speed actual value
Motor load torque
Motor torque

Ld
Lq
Flux Linkage

Plant model (JMAG)

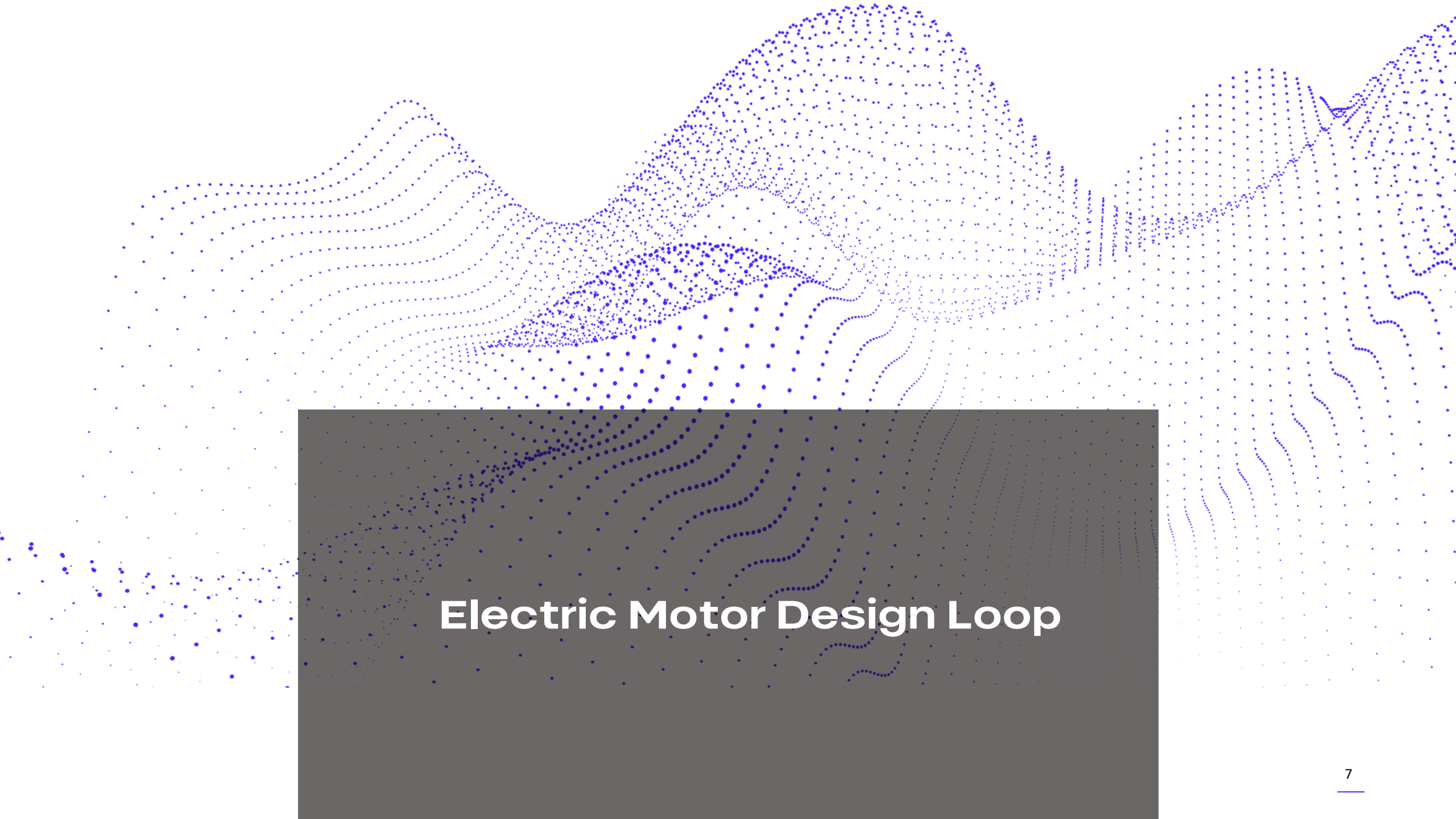
System Verification Calibration (HIL)

JMAG-RT

Typhoon HIL

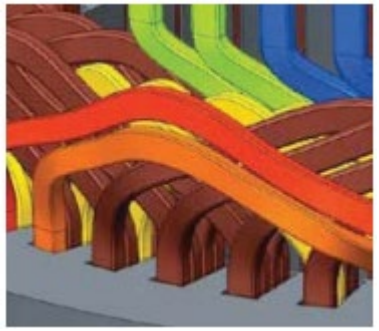
Product verification & Testing

ECU Validation | Driving Simulation | Powertrain Vibration | Vehicle Vibration

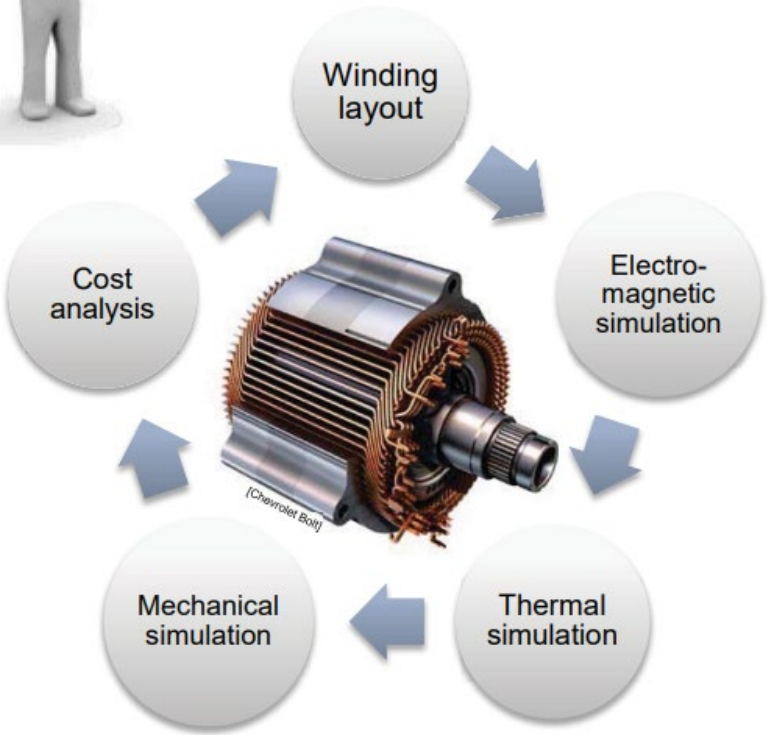

Electric Motor Design Loop

Electric Motor Design Loop

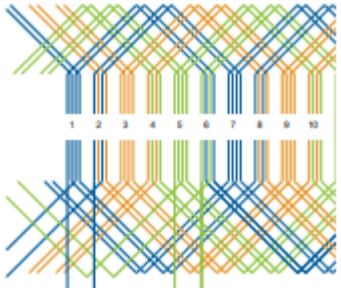
- Detailed bottom-up calculations including material, manufacturing, tooling and overhead costs
- Bill of material, cost reports
- Main cost drivers and economization suggestions

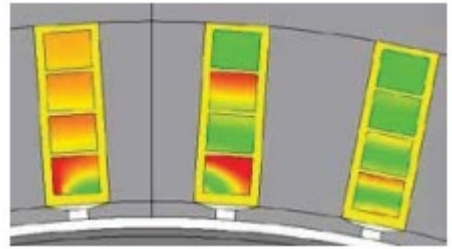


- Coordination of supplier specifications.
- 3D CAD design, assembly instructions
- Verification of produceability, creepage distances, mechanical stability.
- Tolerance requirements and impacts

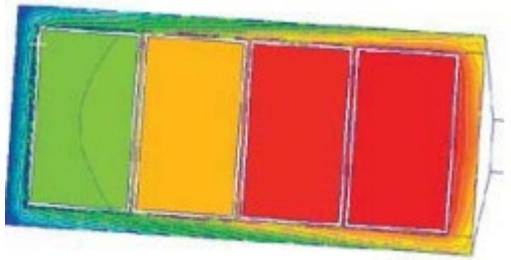


- Customized layout of hairpin windings
- Adaption concepts for machine scaling
- Early assessment of produceability





- FEA simulation of the current displacement.
- Calculation of additional AC loss
- Calibration of analytical estimation models.



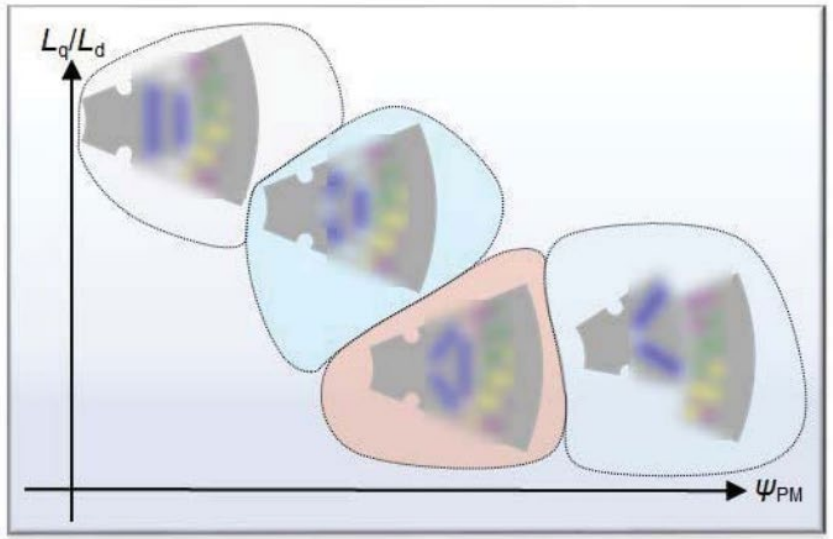
- FEA and lumped circuit thermal calculation.
- Continuous operation and temperatures cycles.
- Cooling dimensioning.

