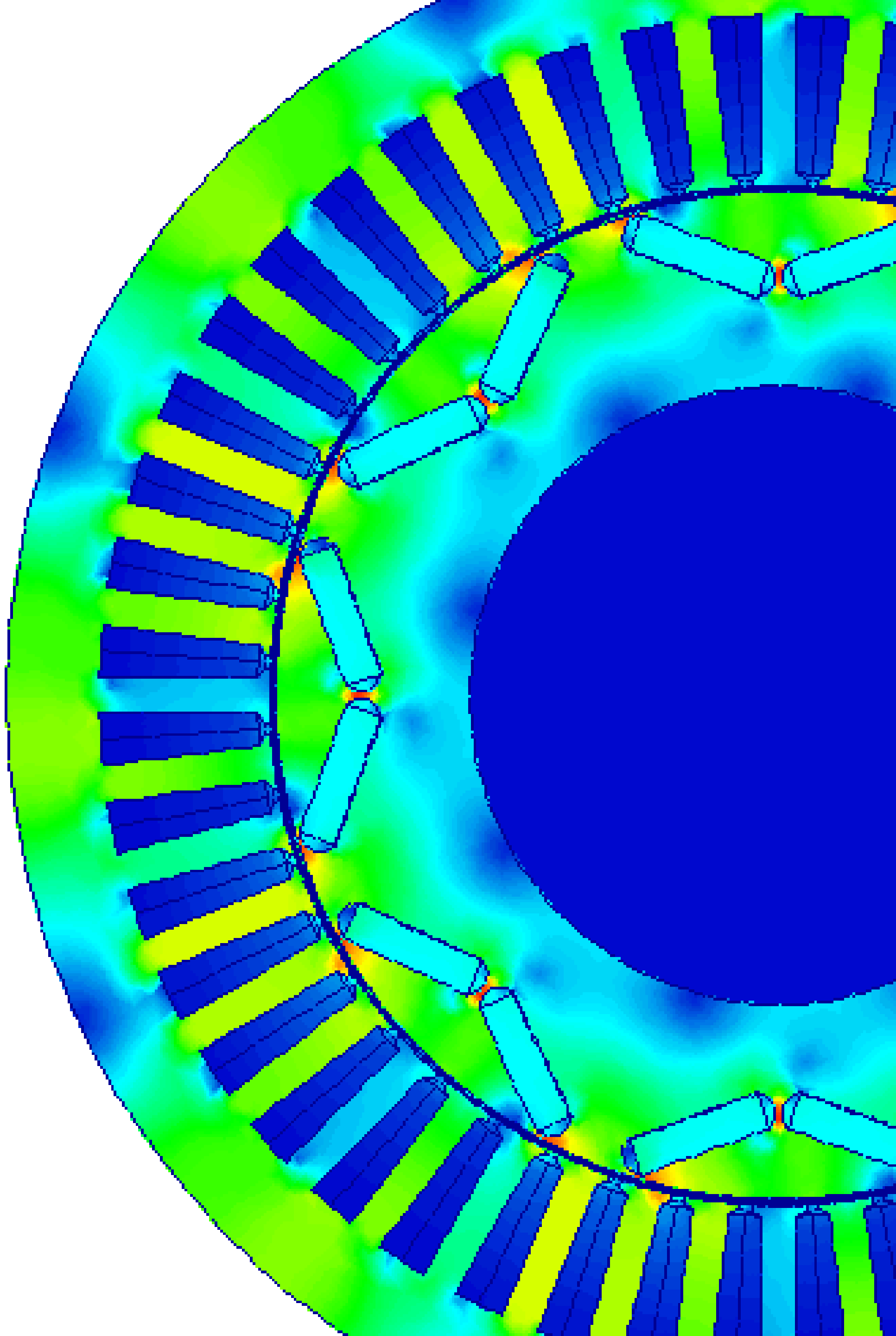
Electromagnetic Losses Modelling in Motor-CAD

Mircea Popescu, June 2021



Agenda

- Introduction to electromagnetic losses in Motor-CAD
- Electric Steel
- AC Winding losses
- Permanent Magnet
- Banding and Sleeve

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Electrical Steel Types

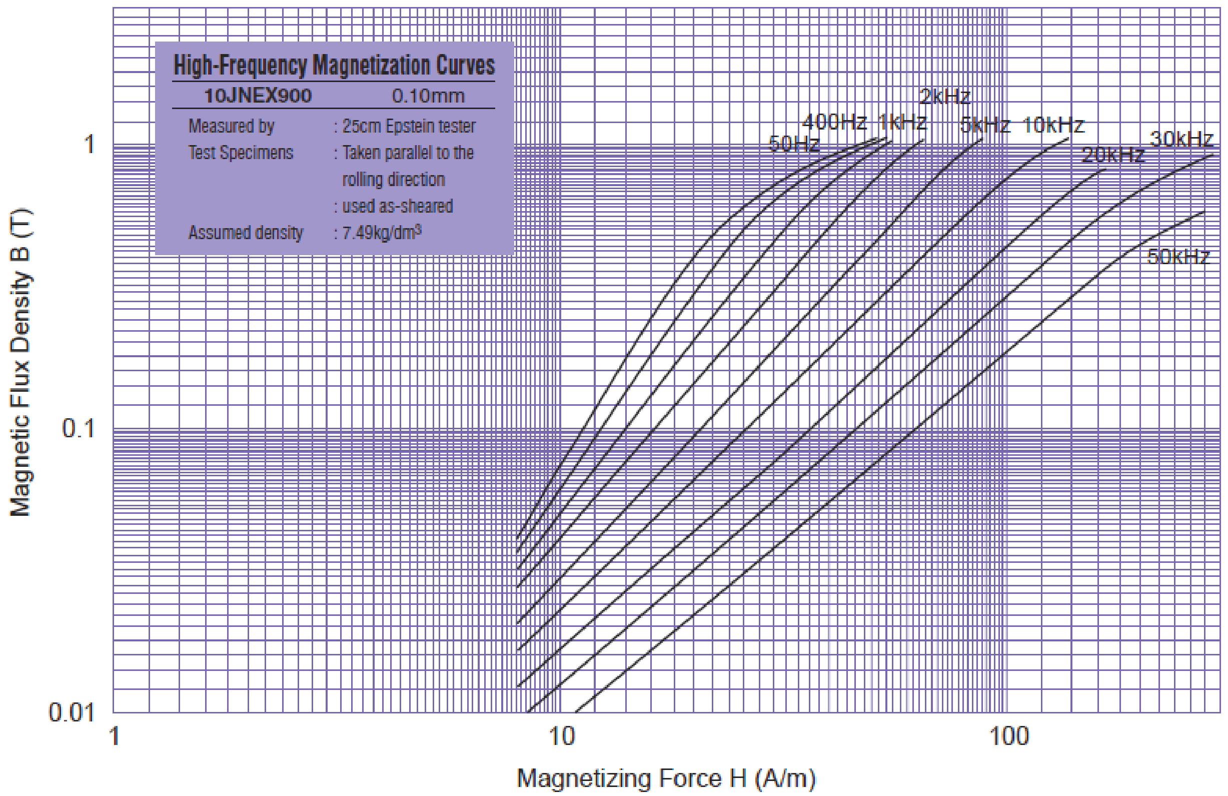
- Silicon iron very popular with more silicon and thinner laminations to reduce iron losses

- Cobalt iron in very specialist applications
  - More expensive and requires carful processing (annealing)

- Certain trend to use powder iron – soft magnetic composites (SMC).
  - can make use of 3D magnetic shapes
  - Has increased hysteresis loss and reduced eddy current loss compared to silicon iron so best used with high frequency applications
  - Reduced saturation level compared to silicon iron

