High Fidelity and Efficient Computation of Losses in Brushless Permanent Magnet Machines

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Special Session

Overview of presentation

- Introduce accurate computationally efficient techniques for estimating loss in PM machines over their full working envelope
- Basis is to use a minimum number of numerical finite element analyses (FEA) to populate analytical functions describing the loss component variations with operating point
- Loss components catered for
  - Core loss
  - Winding AC loss
  - Magnet loss
- Techniques illustrated with test results and analyses from permanent magnet EV propulsion machines

Core losses

When calculating iron loss the working flux density of the various regions of the magnetic circuit should be known

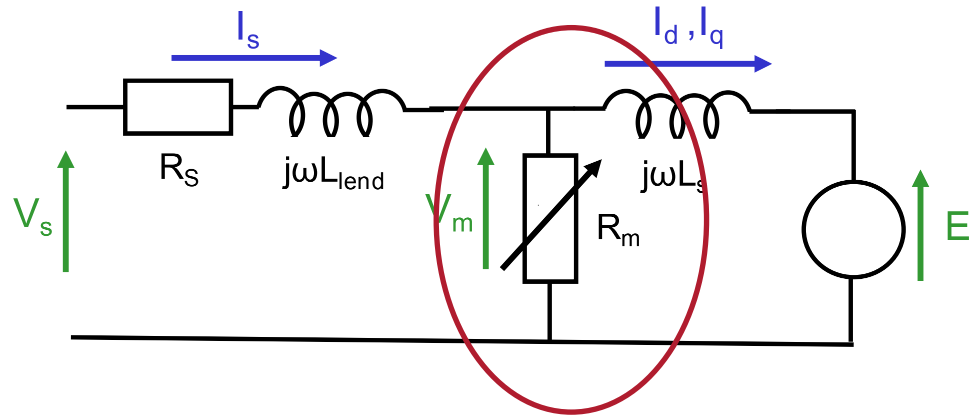
Finite element analyses packages account for this by calculating the loss in every element and averaging. For example using the modified Steinmetz form

$$W_{FE} = k_F k_H B_{pk}^2 f + k_F \sum_{\Delta T} \left[\sigma \frac{d^2}{12} \left(\frac{\Delta B}{\Delta T} \right)^2 + k_E \left(\frac{\Delta B}{\Delta T} \right)^{3/2} \right] \Delta T f$$

This is clearly computationally time consuming if the loss is to be mapped over the full motor operating envelope

Stator core loss in PM machines

Main stator flux path



Induced voltage V_m associated with main flux path

- The strength of the main flux path determines the induced voltage V_m at the motor terminals
- There is a strong correlation between V_m and the stator core loss
- The correlation factor is largely independent of the motor operating point

Main path loss model

1. Magnetostatic 2D finite element field solutions are performed for **open circuit** at discrete positions (times) over an electrical cycle at an arbitrary frequency (f)
2. Emf constant $\lambda = E_{prms} / f$ is obtained from this analysis
3. The core loss is calculated in terms of hysteresis, eddy current and excess loss components

$$P_{FE}^{OC}(f) = a_h f + a_J f^2 + a_{ex} f^{1.5}$$

4. Iron loss expressions are converted into equivalent voltage functions by substituting the emf constant

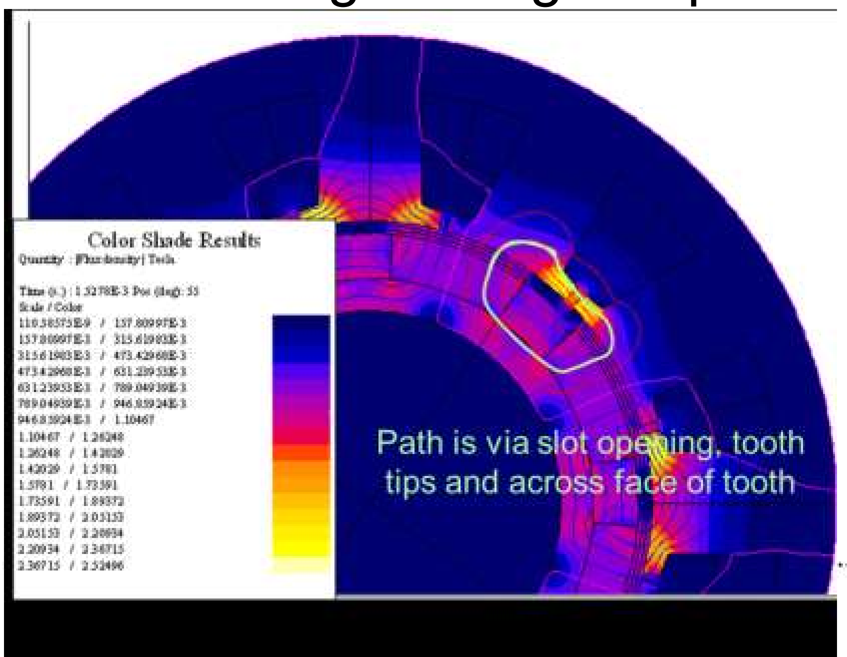
$$g_1(V_m) = \frac{a_h}{\lambda} V_m + \frac{a_J}{\lambda^2} V_m^{\ 2} + \frac{a_{ex}}{\lambda^{1.5}} V_m^{\ 1.5}$$