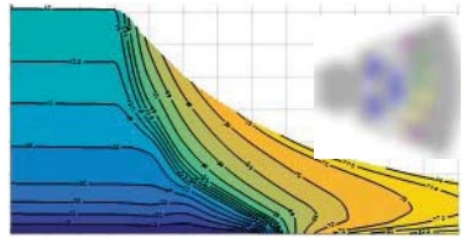
Machine Design using Pre-calculated Maps

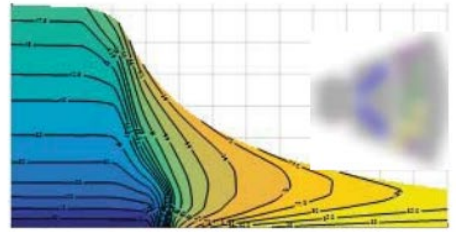
- Usual machine design starts with a predefined geometry with a fixed parameter set.
- **Problem:** Only a local optimum can be found; the global optimum might need a completely different starting geometry.
- **Solution:** Use of precalculated parameter maps for thousands of geometry variants.
- The input parameters are DC voltage V_{DC} , Current limit I_{max}, peak torque T_{max} and peak power P_{max}

Pre-calculated Parameter Maps

- Use of equivalent circuit parameters : permanent magnet flux linkage $\emptyset_{PM}$, direct and quadrature inductance L_d and L_q.
- Parameters depend on rotor structure: magnet and air chamber arrangement.
- More magnet layers ⟶ lower permanent magnet flux and higher reluctance torque.
- Parameter map precalculated using JMAG used as a database for specific design problems.







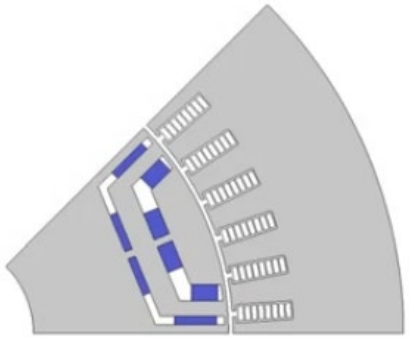
Introduction

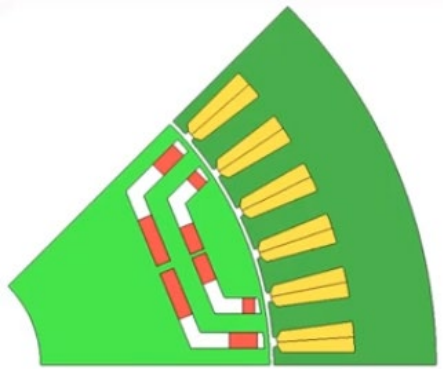
Hairpin winding

Hairpin Winding - Introduction

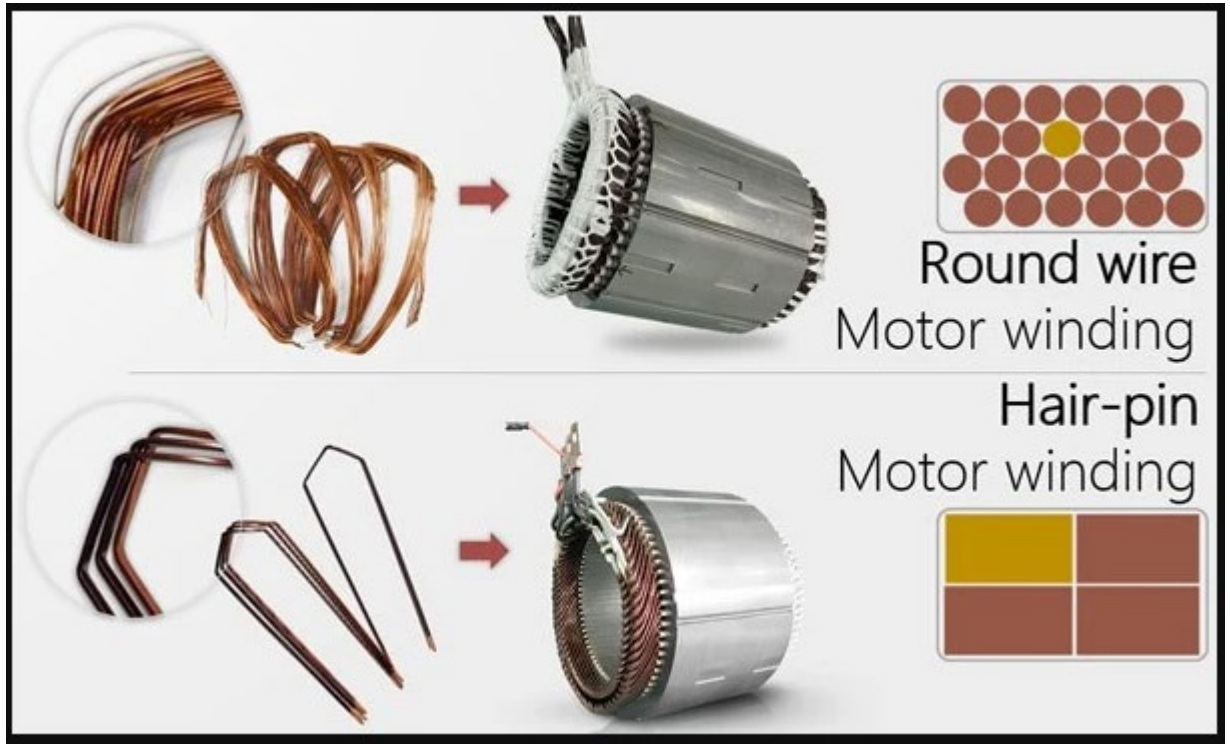
- Bars will be premanufactured in I or U shape
- Straight line will be feed through machine and twisted, and widened at the other end.
- Twisting to the next connection point of the winding

Hairpin winding technology	Round wire technology
Higher fill factor	More winding design flexibility
Reduced DC losses	Reduced AC losses
Stronger insulation system	Less complex manufacturing
Reduced iron losses	
Improved space utilization	





Hairpin Winding - Introduction



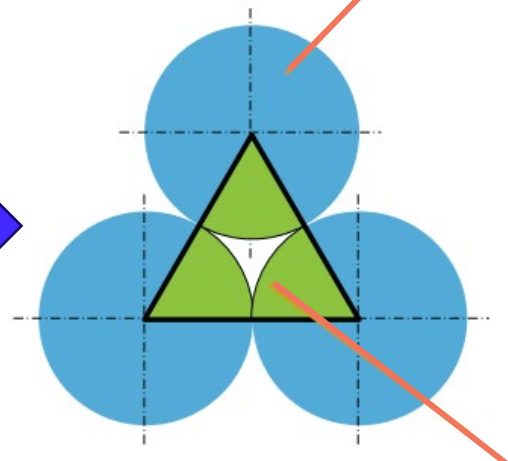
- High power density
- High efficiency
- High reliability

- Improved heat dissipation
- Reduced NVH
- Automated Manufacturing

Hairpin windings with preformed conductors are the current/next generation solutions for high performance EV traction motors.

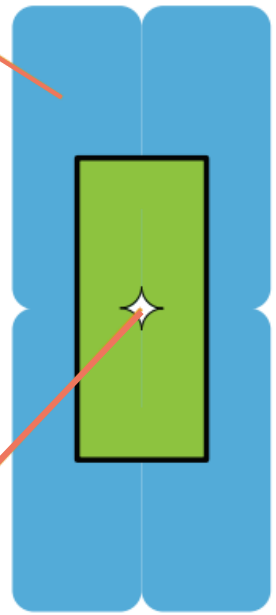
Comparison of Fill Factors

Classical round wire winding, distributed or concentrated

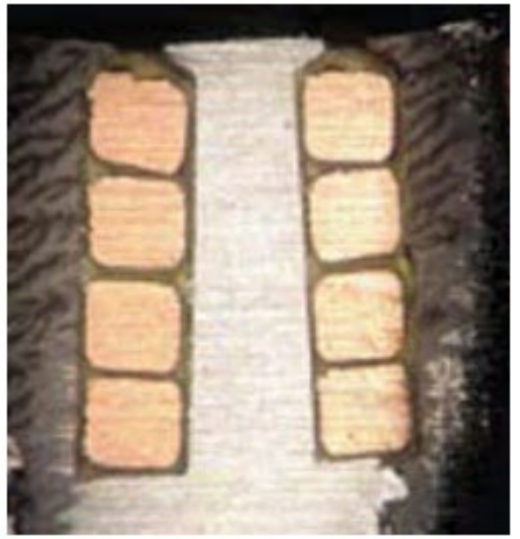


Same winding space

Different fill factors



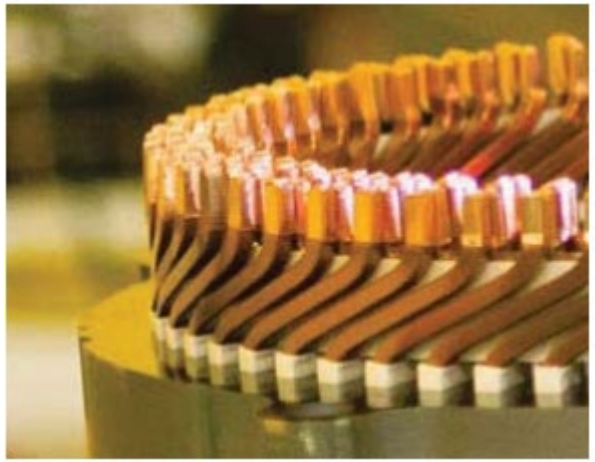
Hairpin winding



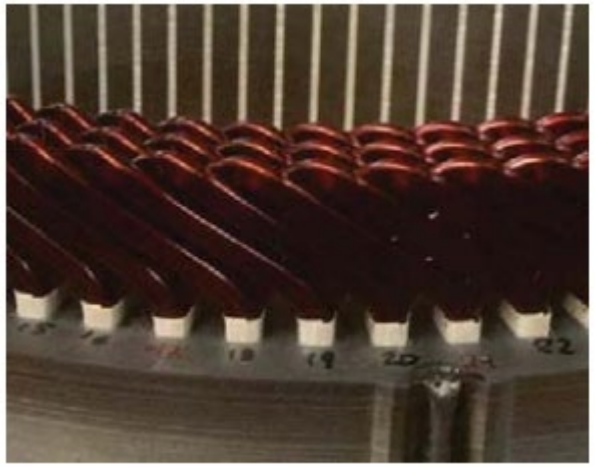
Hairpin windings provide the highest copper fill factor