Electrical Steel Types

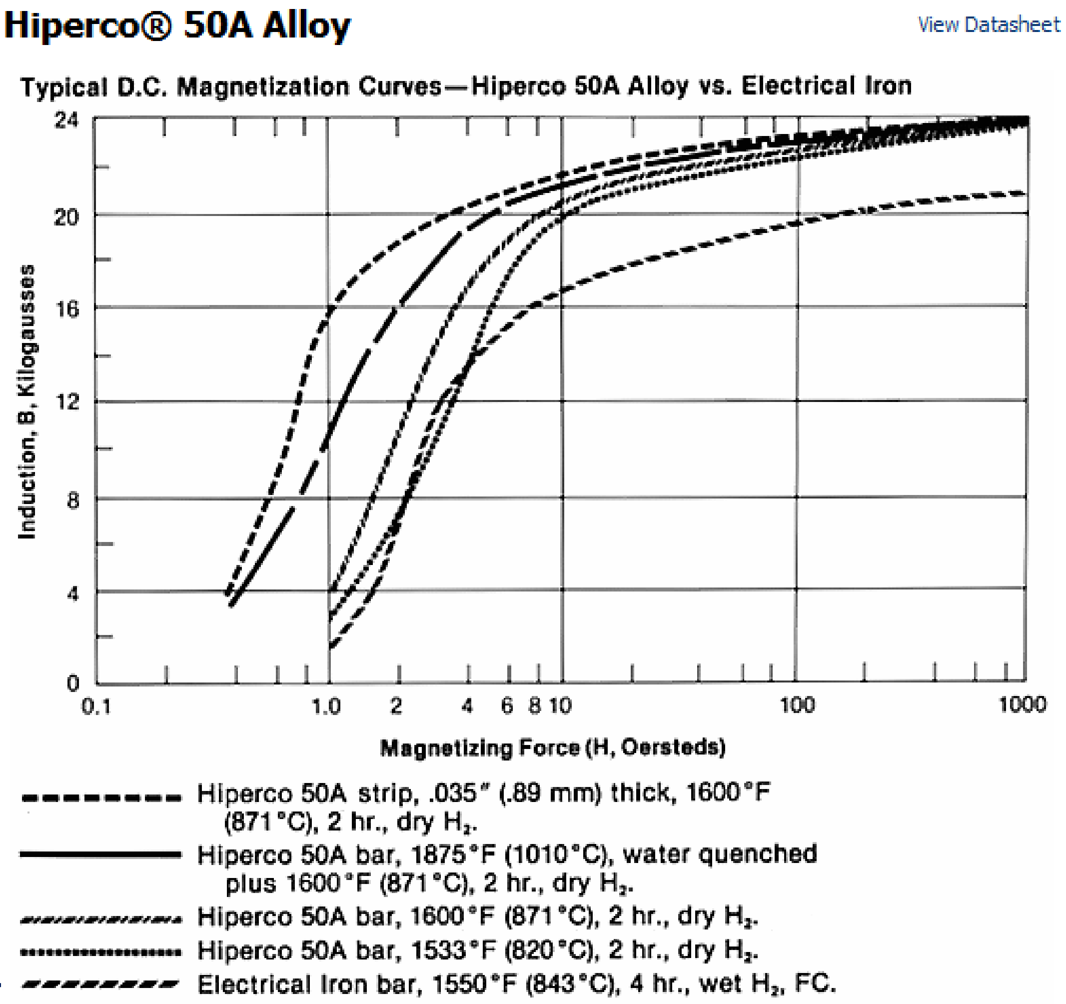
- **Silicon iron** very popular with more silicon and thinner laminations to reduce iron losses
- Thin gage steel materials in default data base:
  - Arnon 4, 5, 7
  - Cogent NO10, NO20
  - JFE Steel 10JNEX



Source: JFE Steel Corp.

Electrical Steel Types

- **Cobalt iron** in very specialist applications
  - Highest permeability for electrical steel
  - More expensive and requires careful processing (annealing)
  - Carpenter
  - VAC



Source: Carpenter Specialty Alloys.

Electrical Steel Types

Source: Höganäs

- **Powder Iron** in very specialist applications
- Benefits
- Up to 60% size and weight reduction
- Natural choice for TFM/Claw-pole and linear brushless DC motors
- Cost-efficient material for high

Typical Data

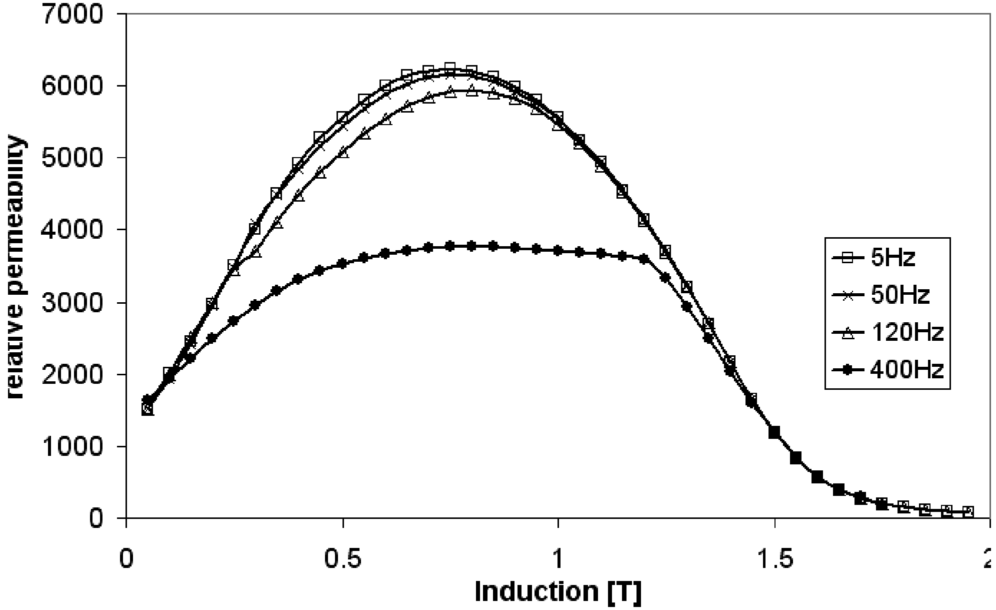
Somaloy Material	Resistivity [µΩ.m]	TRS [MPa]	B@10000 A/m [T]	μ_{max}	Core Losses @ 1T [W/kg]			
					5x5 mm*			15x15 mm
					100 Hz	400 Hz	1000 Hz	1000 Hz
Baseline								
1P Somaloy 130i	8000	35	1.40	290	12	54	145	147
1P Somaloy 700	400	40	1.56	540	10	44	131	158
1P Somaloy 700 HR	1000	35	1.53	440	10	46	134	145
High strength, high permeability								
3P Somaloy 700	200	125	1.61	750	10	46	137	189
3P Somaloy 700 HR	600	120	1.57	630	11	48	137	157
3P Somaloy 1000	70	140	1.63	850	10	46	144	287
Lowest losses								
5P** Somaloy 700 HR	700	60	1.57	600	6	32	104	115

Electrical Steels Losses

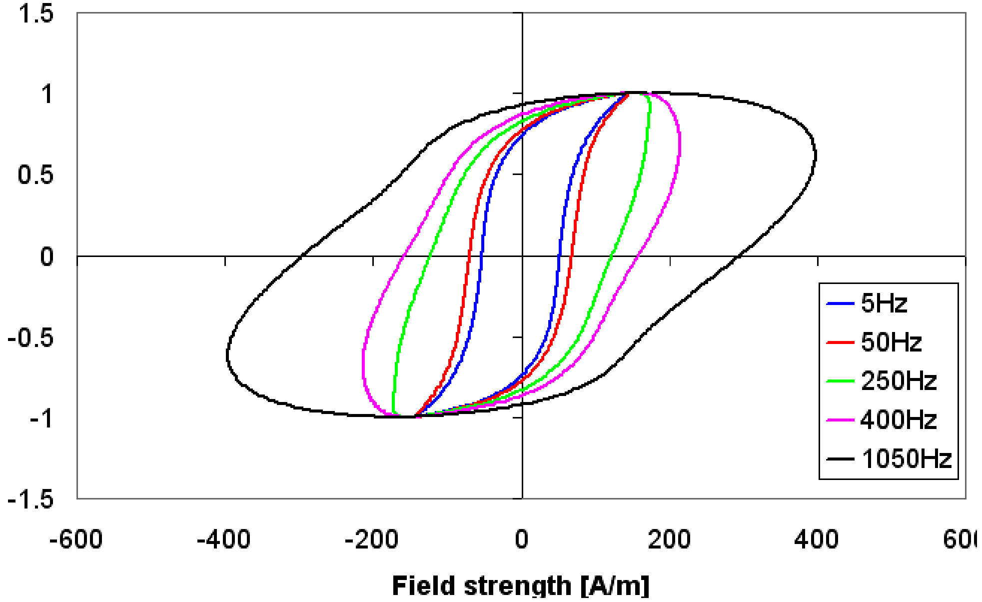
- Significant loss component at high speed, lower number of poles machines
- Difficult to measure or calculate
- Various engineering approaches proposed
- Electric steel changes properties with magnetization level, frequency and manufacturing
- Non-sinusoidal supply increase further the iron losses with 20% to 40%

Electrical Steels Losses

- Electrical steel parameters vary with induction and frequency



Measured relative permeability curves vs peak induction for different frequency levels – fully-processed material M43



Dynamic hysteresis loops for peak induction 1T – fully-processed material M43

Electrical Steels Losses

Core Loss Fundamentals

- Nature of core losses
  - Hysteresis cycle
  - Hysteresis, eddy current, excess losses
- Motor-CAD models
  - Engineering/empirical models
  - Loss coefficients extracted from test data assuming sinusoidal field
  - Best fit using Particle Swarm solder for error minimization

Bertotti Classical

$$W_{Fe}[W/kg] = K_h f\ B^{\alpha} + \frac{(\text{Lamination thickness})^2}{12 \cdot \text{density} \cdot \text{electric resistivity}} f^2 B^2 + K_{exc} f^{3/2} B^{3/2} \quad (1)$$

$$W_{Fe}[W/kg] = K_h f\ B^{\alpha} + K_{eddy} f^2 B^2 + K_{exc} f^{3/2} B^{3/2}$$