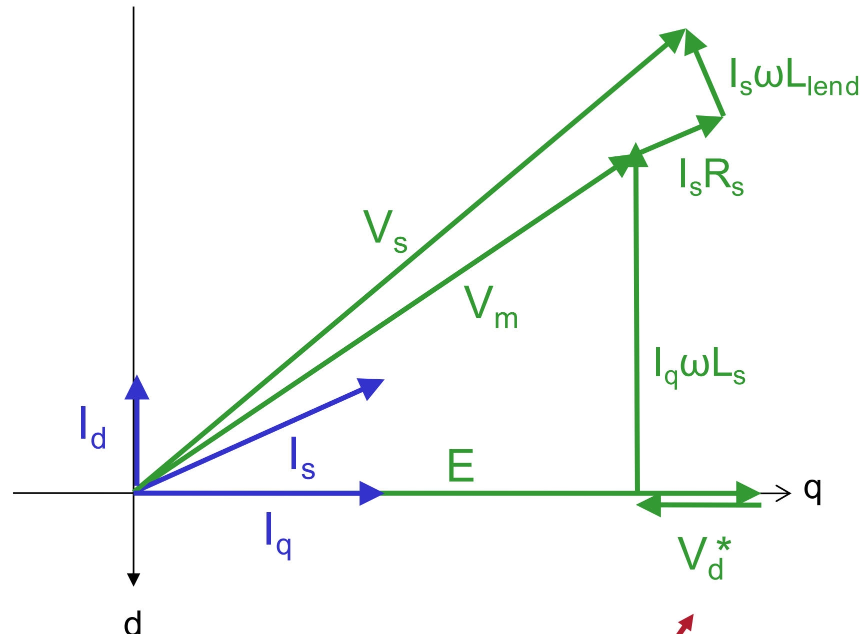
Operation at an arbitrary load point

Core loss is found from the superposition of two effects:

Loss associated with the main flux path

\+ Additional loss associated with the demagnetising flux path





Voltage V_d^* associated with demagnetising flux path

Ideal short circuit $V_d^* = E$ (emf)

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Demagnetising path loss model

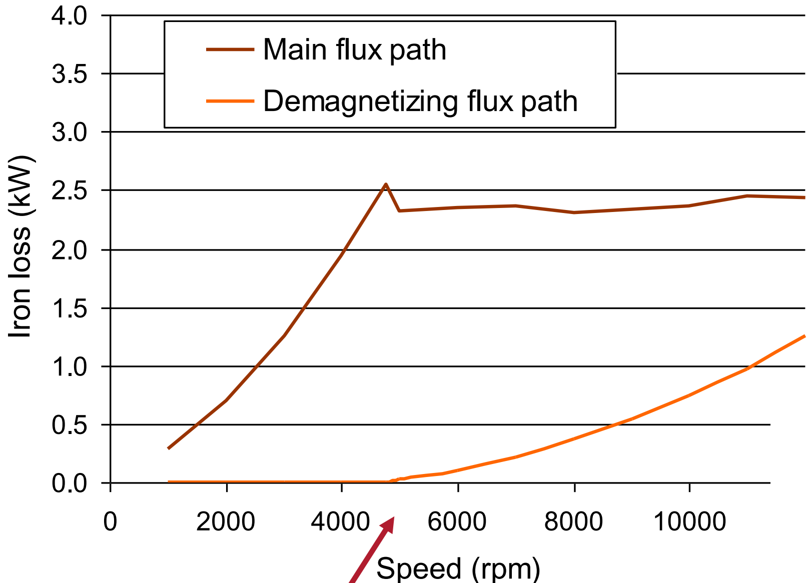
1. Magnetostatic 2D finite element field solutions are performed for **short circuit** at discrete positions (times) over an electrical cycle at an arbitrary frequency (f)
2. The core loss is calculated in terms of hysteresis, eddy current and excess loss component.

$$P_{FE}^{SC}(f) = b_h f + b_J f^2 + b_{ex} f^{1.5}$$

4. Iron loss expressions are converted into equivalent voltage functions by substituting the emf constant

$$g_2(V_d^*) = \frac{b_h}{\lambda} V_d^* + \frac{b_J}{\lambda^2} V_d^{*2} + \frac{b_{ex}}{\lambda^{1.5}} V_d^{*1.5}$$