Axial Space requirement

Hairpin winding



Welded wide

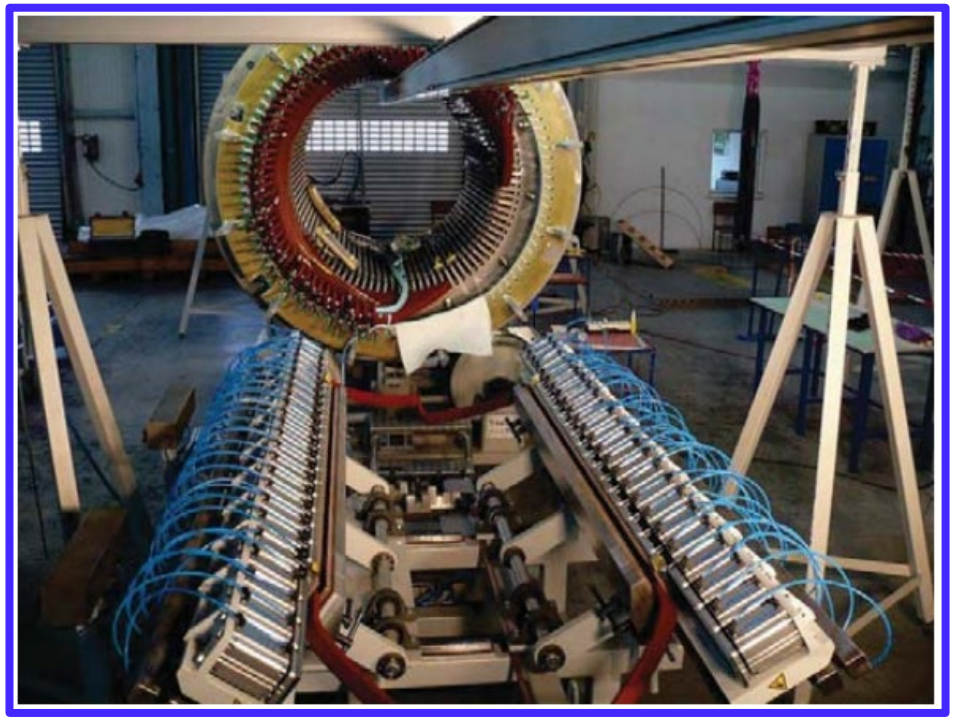


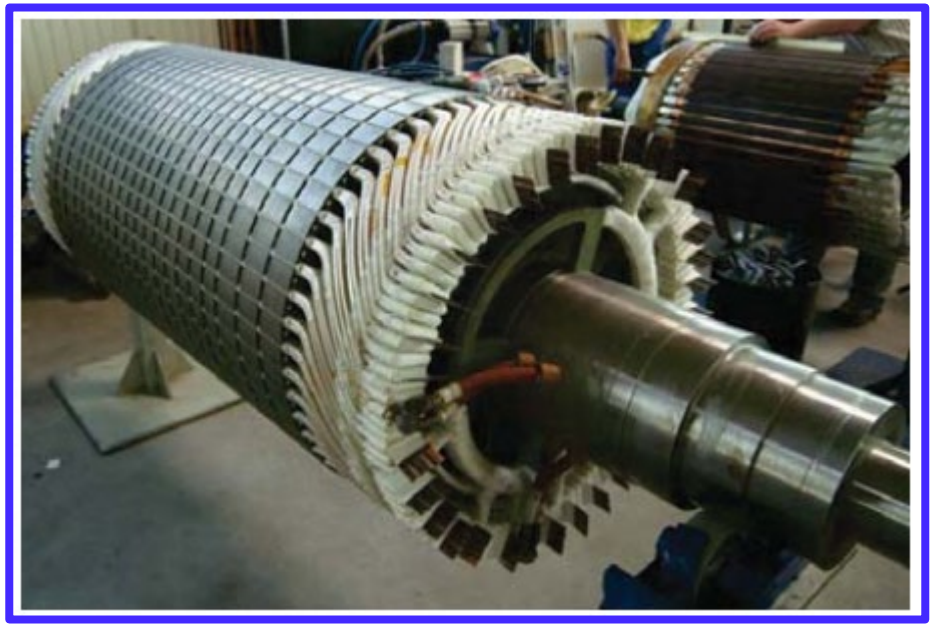
Bent side

Hairpin winding compared to distributed winding

Hairpin winding provides the smaller end turn height

Hairpin Technology in Industry





- Industry uses other nomenclature (Preformed coil or diamond coil)
- Widespread in industry
- Usually applied to high power machines >1MW and voltage levels >6kV
- Semi-automated manufacturing.

Manufacturing – Welding Process

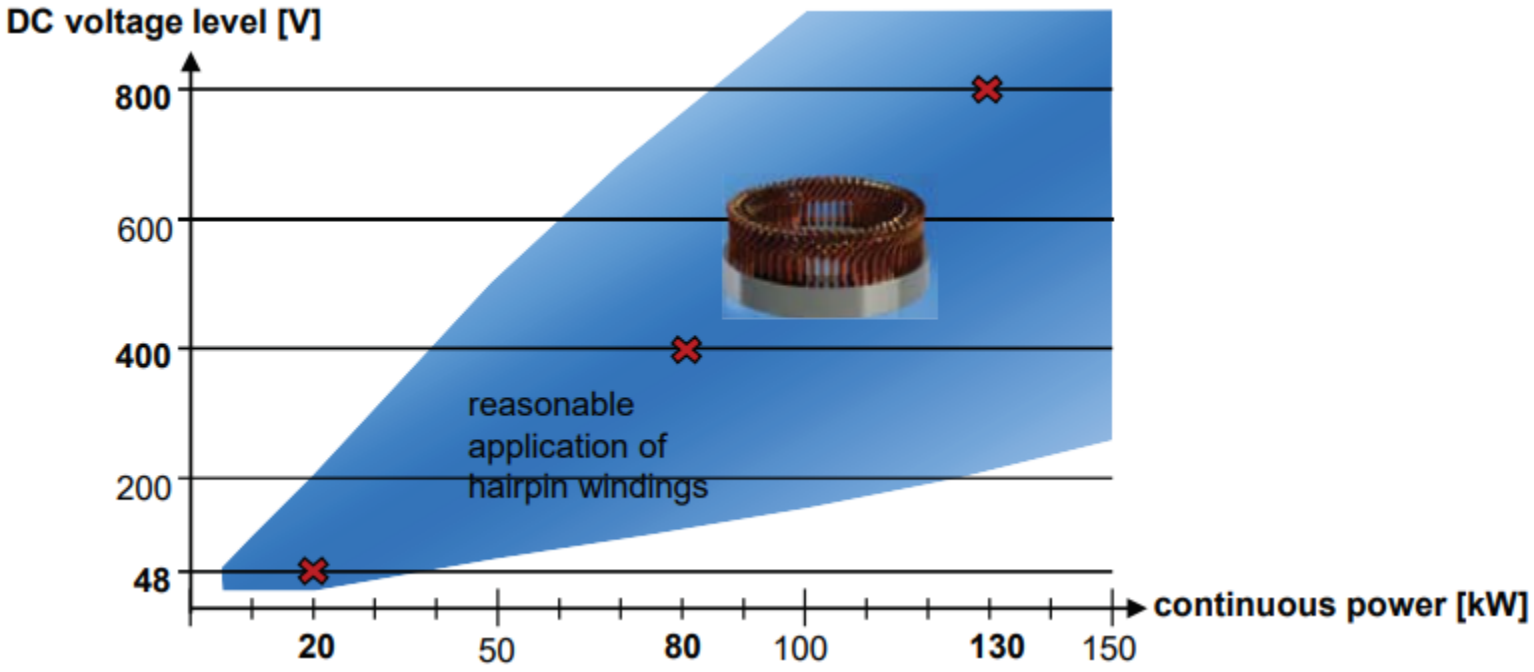
- Welding is done one or both sides (I-Pin winding).
- Laser welding preferred.

- Widening of the heads makes small winding heads and keeps space for the connecting.
- Connecting can be led between layers or spreaded across multiple axial planes.

Application region

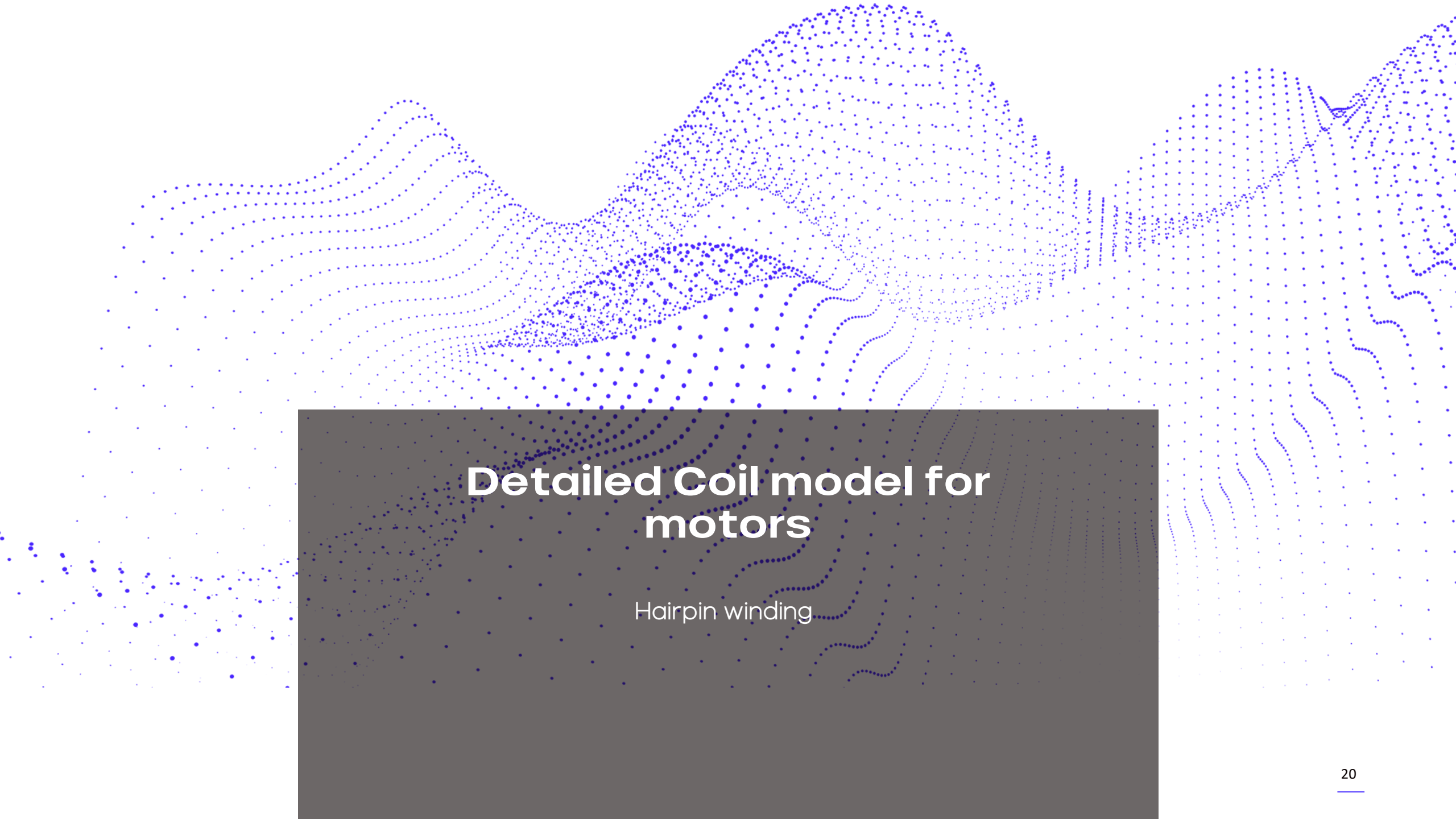
Hairpin Winding

Hairpin winding : Application Region



Reasons for the upper and lower voltage boundaries:

- The number of copper bars per slot is limited (about 5 to 8).
- Hairpin winding usually form an integer slot winding (Slot per pole and is 1 to 2)
- The minimum stator slot pitch is technologically limited to about 10mm



Detailed Coil model for motors

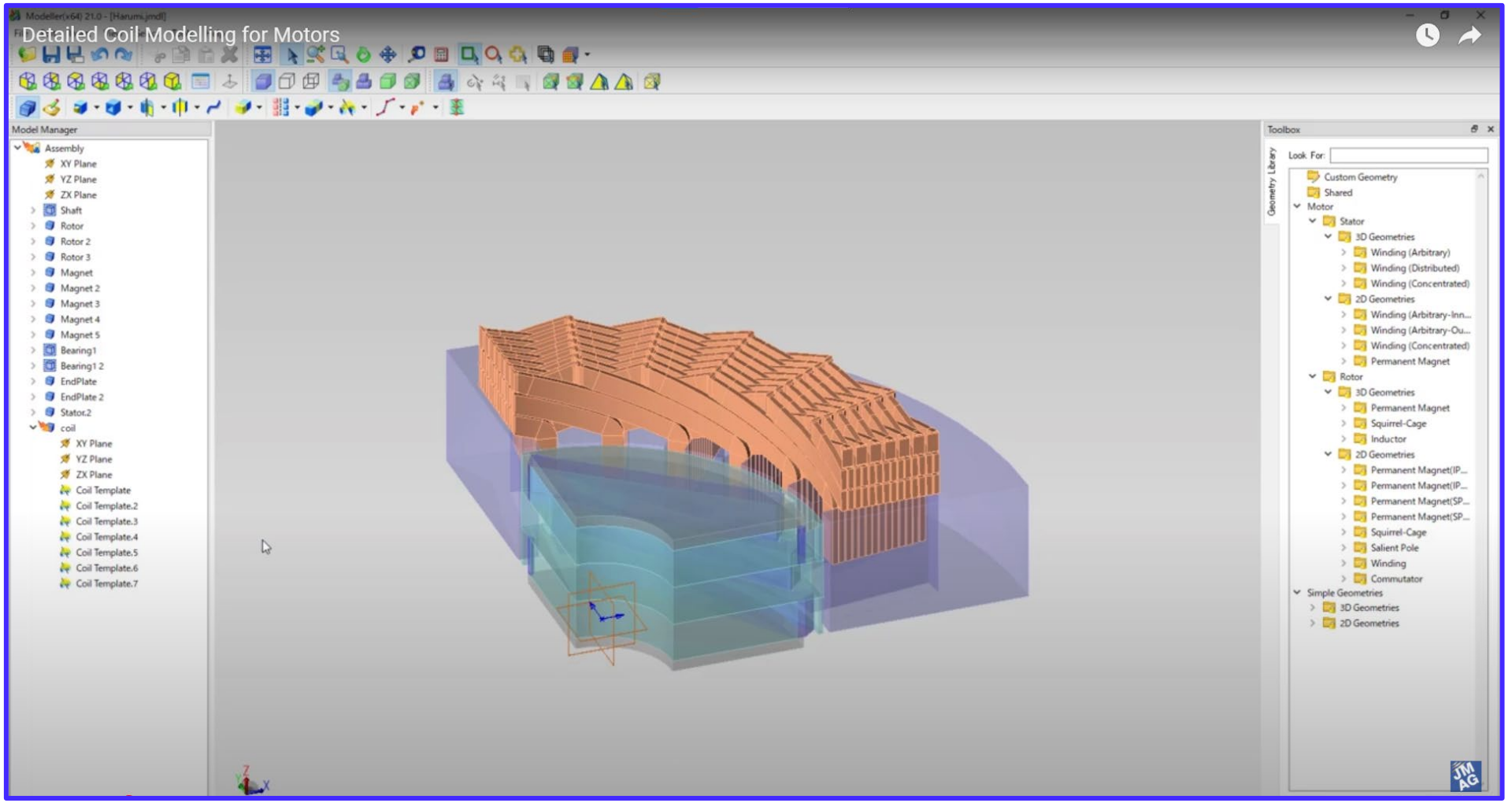
Hairpin winding

Hairpin modelling in JMAG designer

- In JMAG it is possible to create 3D coil geometry including coil ends simply by configuring parameter settings.

Coil template

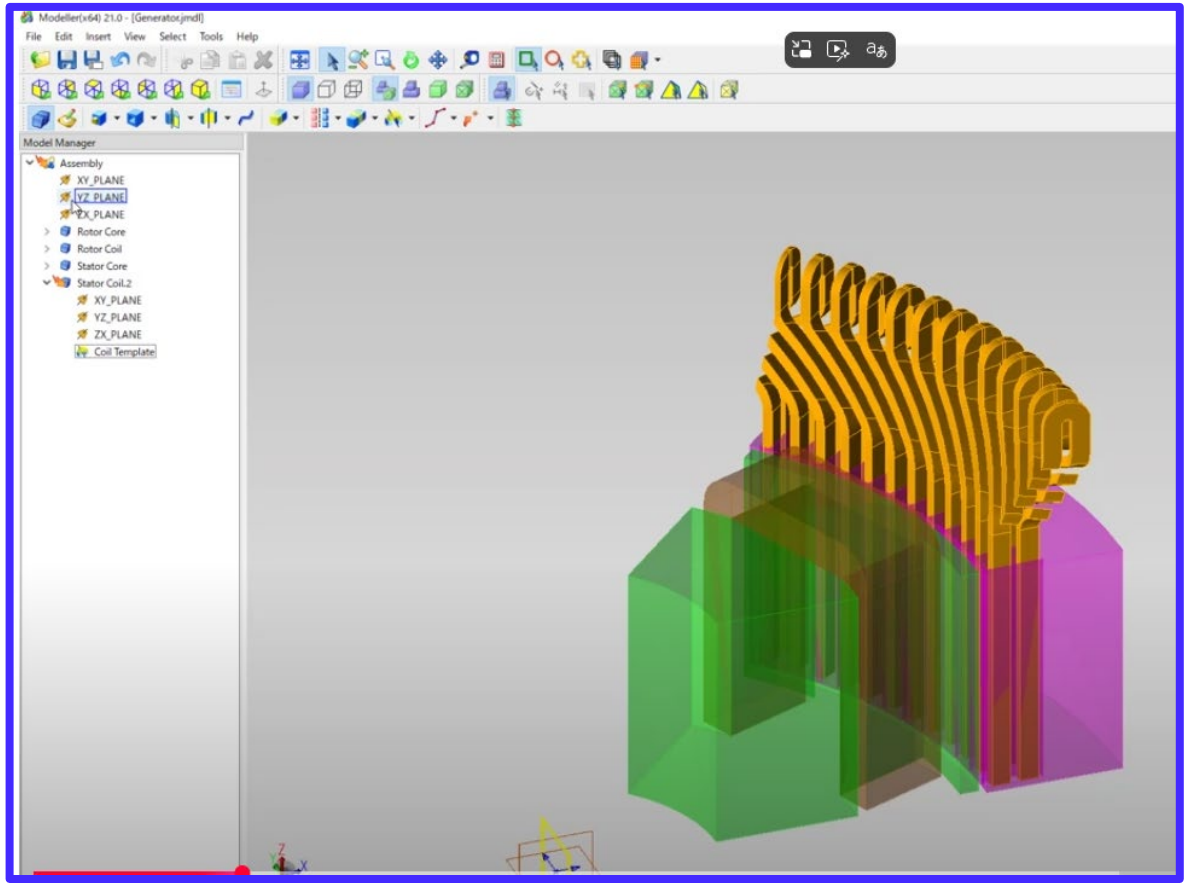
- Coil template function are used creating geometry that include coil end by specifying numerical parameters.

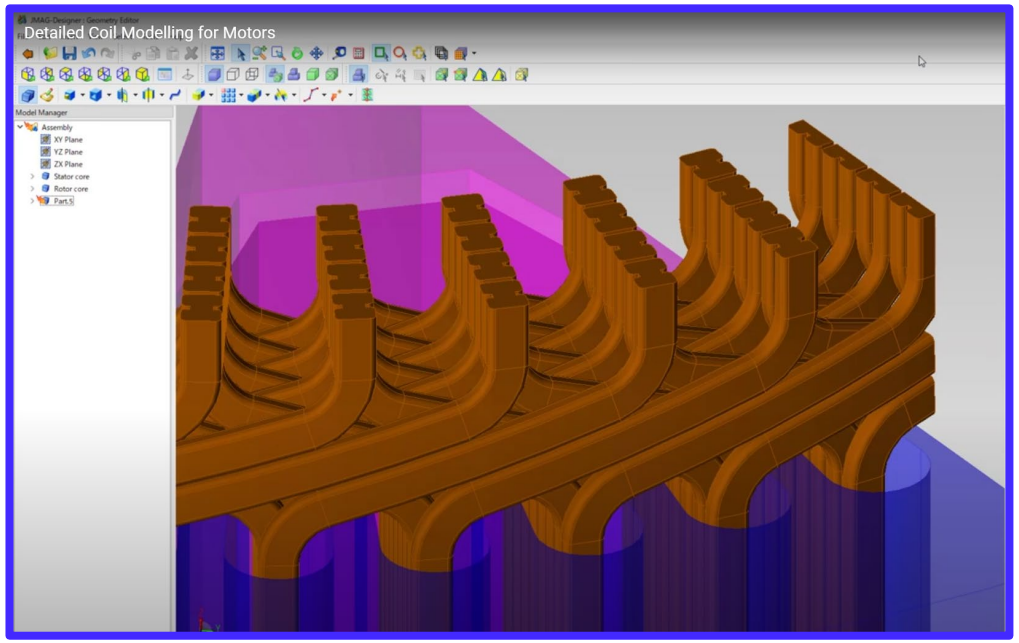


*https://www.jmag-international.com/support/mod/tutorial/note/JFT018GeometryCreationUsingCoilTemplate-e.pdf

Hairpin modelling in JMAG designer

- JMAG coil template features enables the evaluation of losses due to 3-dimensional leakage flux and leakage inductance.
- Winding geometry like hairpin winding for traction motors and the winding for large machines can be created by only entering the parameters.