Bertotti Maxwell

$$W_{Fe}[W/kg] = K_h f\ B^2 + \frac{\pi^2 (\text{Lamination thickness})^2}{6 \cdot \text{density} \cdot \text{electric resistivity}} f^2 B^2 + K_{exc} f^{3/2} B^{3/2} \quad (2)$$

$$W_{Fe}[W/kg] = K_h f\ B^2 + K_{eddy} f^2 B^2 + K_{exc} f^{3/2} B^{3/2}$$

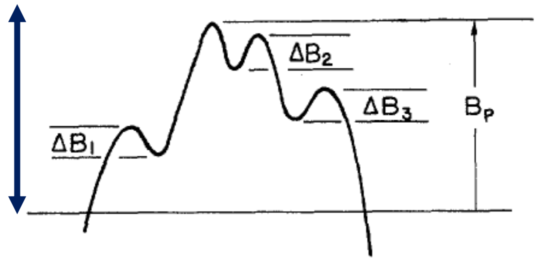
Steinmetz Modified

$$W_{Fe}[W/kg] = K_h f \cdot B^{(\alpha + \beta \cdot B)} + 2 \cdot \pi^2 \cdot K_{eddy} f^2 B^2 \quad (3)$$

Electrical Steels Losses

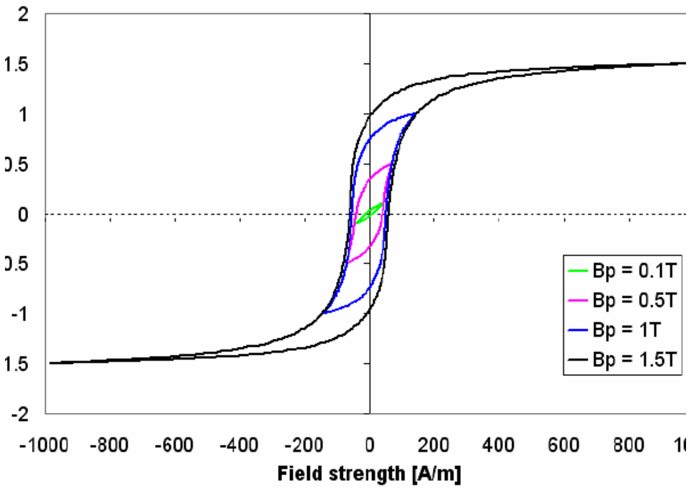
- Electric Steel losses model
- The effect of space and time harmonics is included by using flux-density derivative per components
- Minor hysteresis loops effect included using Lavers (1978) method – track local variation of flux-density amplitude per components
- Few methods to estimate minor hysteresis losses implemented in Motor-CAD

$$K(B_m) = 1 + \frac{K_c}{B_p}\sum_{i=1}^{N} \Delta B_i$$

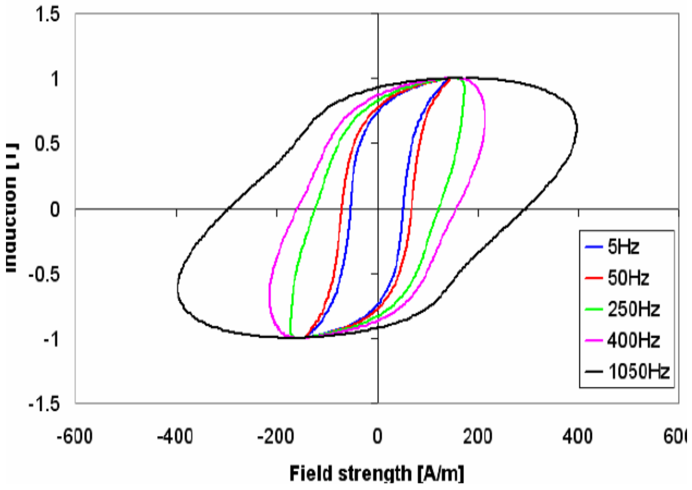


Electrical Steels Losses

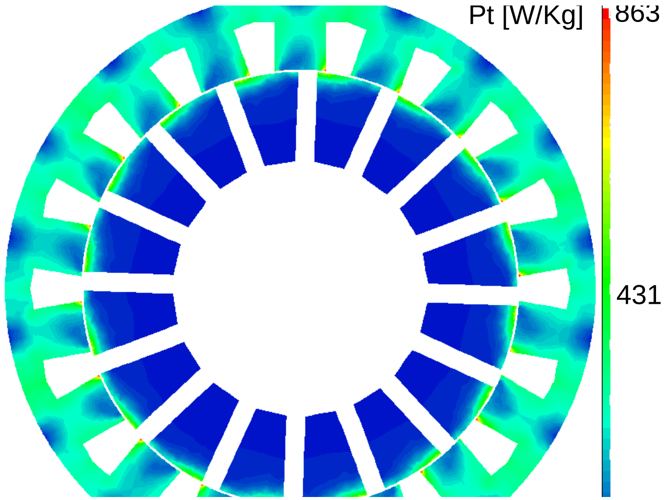
- Test data will capture hysteresis loops
- Calculation shows:
  - loss distribution total and per components
  - Induction components variation in tooth and yoke



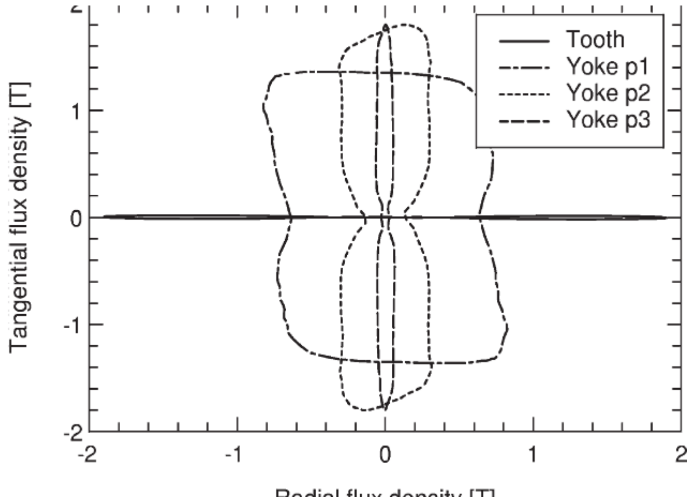
Test Static core losses (low Hz)



Test Dynamic core losses (high Hz)



Core losses distribution in BPM



Induction components variation

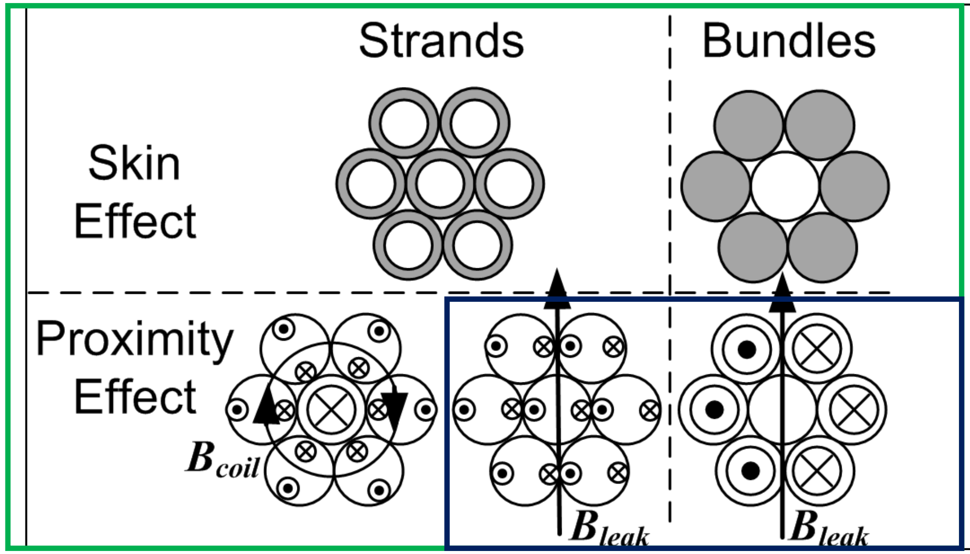
Agenda

- Introduction to electromagnetic losses in Motor-CAD
- Electric Steel losses
- AC Winding losses
- Permanent Magnet losses
- Banding and Sleeve losses

AC Winding Losses

- Eddy currents are induced in conductors in the winding due to their exposure to a changing magnetic field.