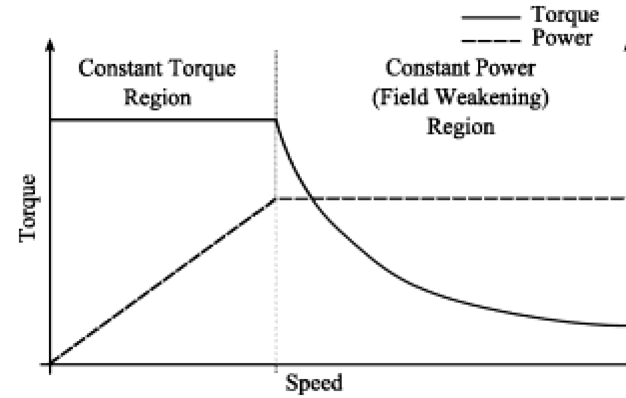
Core loss during field weakening

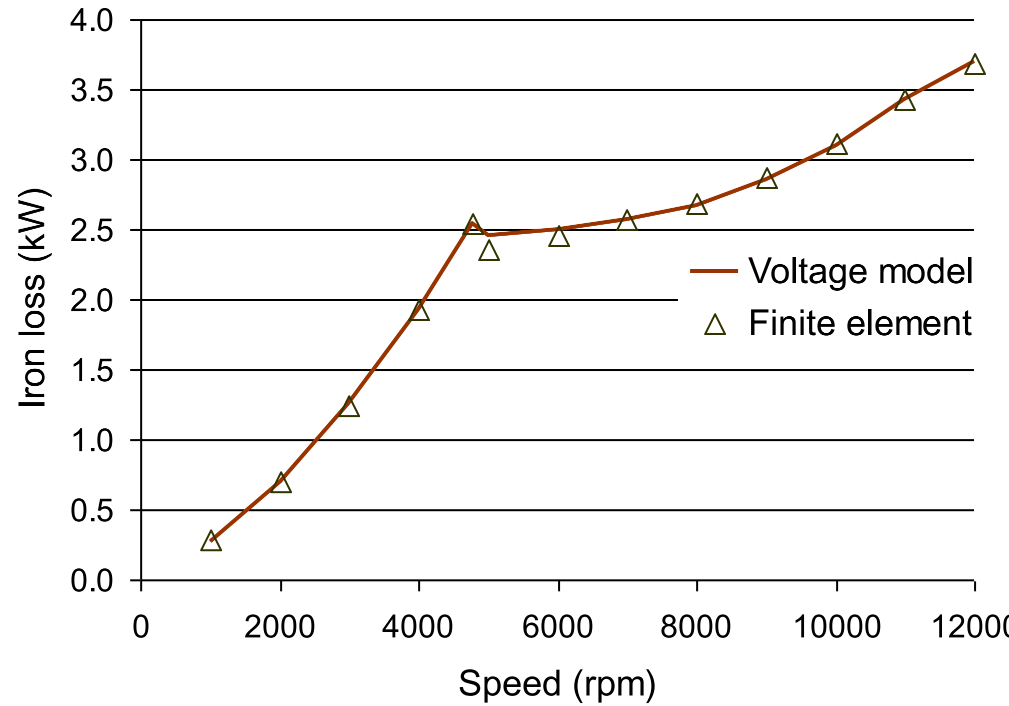


$g_1(V_m)$

$g_2(V_d^*)$

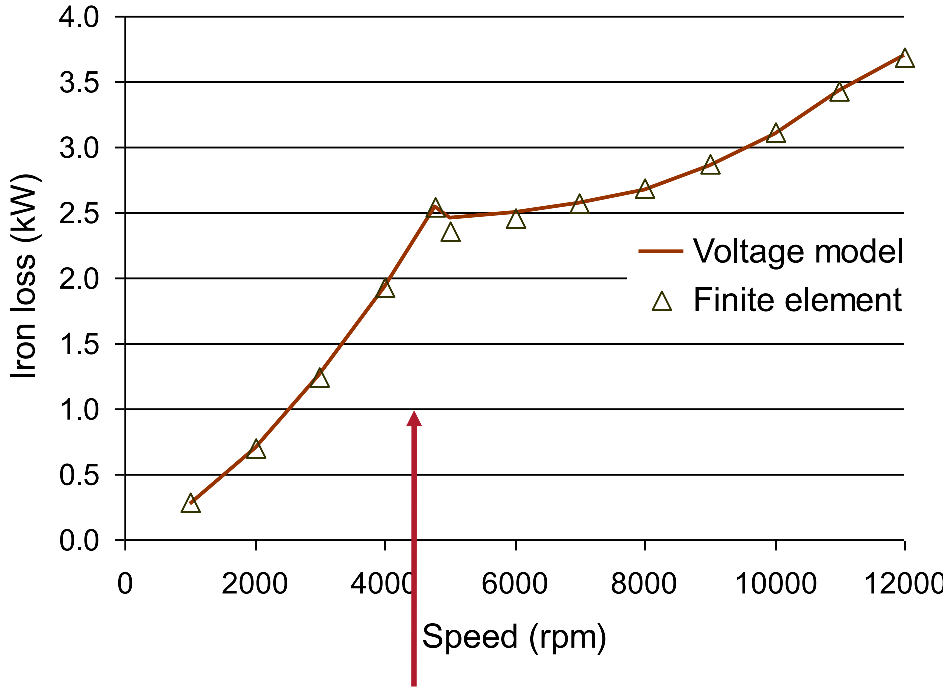
Point of field weakening





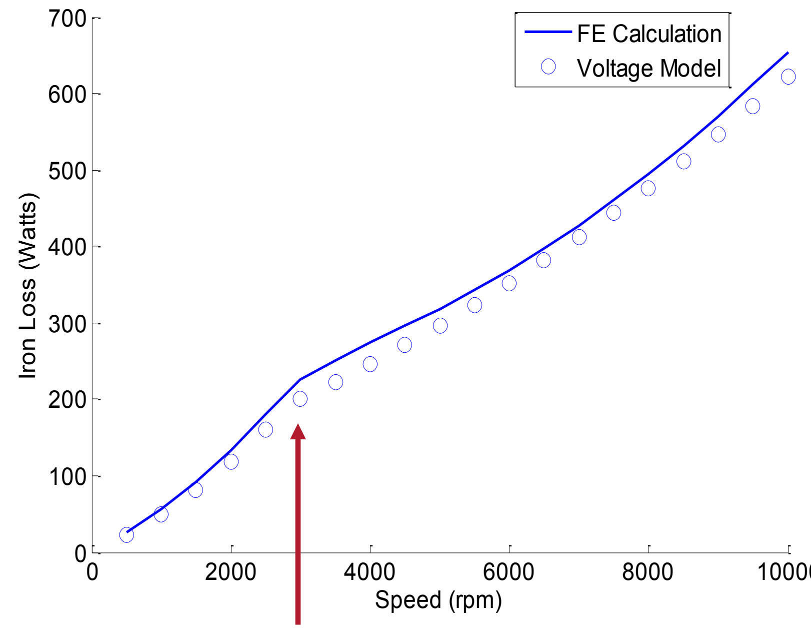
Iron loss trends for different pole slot combinations

12 slot, 8 pole