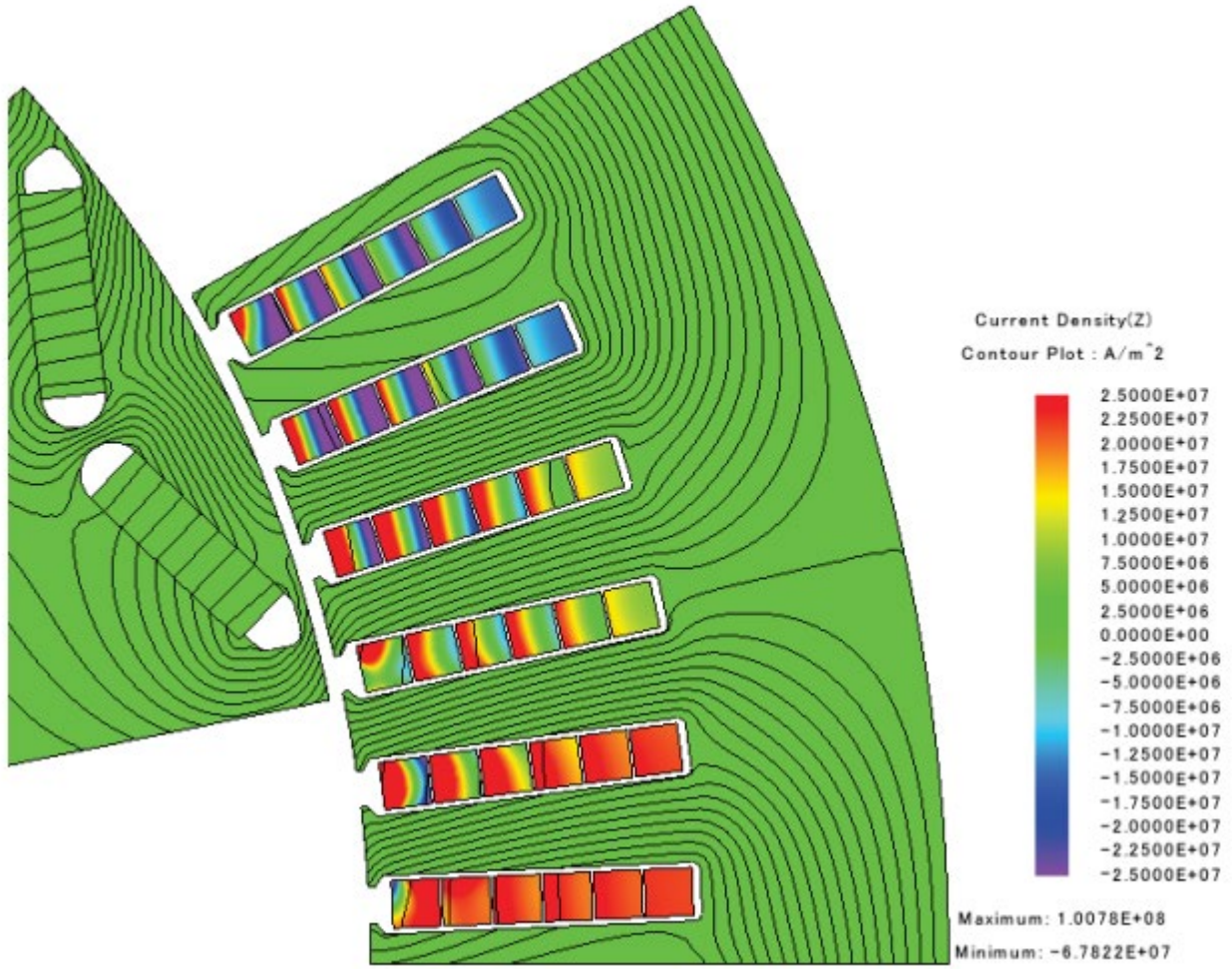
*https://www.jmag-international.com/support/mod/tutorial/note/JFT018GeometryCreationUsingCoilTemplate-e.pdf

Analysis using JMAG software

Hairpin winding

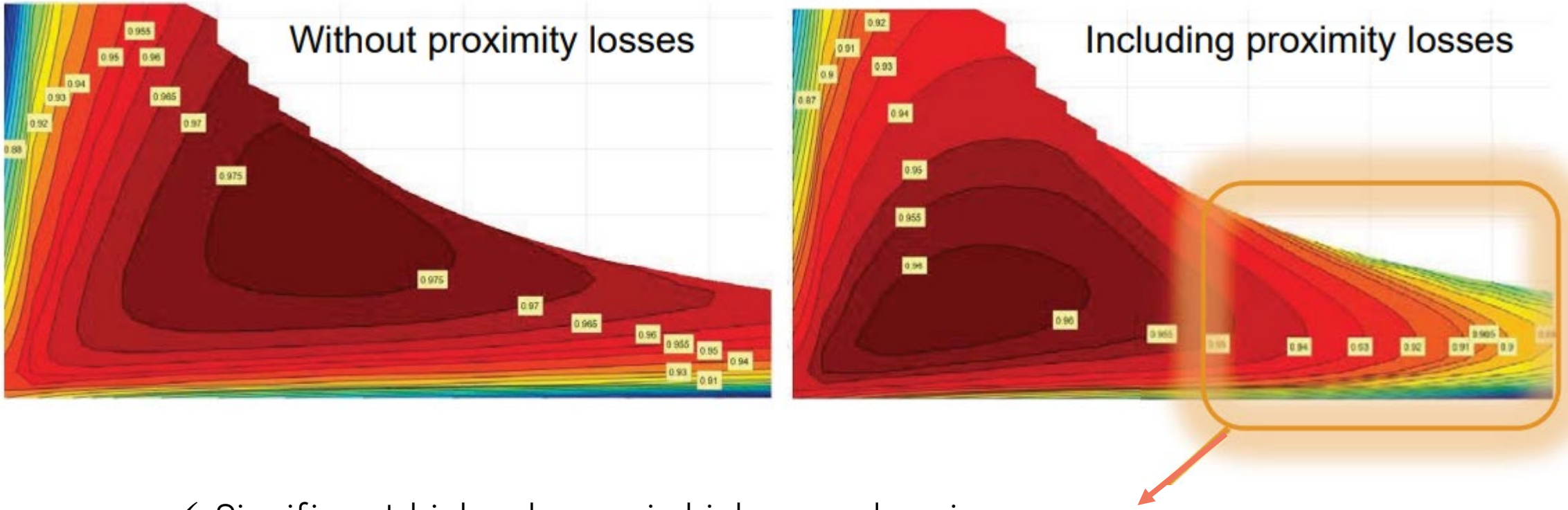
Skin/Proximity Losses

- With increasing speed, the current distribution is inhomogeneous
- The bars closer to the airgap are mostly affected
- Additional AC losses to be considered – high numerical effort to calculate



*https://www.jmag-international.com/wp-content/uploads/members/en/documentation/pdf/uc2018_17_eng.pdf