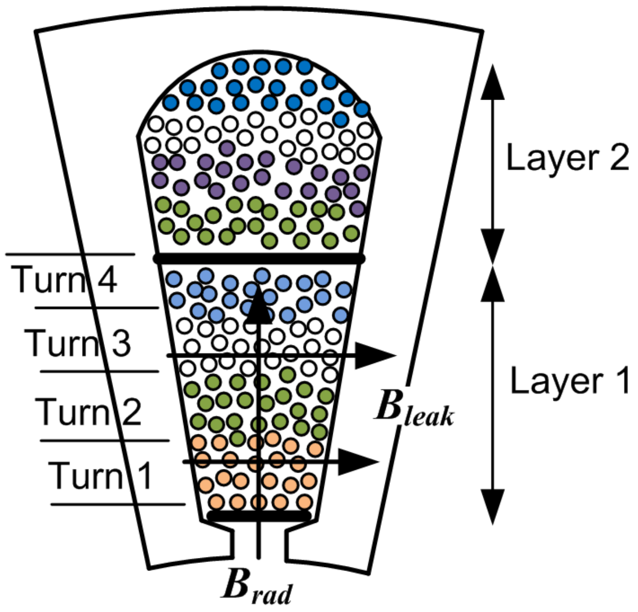
- This magnetic field seen by a conductor is generated by either
  - The conductor (strand or turn) carrying it's own AC current, the skin effect
  - AC currents in adjacent conductors (strands or turns), the proximity effect
  - The field from the rotor during operation, can be significant for machines with large slot openings
- These eddy currents cause the current to flow non-uniformly in the conductor
- This non-uniform current distribution can be considered as an effective increase in resistance. Hence, AC loss is often referred to as an R_{ac}/R_{dc} ratio



Motor-CAD Method: Full FEA –

Motor-CAD Method: Hybrid –

AC Winding Losses



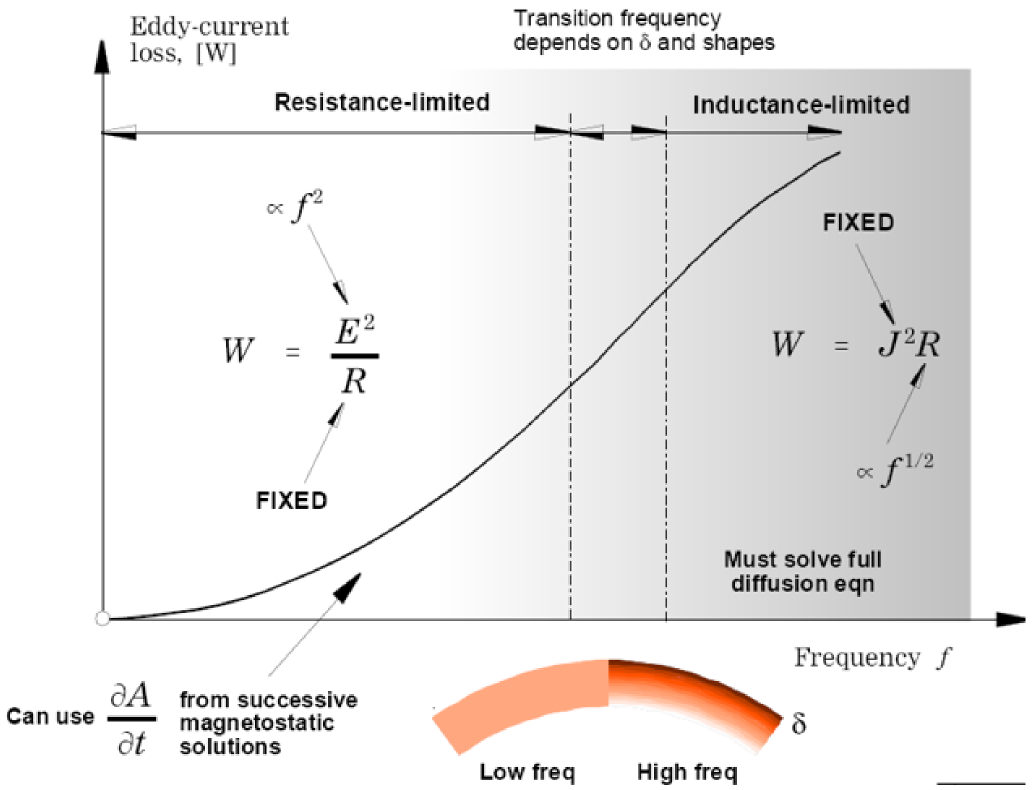
- Self-induced skin effect is mitigated via:
  - Smaller wire size

- The proximity effect is mitigated via
  - Transposition, the field creating the eddy currents is cancelled
  - Minimisation of the height of the bundle in the radial direction, *h*, AC losses are proportional to h^4!
  - Position of the turns within the slot, the leakage field is much higher nearer the slot opening

- The rotor excitation effect is mitigated via:
  - Smaller slot opening
  - Magnetic slot wedges
  - Position of the turns within the slot

- The proximity effect is typically the most significant aspect and most challenging to deal with.

AC Winding Losses



- The induced eddy currents scale with f^2 at lower frequencies.
- At higher frequencies the eddy currents become inductance limited and the increase with frequency is reduced.
- The transition from resistance limited to inductance limited occurs when the skin-depth δ < turn height h:

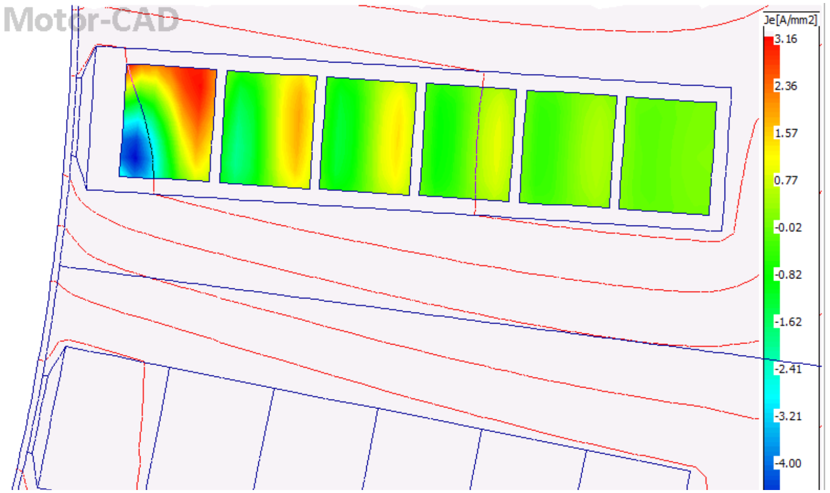
$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} \leq h$$

- ρ resistivity of the conductor
- ω frequency
- μ relative permeability

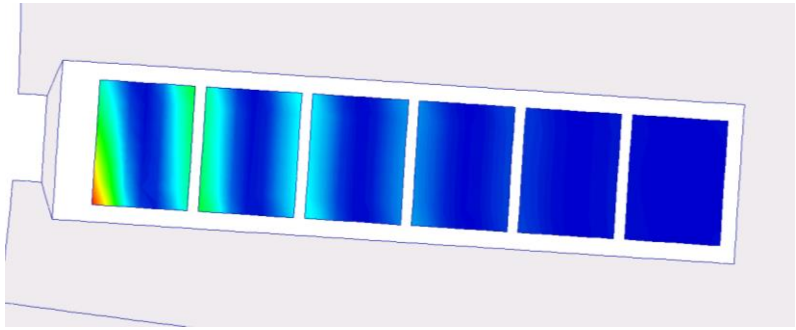
AC Winding Losses

Full FEA

- Eddy current diffusion equation is solved using the 2D FEA transient solver in Motor-CAD
- This calculates the current density distribution for any operating point and hence the total joule loss in each conductor
- Assumptions:
  - Only a single slot is populated with conductors in the FEA solution to reduce computation time
  - We assume that there are no AC losses in the end windings
  - No transposition is accounted for



Instantaneous eddy currents in the conductors during operation



Loss distribution in the conductors over 1 electrical cycle. Note conductors at the back of the slot have a very even current distribution unlike the conductors near the slot opening.

AC Winding Losses

Model Validity	Skin Effect	Proximity effect
Single Strand	FEA	FEA/Hybrid
Multi Strand	FEA	FEA/Hybrid
Multi Strand Double Layer	FEA	Limitation due to circulating currents
Hairpin	FEA/Hybrid	FEA/Hybrid

- Hybrid model is good for resistance limited eddy-currents domain, i.e. skin-depth >= conductor dimensions
- Hybrid model needs correction for inductance limited eddy-currents domain, i.e. skin-depth << conductor dimensions
- FEA model is always valid, but limited in multi-strand double layer problems due to missing the circulating currents effect