Point of field weakening

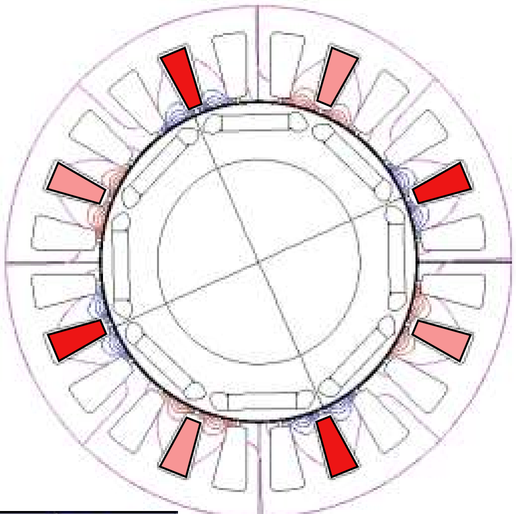
12 slot, 10 pole



Point of field weakening

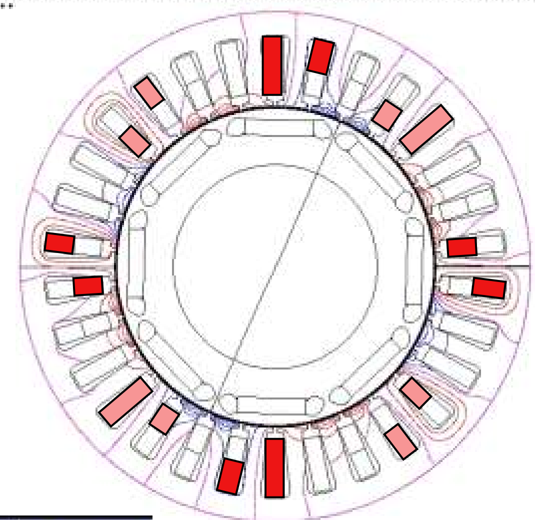
Winding format versus loss during field weakening

8 pole
24 slot



k_{w1}	k_{w3}	k_{w5}	k_{w7}
1.00	1.00	1.00	1.00

8 pole
30 slot



k_{w1}	k_{w3}	k_{w5}	k_{w7}
0.91	0.38	0.00	0.09

[redacted]