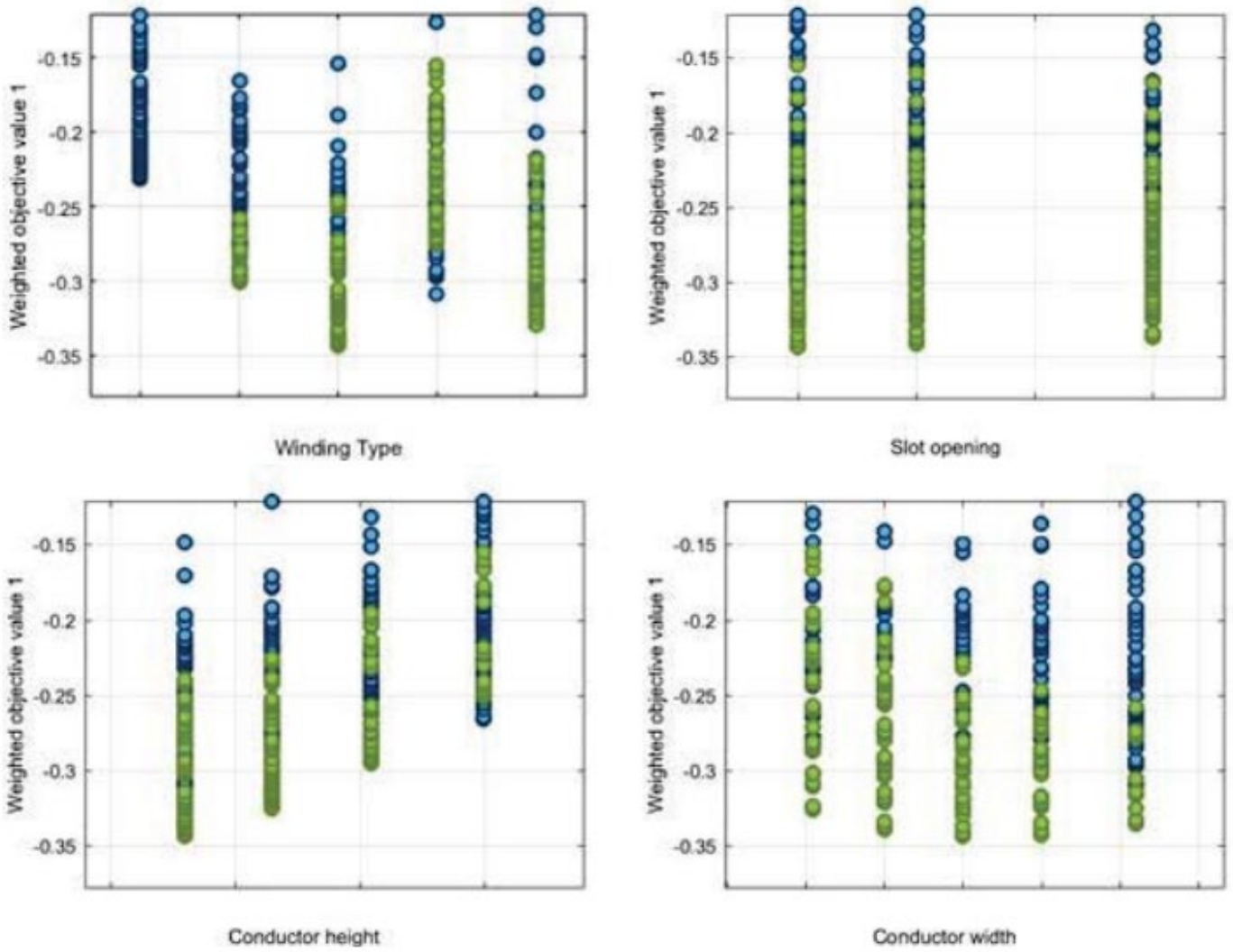
Efficiency Map Comparison



- ✓ Significant higher losses in high-speed region.
- ✓ Lower continuous power due to excessive additional losses
- ✓ Limitation of maximum driving speed for BEV.

*https://www.jmag-international.com/wp-content/uploads/members/en/documentation/pdf/uc2018_17_eng.pdf

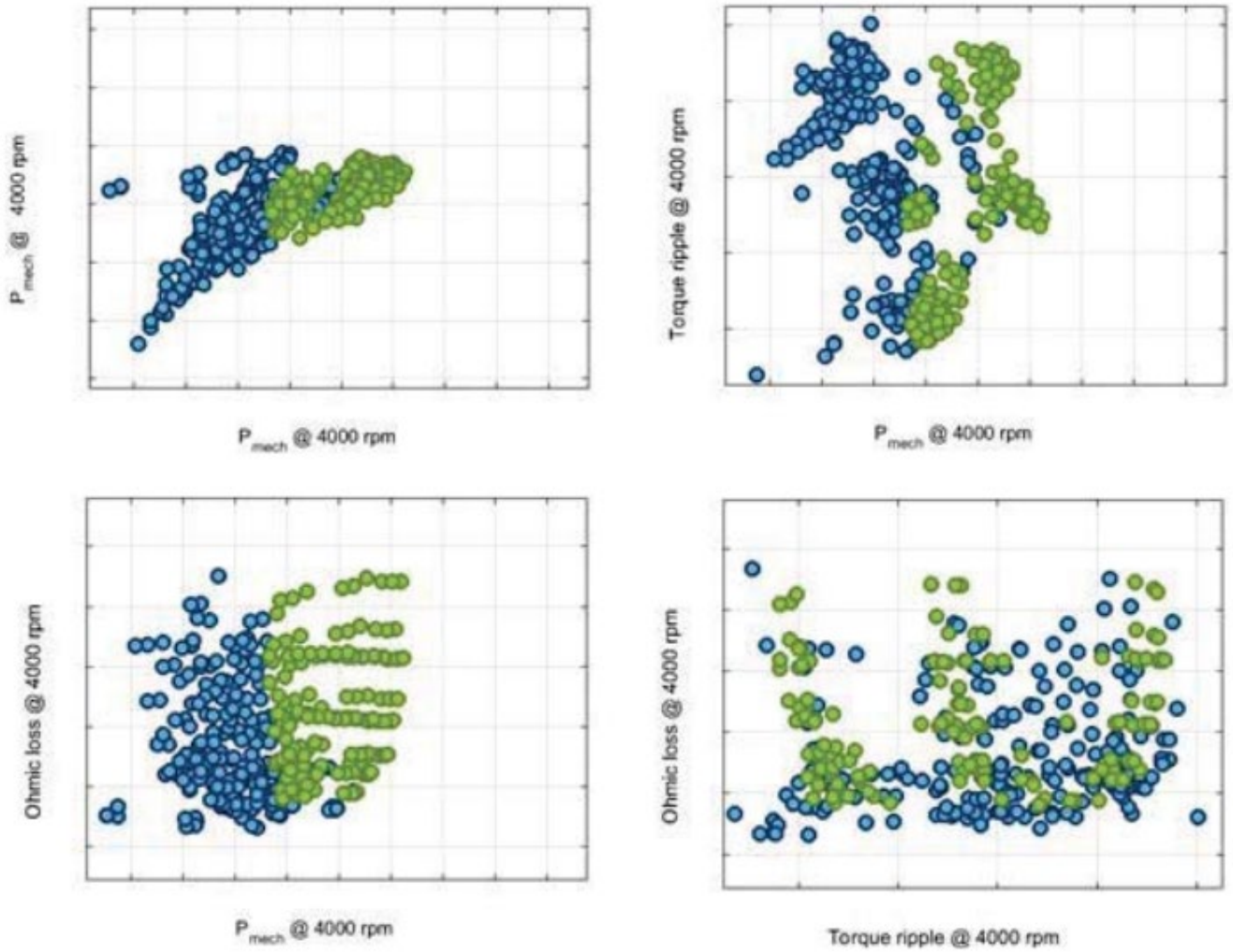
Influence of the design parameters



- Short pitched winding allow for best overall behavior
- Slot opening without noteworthy effect on objective value.
- Flat conductors (low height) show best behaviour.
- Conductor width with only small effect. Best results are reached between 4 and 5 mm.

Example from real BEV motor

Benefit analysis - dependencies

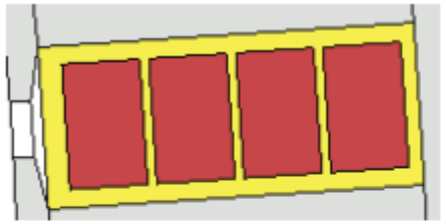


- Low torque ripple requires an approximately 5% reduced performance.
- Ohmic loss is almost independent of the maximum performance.
- Both low torque ripple and low ohmic loss is simultaneously achievable.

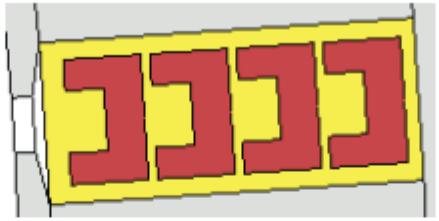
Example from real BEV motor

Reduction of conductor cross sectional area

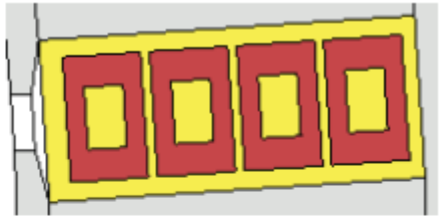
- No typical "skin effect current distribution" with high density at conductor surface → Proximity effect dominates
- Reduction of cross-sectional area to reduce eddy currents → other concepts than skin effect typical hollow conductors might be promising.
- Comparison of the following, each form with copper or aluminium.



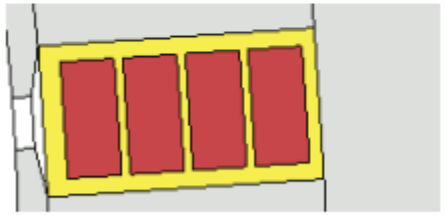
Solid, reference



U-form inner open,
25% reduced area



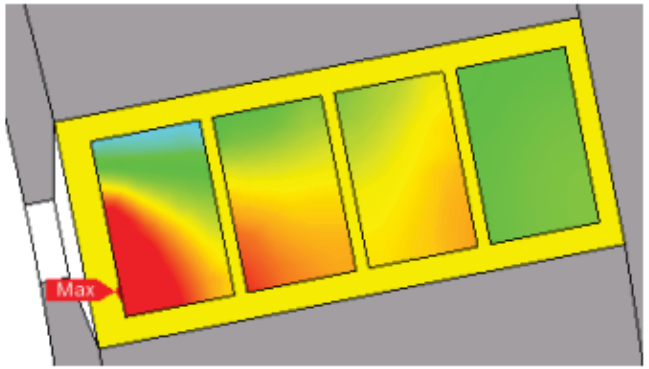
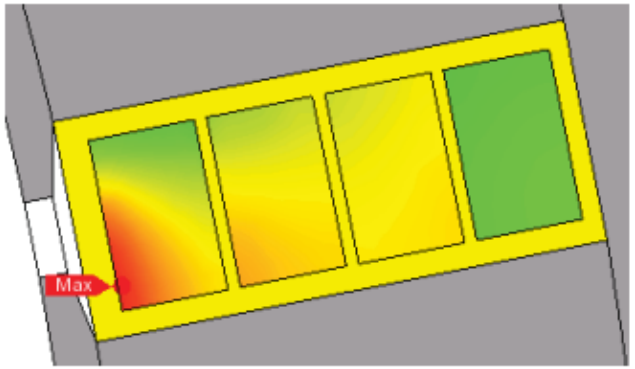
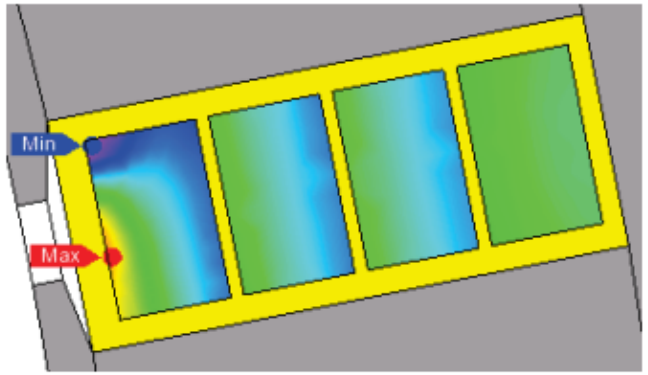
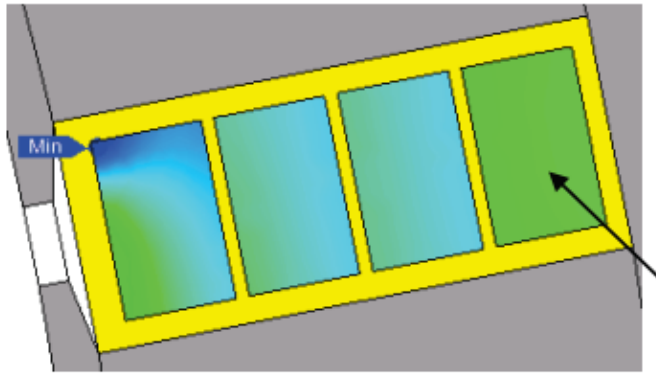
O-form (hollow),
25% reduced area