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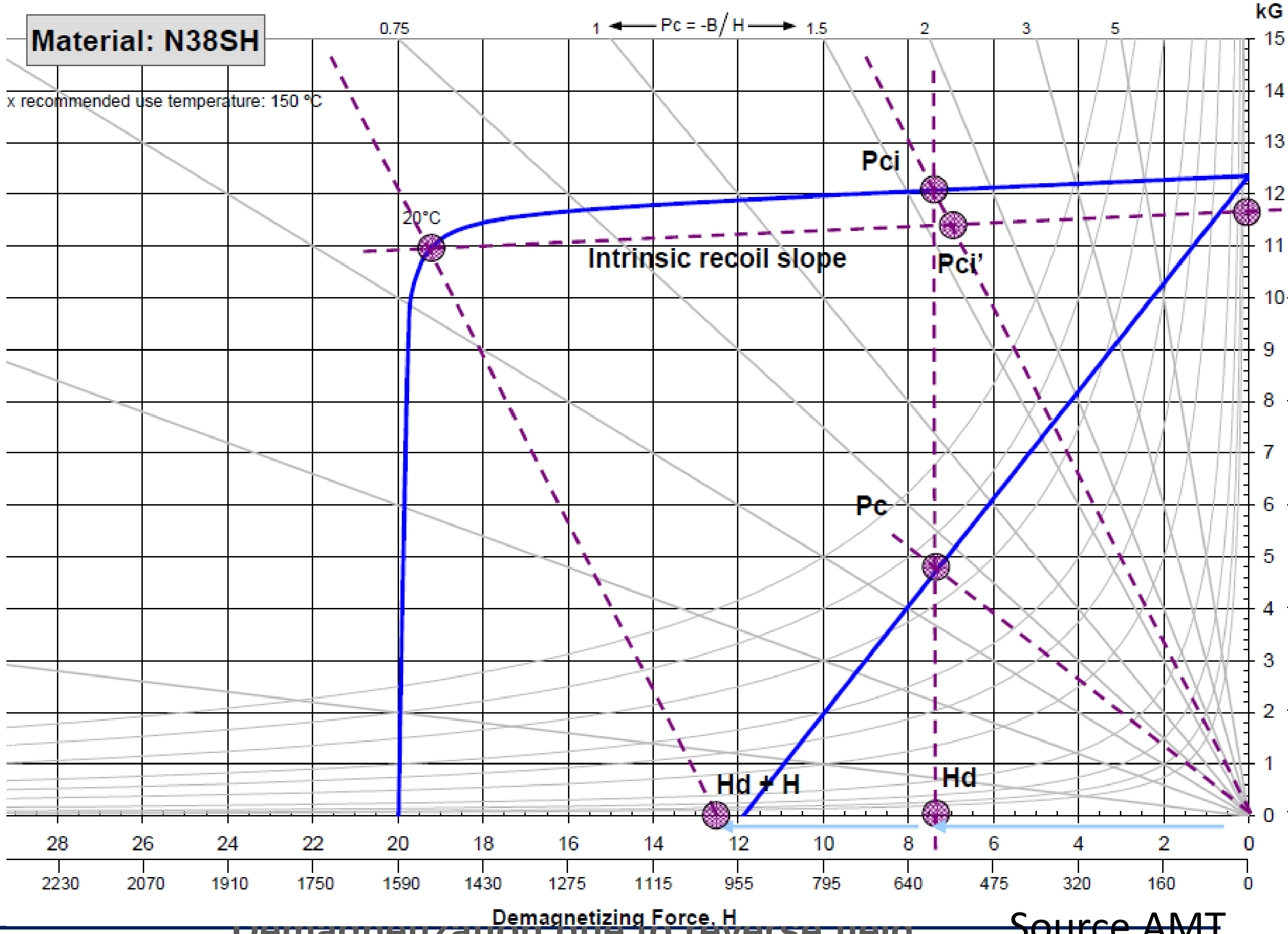
Permanent Magnets

- PM lead to designs with the highest torque density in electric machines
- Significant development last 30 years
- Various applications from renewable energy to HEV and home appliances
- Can be irreversibly demagnetized due to thermal stress and electric load
- Need of combination between optimised electrical design and efficient cooling systems
- Rare-earth magnets types:
  - SmCo
  - NdFe



Demagnetization due to reverse field

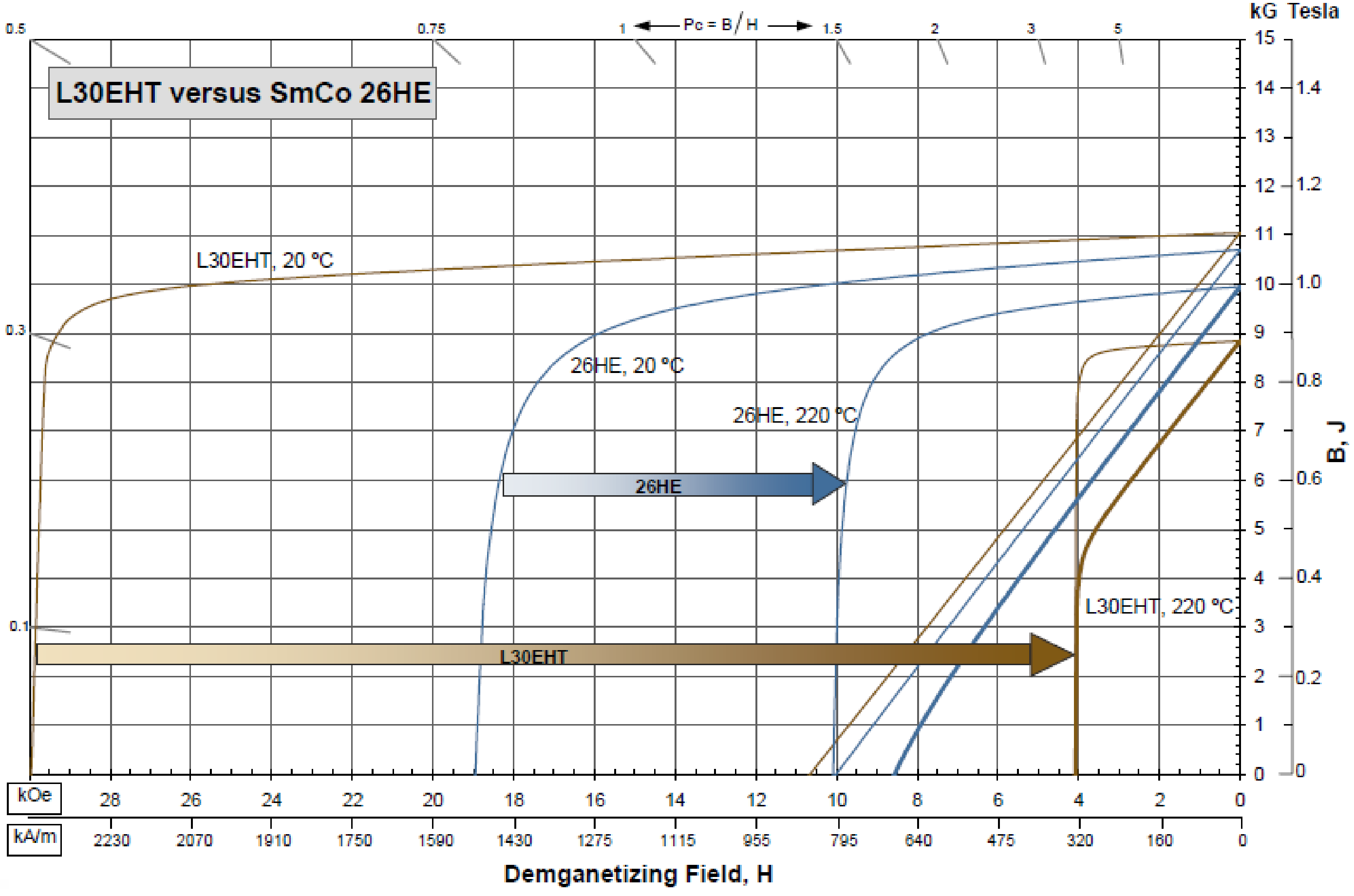
Source AMT

www.motor-design.com

Permanent Magnets

- SmCo have the highest operation temperature
- NdFeB have the highest levele of stored magnetic energy
- In same volume, SmCo will exhibit almost double amount of losses vs NdFeB
- Trade-off between cost and technical solution to cool the system

Temperature Effect on NdFeB and SmCo



Source AMT

Permanent Magnets Losses

- Magnet are electrically conductive
- Conductivity less influence by temperature (6% to 10% for 100C temperature rise)
- Higher magnet losses in surface BPM than interior BPM
- Surface BPM may require retainer sleeve – extra losses
- Retainers made of various materials
- Induced eddy-currents create losses
- Eddy-current induced by:
  - space MMF harmonics;
  - permeance variation;
  - time current harmonics;

Electrical Resistivity Values [Ωm]

Material	Value
Copper	1.724×10^{-8}
Iron	10×10^{-8}
Aluminum	2.8×10^{-8}
SmCo 1-5 Alloys	50×10^{-8}
SmCo 2-17 Alloys	90×10^{-8}
NdFeB – sintered	160×10^{-8}
NdFeB – bonded	14000×10^{-8}
Ferrite	10^{5}

- Magnet losses mitigated via:
  - Integer or fractional slots/pole
  - Segmentation

Permanent Magnets Losses

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}}$$ **Skin-depth formula**

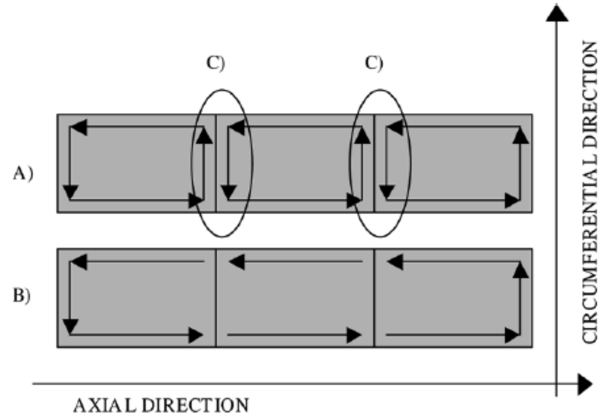
- σ is the conductivity of material in which the eddy-currents are flowing, in [S/m]; μ is the permeability in [H/m], and ω is the relevant exciting frequency in [rad/s].
- Comparison of the skin depth with a “relevant dimension” gives rough idea as to whether the eddy-currents are “resistance limited” or “inductance limited”.
- Resistance-limited eddy-currents are characteristic of low-frequency operation when δ is larger than the “relevant dimensions”
- At high frequency the eddy-currents can become inductance-limited, to such an extent that they completely shield the interior of the conducting region from the alternating component of flux
- Losses continue to increase with frequency, but a slower rate than they do in the resistance-limited case.