Slot number and loss during field weakening

- Winding distribution defines the ability of stator to develop a reaction field

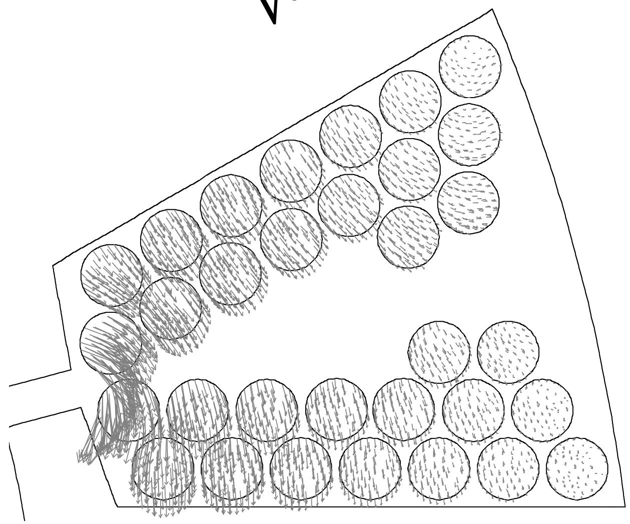
k_{wn}	ϕ_{nR}	Stator iron loss component	Rotor iron loss
>0	Suppressed	Reduced	Stator reaction field will induce a rotor harmonic flux and associated loss
0	Unchanged, no reaction field	Will increase with speed at the same rate as no field-weakening	Unaffected

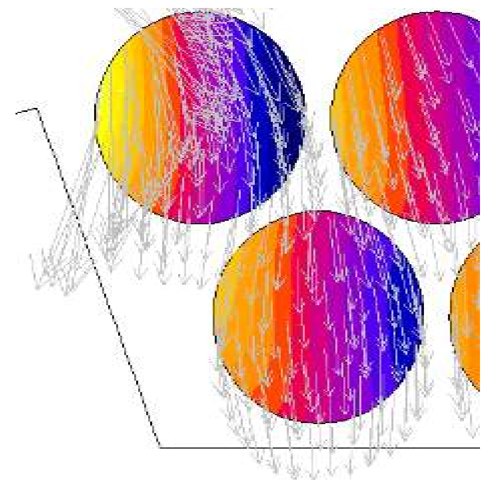
- Inverter acts as a zero impedance (short circuit) to current harmonics – inverter is usually voltage driven and current control loop does not have the bandwidth to track harmonics

Conductor loss considerations

A) Skin effect: skin depth $\delta = \sqrt{\dfrac{2}{\mu\sigma\omega}}$ ~9mm@50Hz, ~2mm@1kHz

B) Proximity effect:





Added complication is AC effects are temperature dependant as a consequence of the change in conductivity

Methodology

- AC winding loss primarily occur over the active region;
  AC effects in the end turns are assumed to be negligible
- Convenient to separate the winding loss into three components;

$$W_{CU}(\theta, f) = I^2(\underbrace{R_{dc\ act}(\theta) + R_{dc\ end}(\theta)}_{\text{DC loss in active and end region - varies with temperature}} + R_{ac\ act}(\theta, f))$$

DC loss in active and end region - varies with temperature

Additional ac loss in active regions – varies with temperature and frequency

- The dc resistance for the active and end winding regions are found from the conductor and winding geometries
- AC component found using analytical or 2D FEA AC Joule loss calculations

Frequency variation

- Functional variations of AC effect are available, e.g.

$$R_{AC} = \left[C_I(h/\delta) + \left(2 \sum_{m=1}^{l-1} N_m + 1 \right)^2 C_{II}(h/\delta) \right] R_{DC} \qquad \delta = \sqrt{\frac{2}{\mu\sigma\omega}}$$

$$C_I(h/\delta) = \frac{1}{2}\left(\frac{h}{\delta}\right)\frac{\sinh(h/\delta) + \sin(h/\delta)}{\cosh(h/\delta) - \cos(h/\delta)} \qquad C_{II}(h/\delta) = \frac{1}{2}\left(\frac{h}{\delta}\right)\frac{\sinh(h/\delta) - \sin(h/\delta)}{\cosh(h/\delta) + \cos(h/\delta)}$$

- If characteristic conductor height *h* or turns distribution are unknown then FEA at can be used to find suitable values
- Alternatively a quadratic or linear variation with frequency can be assumed

Temperature model

- DC resistance component temperature variation:

$$R_{dc} = R_{dc@\theta 0}\left(1 + \alpha(\theta - \theta_0)\right)$$

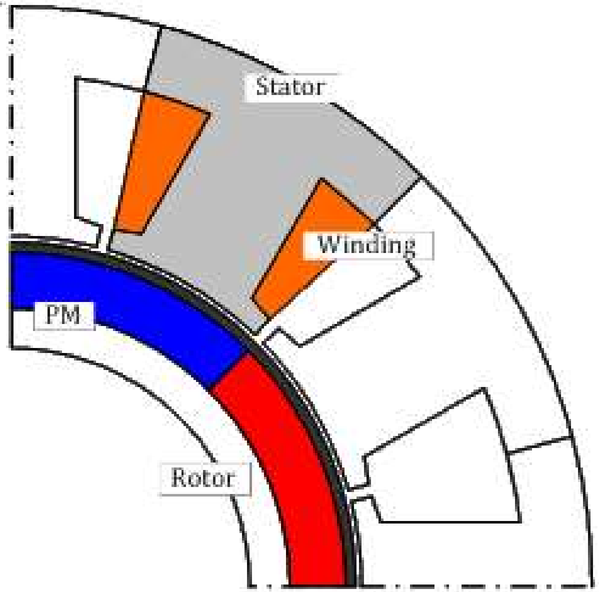
α = 0.00393 $^{o}C^{-1}$ for copper

- AC resistance component temperature variation:

$$R_{ac\ act}(\theta, f) = \frac{R_{ac\ act@\theta 0}(f)}{\left(1 + \alpha(\theta - \theta_0)\right)^{\beta}}$$