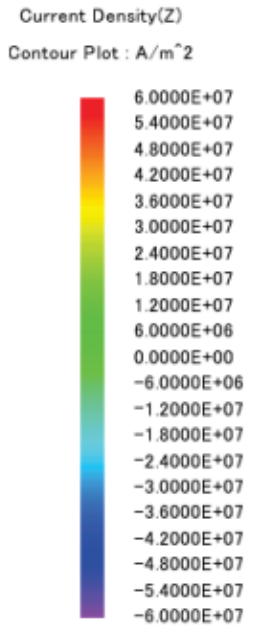


Solid, 25% reduced height

U-form outer open,
25% reduced area

Copper Vs Aluminium

	Copper	Aluminium
600 Arm / 120°, 5000 rpm		
300 Arm / 170°, 14000 rpm		

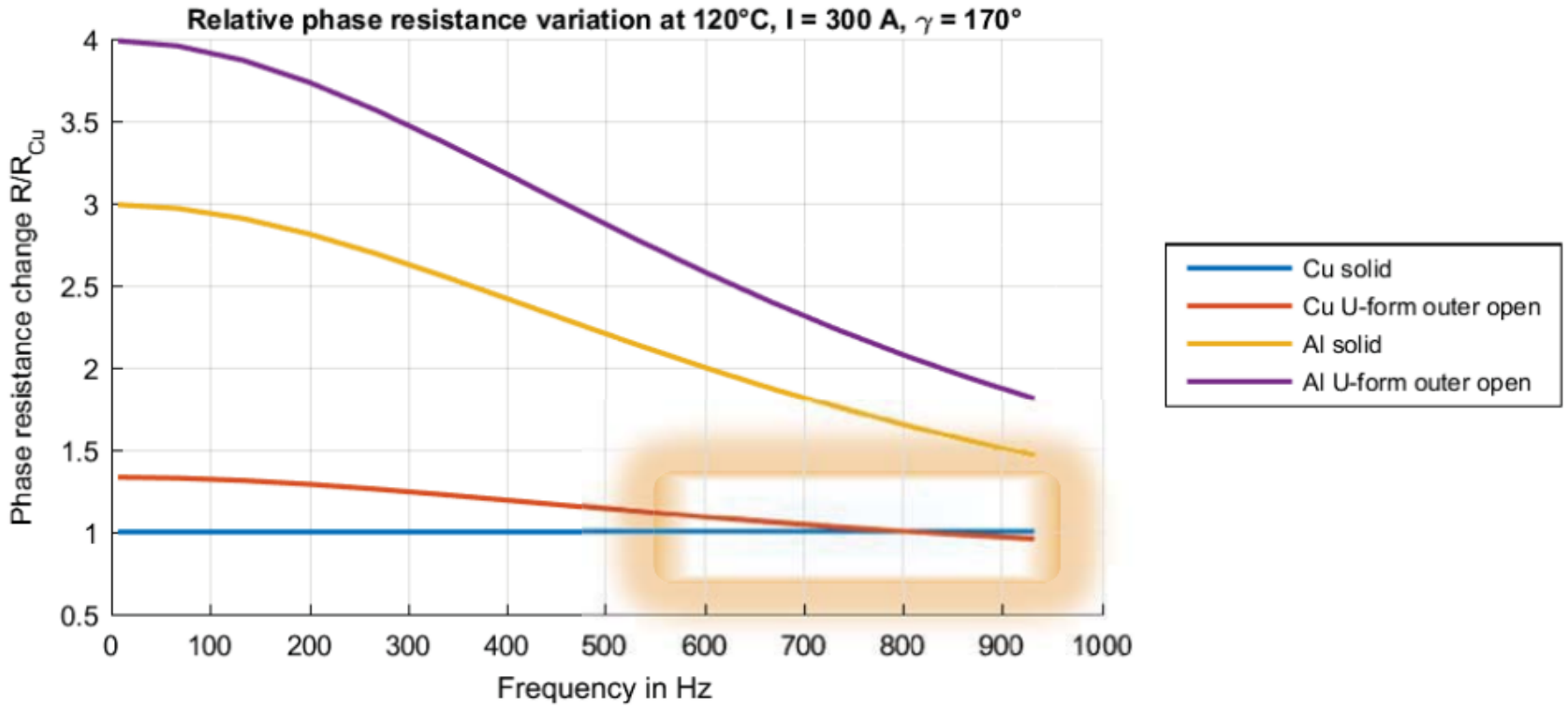


This conductor belongs to different phase

1/3 higher resistivity with Al

Increased losses with aluminum – but what about higher frequencies?

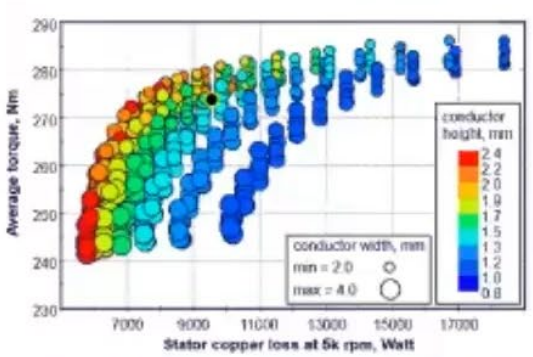
Conductor Variation Results



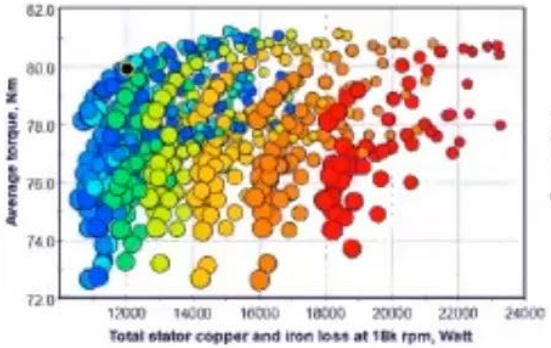
- Above 600-800Hz reduction of Cu conductors cross section area reduces resistance.
- Reducing conductor height is more effective than changing the form.
- U form is more effective than O form (Hollow conductors)
- Aluminium is more effective in high torque (High current)