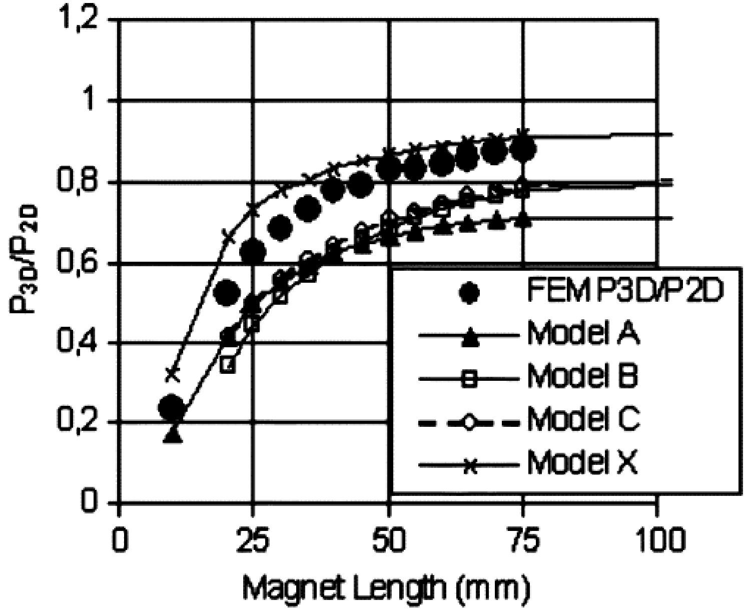
Permanent Magnets Losses

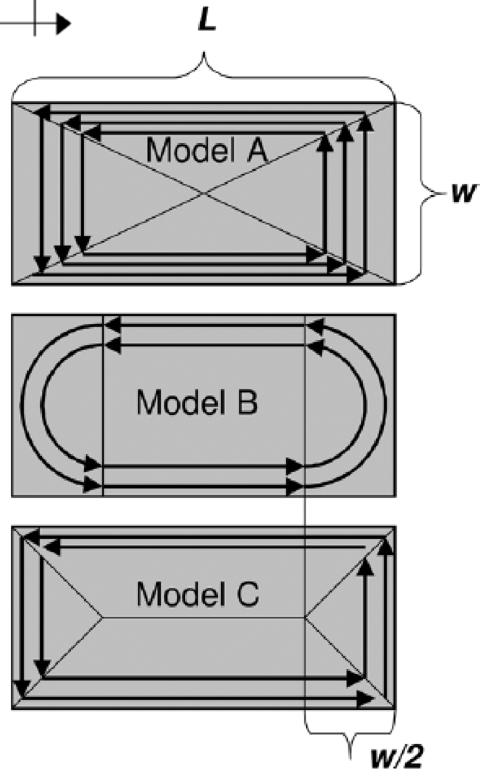
Dimensions effect in modelling of magnet losses

- L = axial length of magnet block
- w = width of magnet block
- Uncertainties in arc shape magnets on w value
- Valid for resistance limited eddy-currents: $\delta = \sqrt{\frac{2\rho}{\omega\mu}} > h$

$$F = \frac{P_{3D}}{P_{2D}} = \frac{3}{4} \cdot \frac{L^2}{w^2 + L^2}.$$



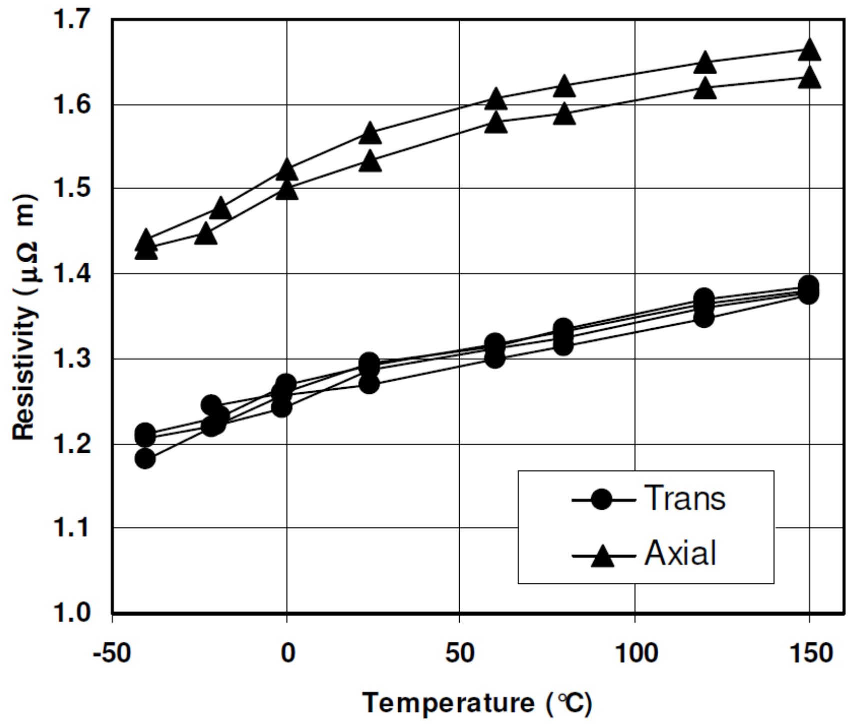




Ruoho et al, Modeling Magnet Length In 2-D Finite-Element Analysis of Electric Machines, IEEE Trans. On Magnetics, 2009,

Permanent Magnets Losses

- Electrical resistivity of permanent magnets varies with temperature, but just about 10% increase for 100C temperature rise
- Temperature coefficient available only via complex measurements
- 2D FEA use the electrical resistivity in axial direction
- In Motor-CAD, user can create different magnet material to account for changes in electrical resistivity



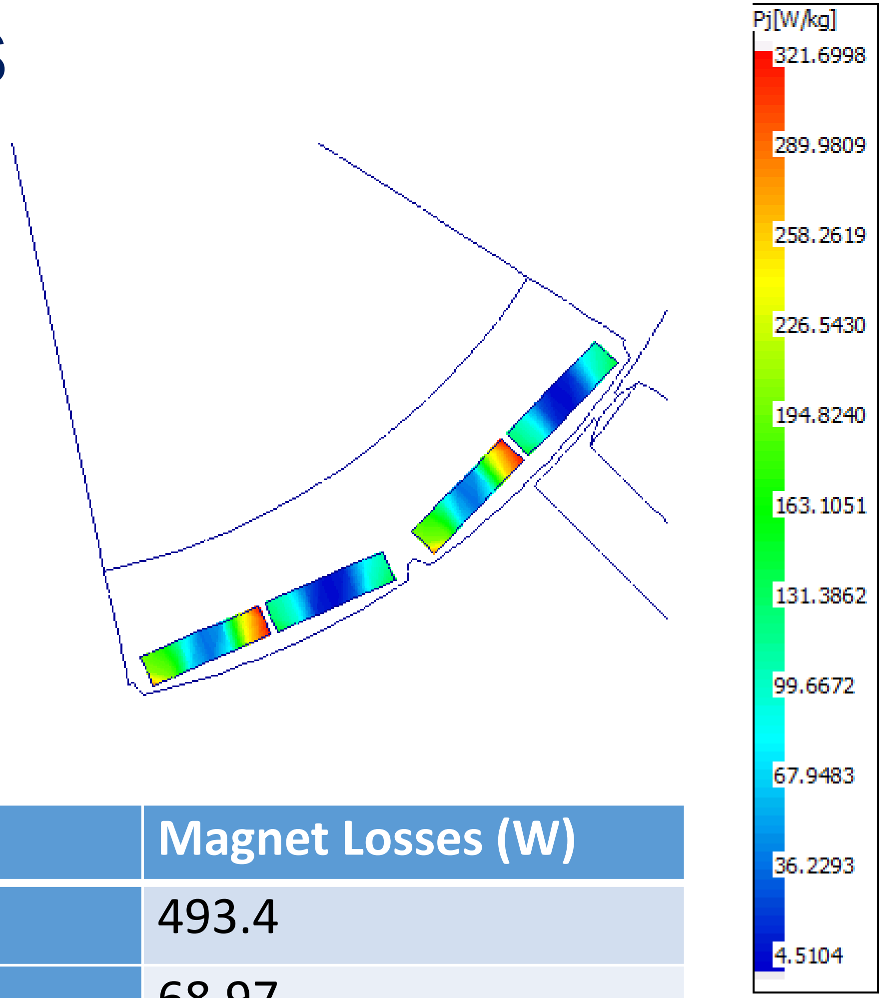
The electrical resistivity of sintered NdFeB magnet material as a function of temperature.
The resistivity in the axial orientation direction is greater than the resistivity perpendicular to the orientation direction (transversal).

S. Ruoho, Modeling Demagnetization of Sintered NdFeB Magnet Material in Time-Discretized Finite Element Analysis, PhD Thesis, Helsinki, 2010

Permanent Magnets Losses

Example: Accord 2005

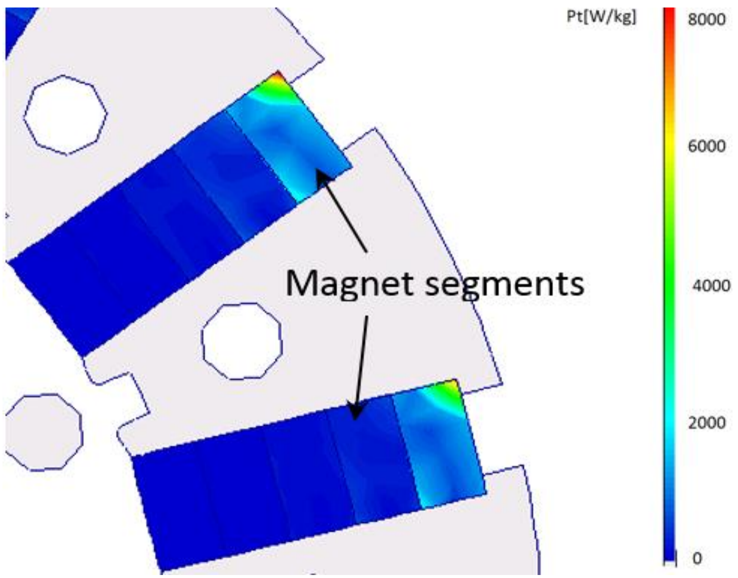
- 24 slots/16 poles
- Rotational speed = 5000rpm
- Peak current = 145A
- Phase advance = 21.5 edge
- Magnet material = N30UH
- Magnet dimensions = (T) 4.46mm X (W) 18.45mm X (L) 8mm



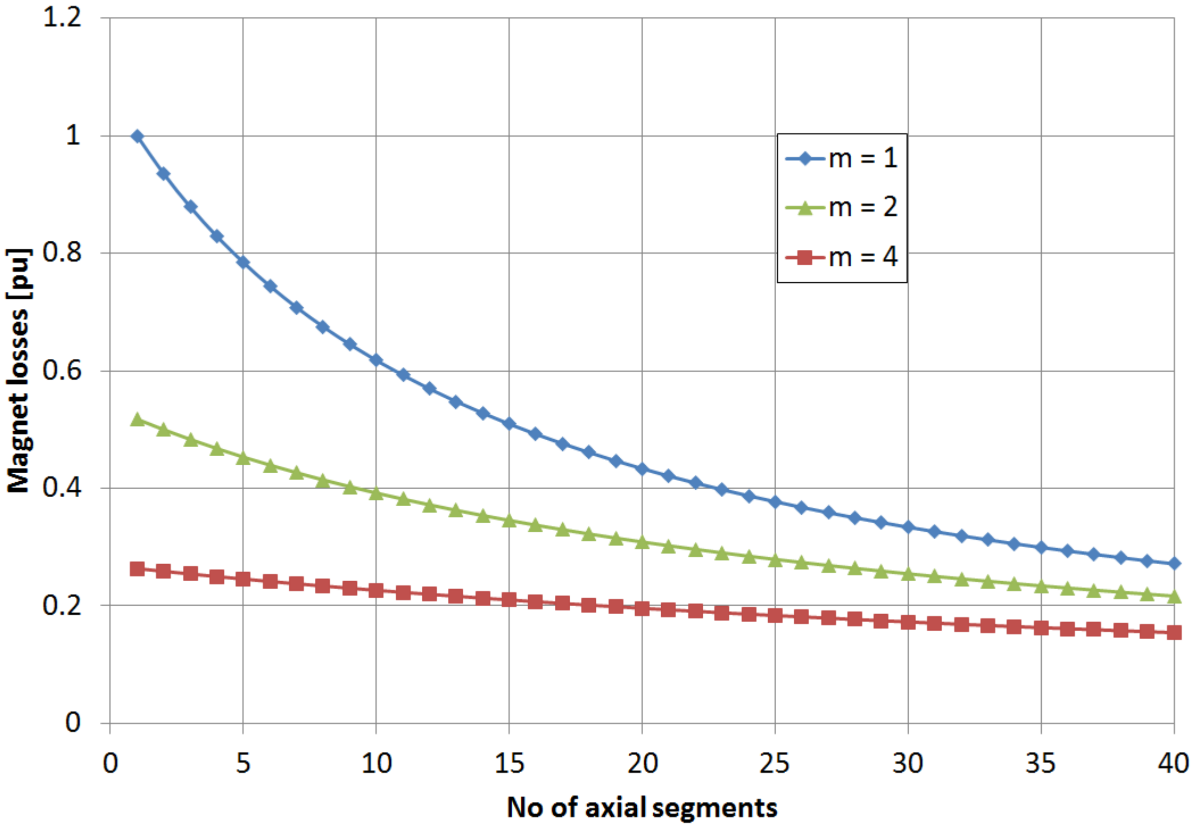
3D Scaling	Magnet Losses (W)
None	493.4
Preprocessing	68.97
Postprocessing	58.56