Case study I: Selection of conductor size

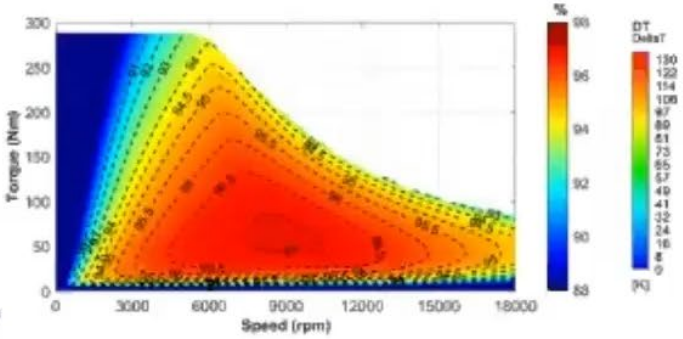
48-slot, 8-pole, 8-layer, aa=2



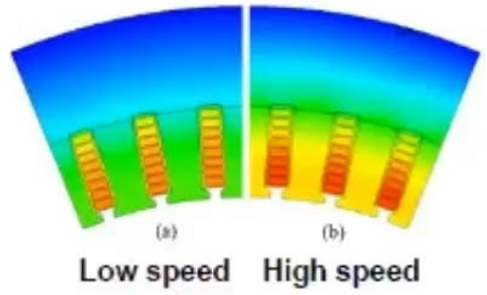
Peak torque operation at 5000rpm



Peak power operation at 18000rpm



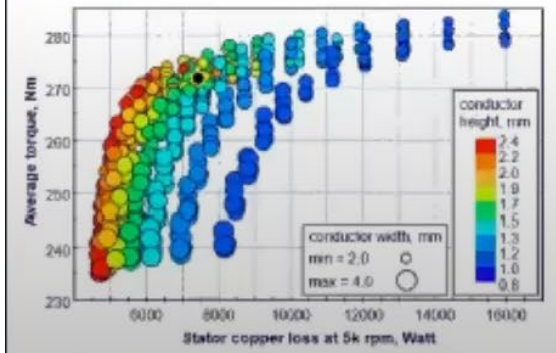
Efficiency map



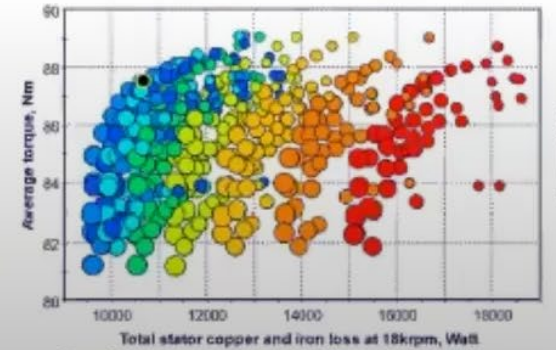
Low speed High speed

Temperature rise distribution

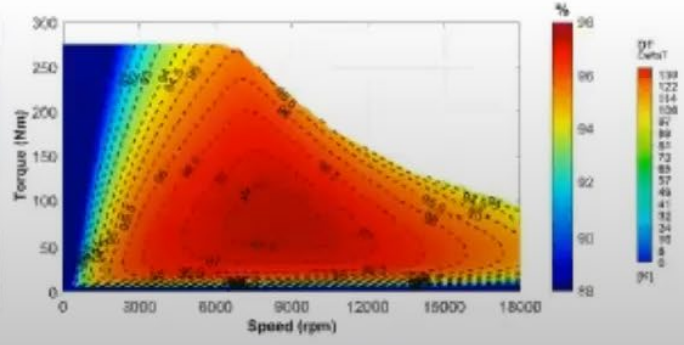
54-slot, 6-pole, 10-layer, aa=3



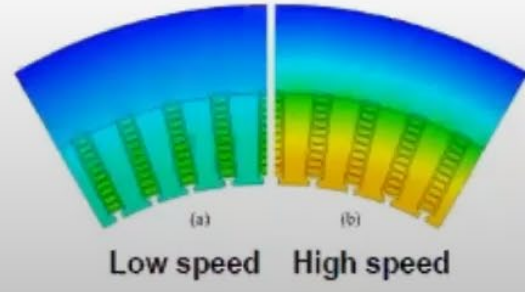
Peak torque operation at 5000rpm



Peak power operation at 18000rpm



Efficiency map



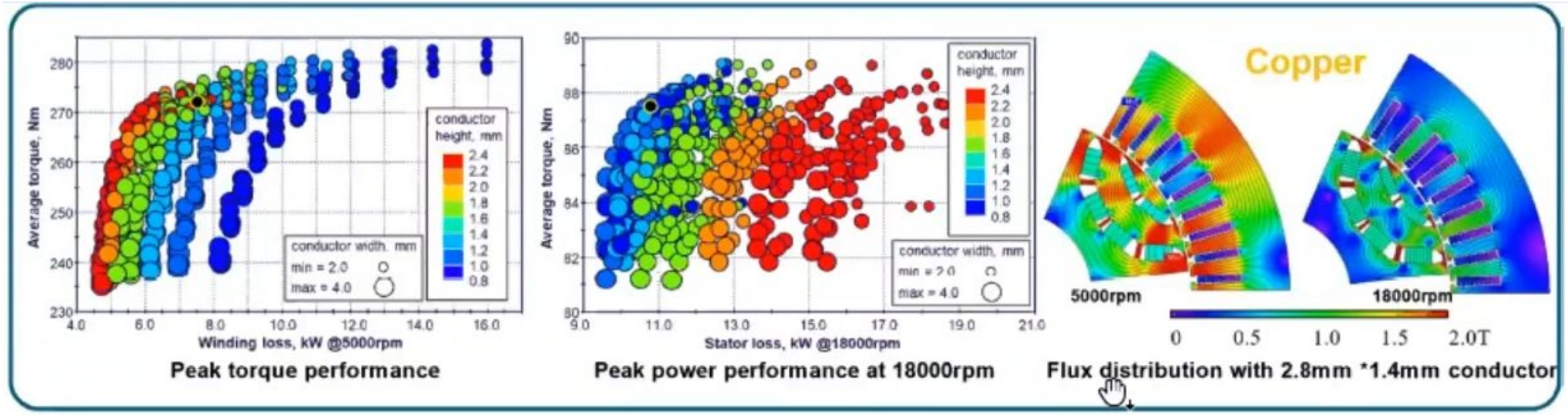
Low speed High speed

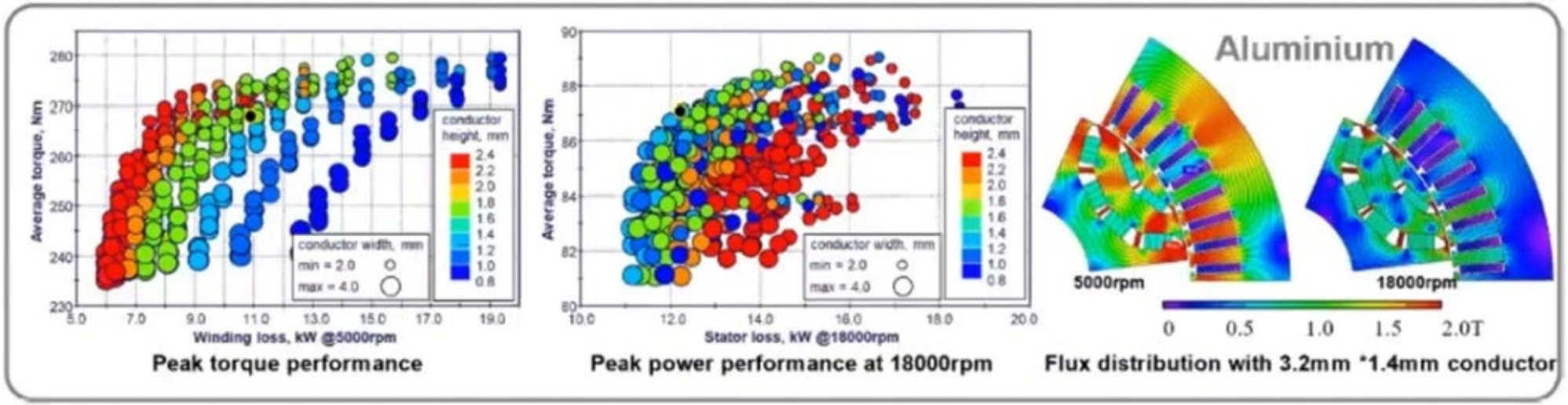
Temperature rise distribution

Based on specific performance requirements 54 slot 8 pole design shows improved efficiency behavior and thermal reliability.

*High performance traction motors with advanced hairpin windings

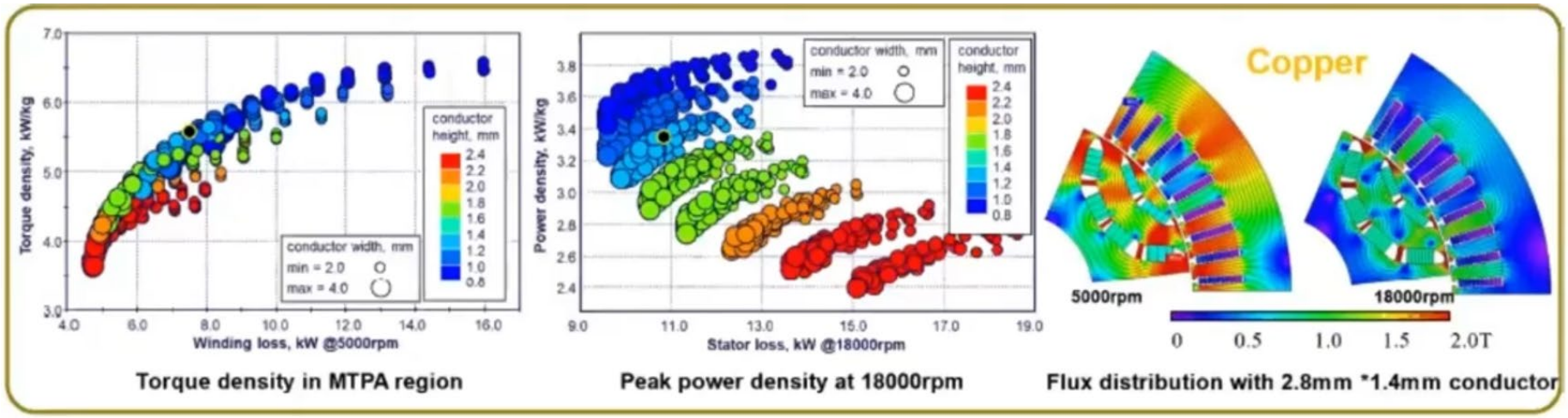
Case study II : Copper Vs Aluminum

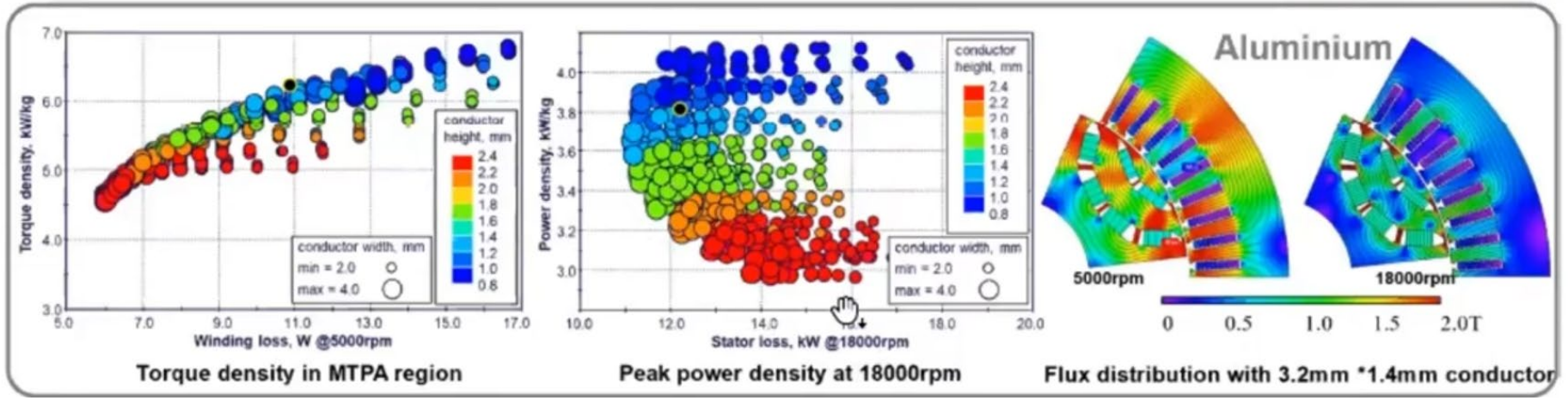




*High performance traction motors with advanced hairpin windings

Case study II : Copper Vs Aluminum





*High performance traction motors with advanced hairpin windings

Conclusion

- Hairpin winding provides benefits to efficiency and manufacturing
- Trend to high-speed machines leads to high frequencies.
- AC losses needs to be minimized to provide good cycle efficiency.
- JMAG can effectively be used for optimization of slot/bar design
- Even slight changes in L_d/ L_q ratio has big effect on cycle losses.
- Pre calculated inductance maps can be used to shorten design time.

Advantages of JMAG

- JMAG Express uses a built-in template to specify fundamental design parameters such geometry, materials, winding pattern and circuit excitation. Model creation takes minutes, and basic performance metrics such as torque vs speed and efficiency are generated in seconds.
- JMAG Designer mesh was specifically developed for extremely high-quality mesh for machine analysis.
- The material database contains about 730 types of material properties (BH and loss) directly provided by the material manufactures. It is also possible to create a custom material and add it to the database.
- Coil settings are easy to apply through an automatic coil winding tool or by manually specifying the coil's input and output slot.
- We can also evaluate the actual drive effects by connecting the machine model to a circuit model and perform analyses by linking to power electronic simulators such as PSIM and MATLAB/Simulink by JMAG-RT.

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