Permanent Magnets Losses

Circumferential Segmentation



Effect of combined segmentation on magnet losses



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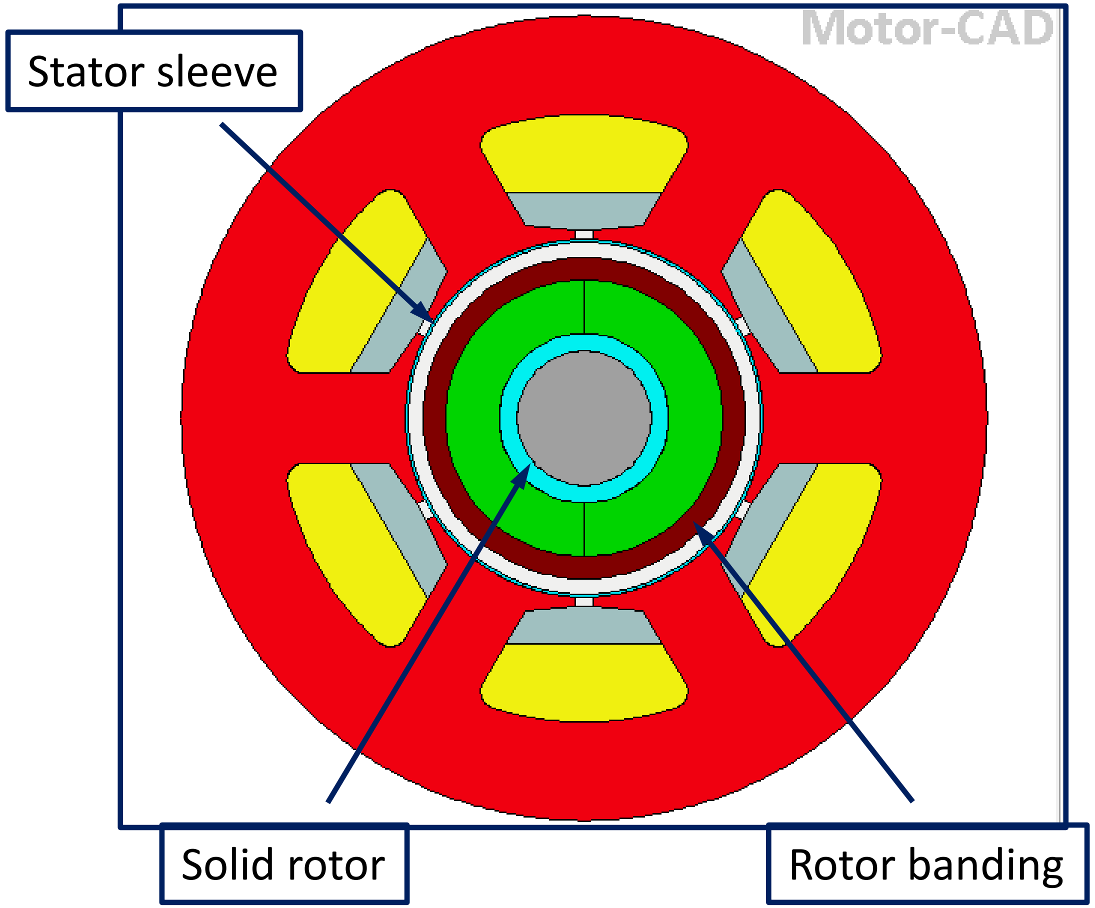
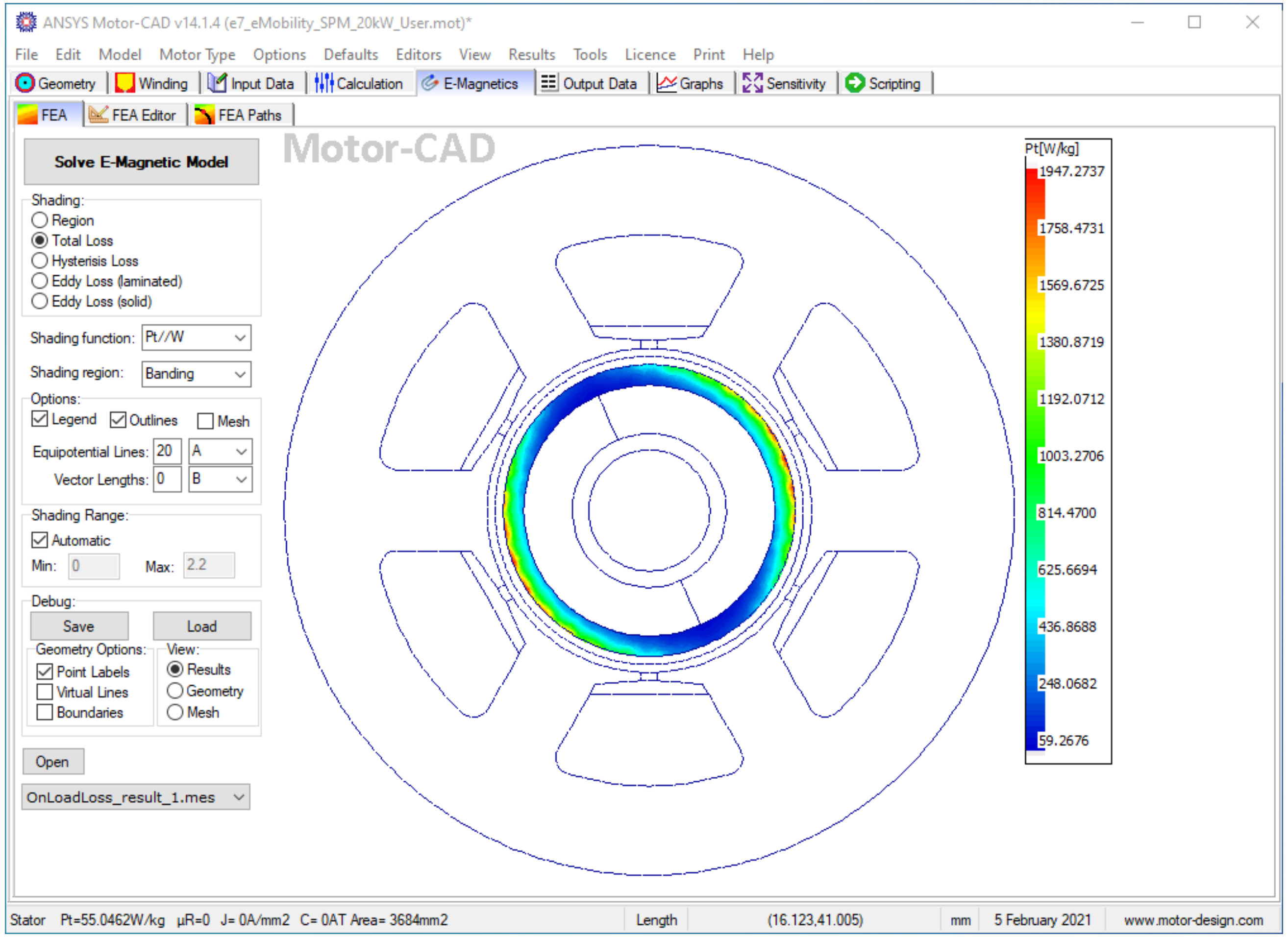
Banding and Sleeve Losses

- Due to the centrifugal force and radial electromagnetic force is often necessary to retain magnets with sleeves;
- Stator sleeve may be present in submersible motors or for special cooling systems, e.g. stator slot forced fluid cooling, to retain the cooling fluid.
- Sleeve materials are electrical conductive, i.e. metals;
- Glass fiber an exception, but less strength at high speed;



Banding and Sleeve Losses

Variable	Value	Units
Armature DC Copper Loss (on load)	0.04227	kW
Magnet Loss (on load)	0.0002258	kW
Stator Sleeve Loss (on load)	1.159	kW
Rotor Banding Loss (on load)	0.05304	kW
Stator iron Loss [total] (on load)	0.1267	kW
Rotor iron Loss [total] (on load)	0.000171	kW



Banding losses
NOTE: Type banding in shading region box

Banding and Sleeve Losses

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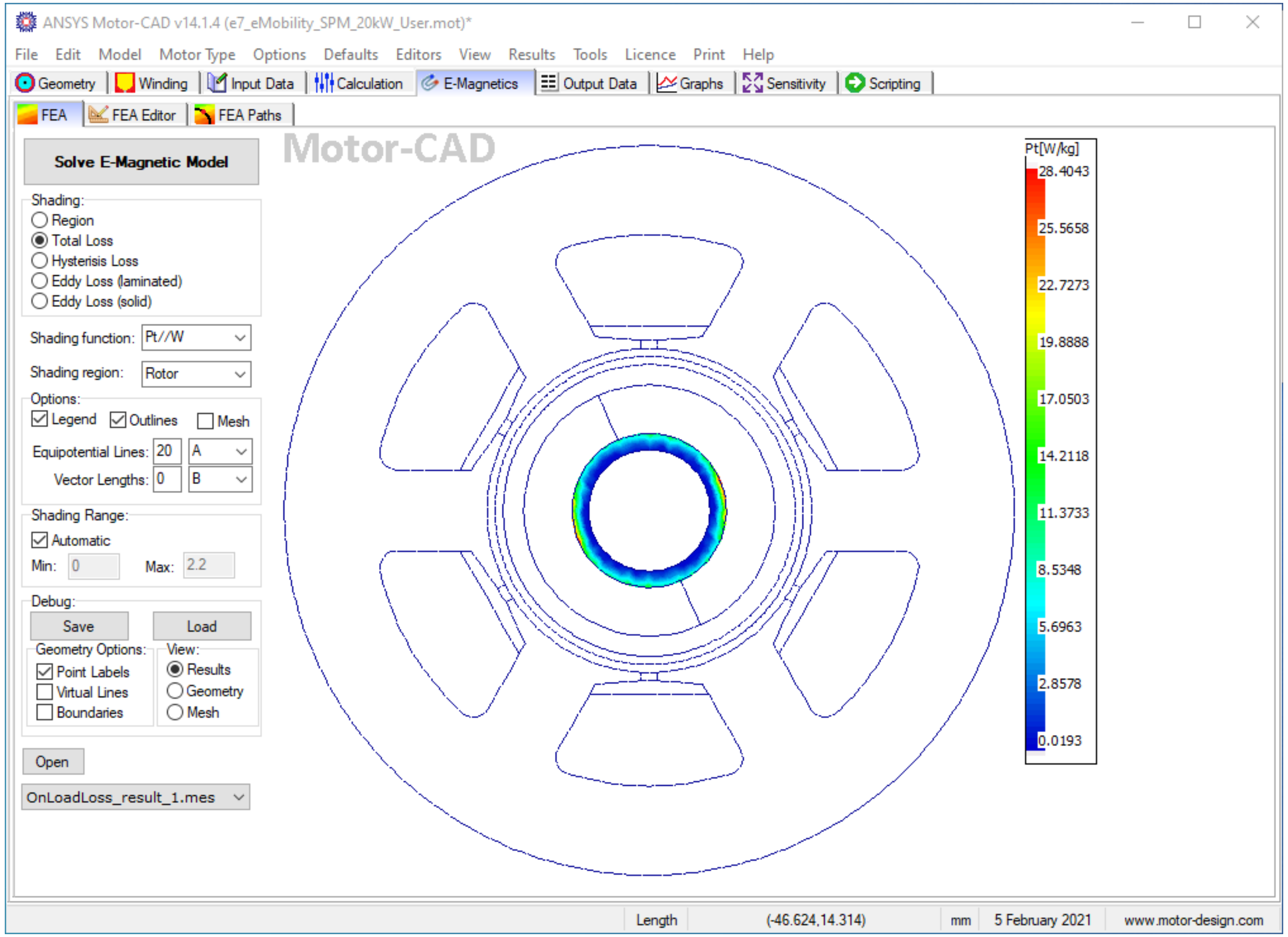

Solid rotor losses

NOTE: Select “Rotor” in shading region box

Conclusions

- In any metallic solid region, i.e. electrical resistivity ~ 1E-6 to 1E-8 ohm*m, a variable electromagnetic field will induce eddy-currents and hence losses
- Metallic stator sleeve to be used only at low frequency < 100Hz, at higher frequencies must use carbon or glass fibre, or any high electrical resistivity that can insulate the stator assembly
- Rotor banding has to be metallic or carbon-fibre due to mechanical strength requirements
- Magnets loss mitigation can be done via segmentation, axial cheaper, circumferential more effective
- Calculation via 2D transient FEA
- 3D/2D effect uncertainty in 2-pole and 4-pole; if possible calibrate via 3D FEA

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