Index β lies between 0 and 1

AC loss example



High power EV propulsion motor

8-pole surface magnet (Halbach) rotor

12 slot concentrated winding

Segmented stator

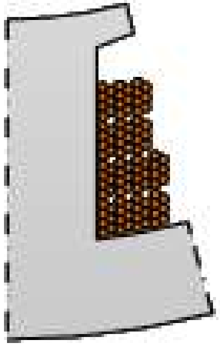
Maximum speed 12,000rpm (800Hz)

- AC effects characterised through tests on wound segments rather than the complete machine

Winding comparisons

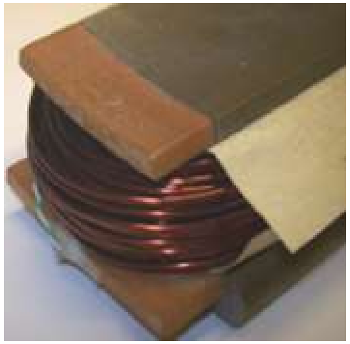
Version I: Multi-stranded winding

Winding lay accurately defined by grouping the 7 parallel conductors which make up each turn using adhesive and careful positioning of the bundle in the slot.

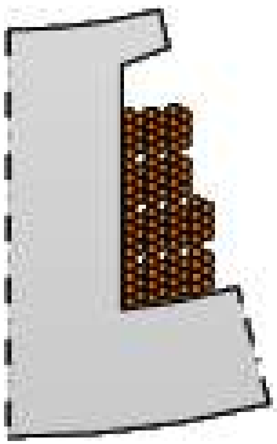


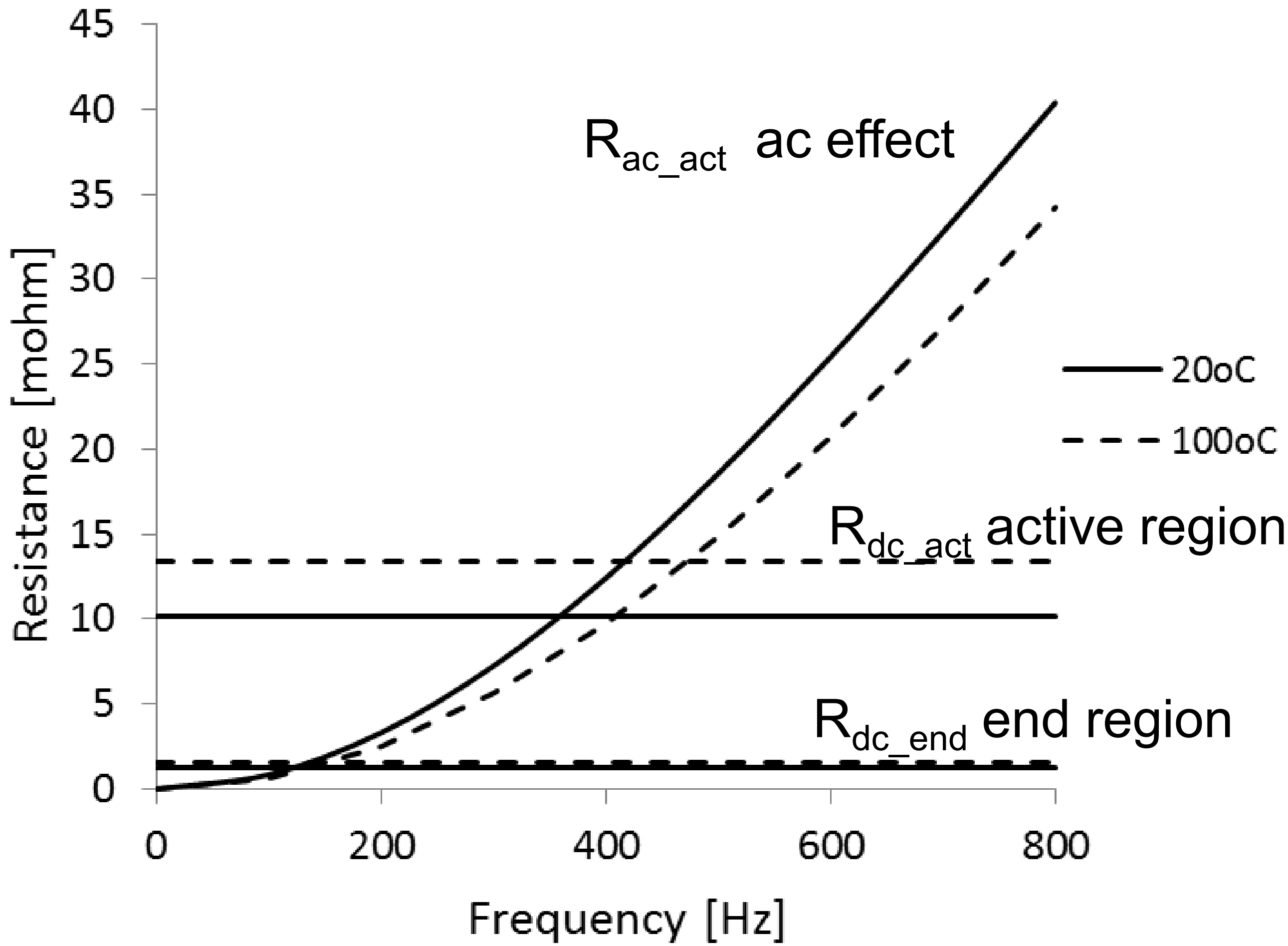
Version II: Multi-stranded winding

Undefined conductor disposition following the natural lay of the 7 parallel strands when wound ‘in hand’.



Results for winding Version I loss separation

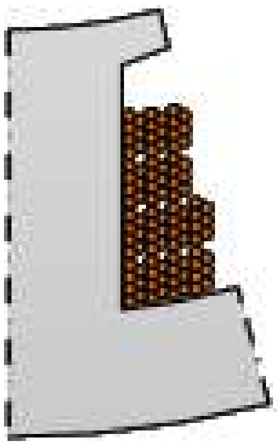


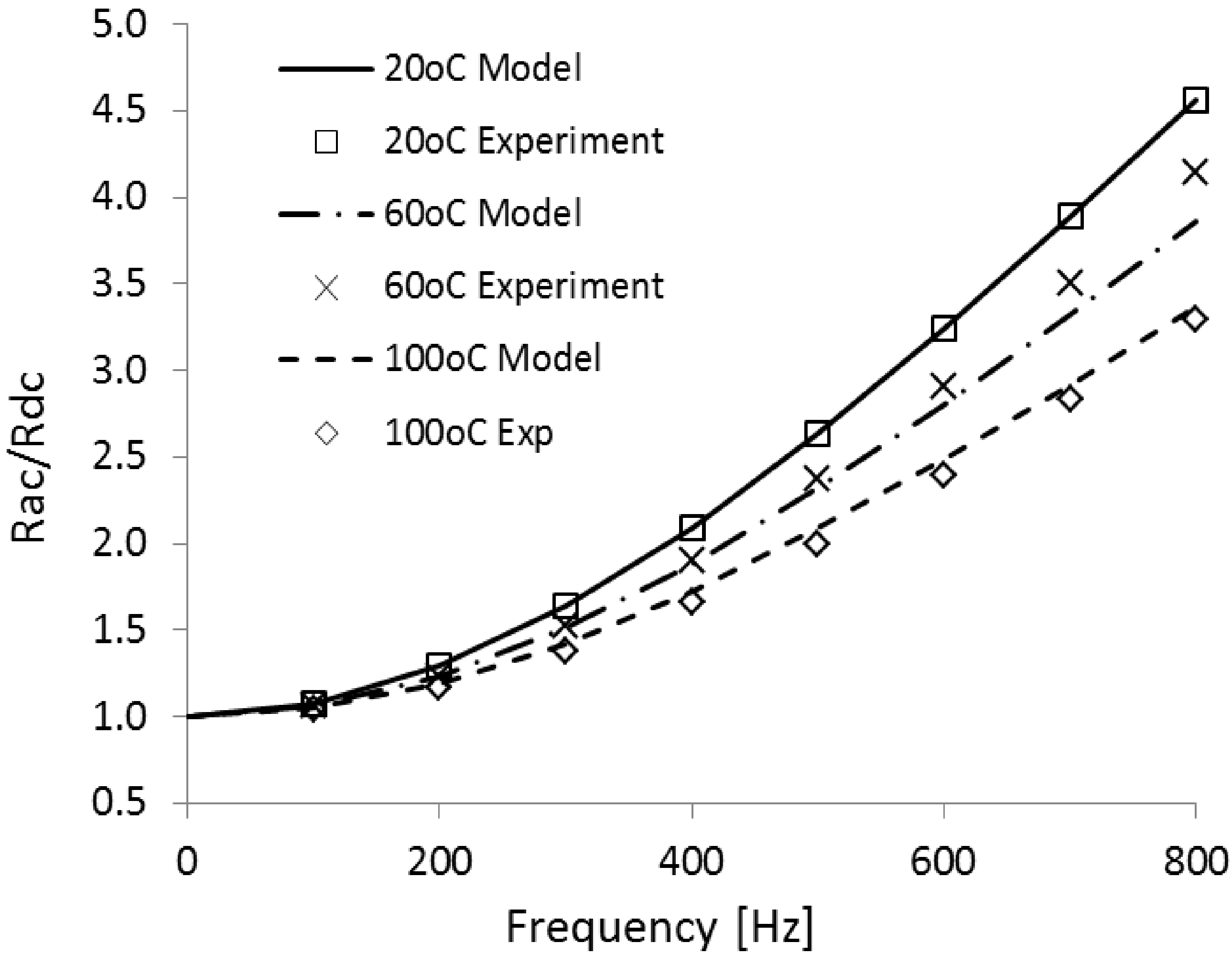


AC loss temperature index:

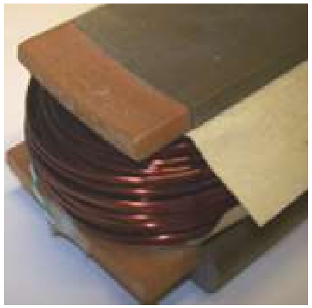
$\beta \approx 0.5$

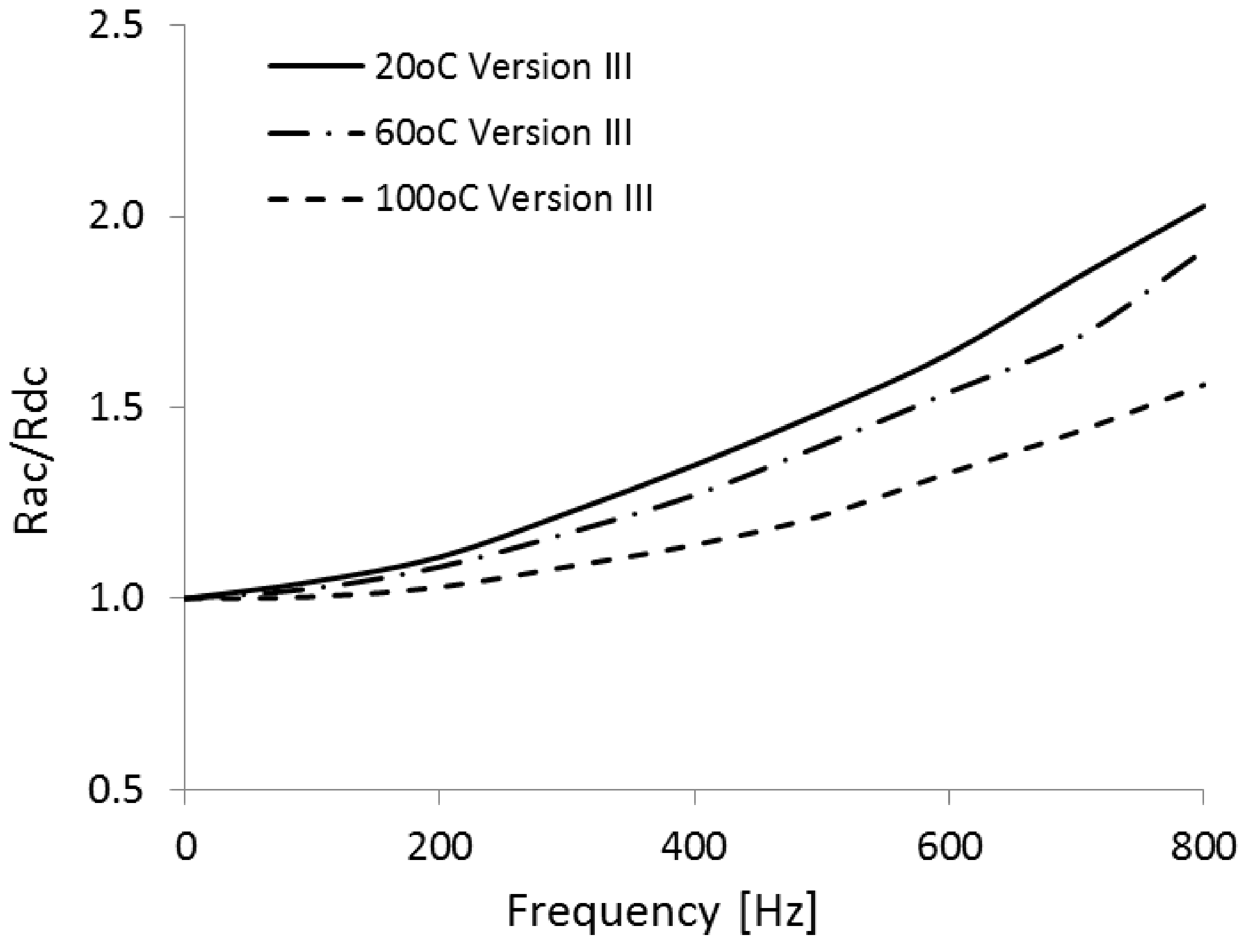
Model trends versus test - winding Version I





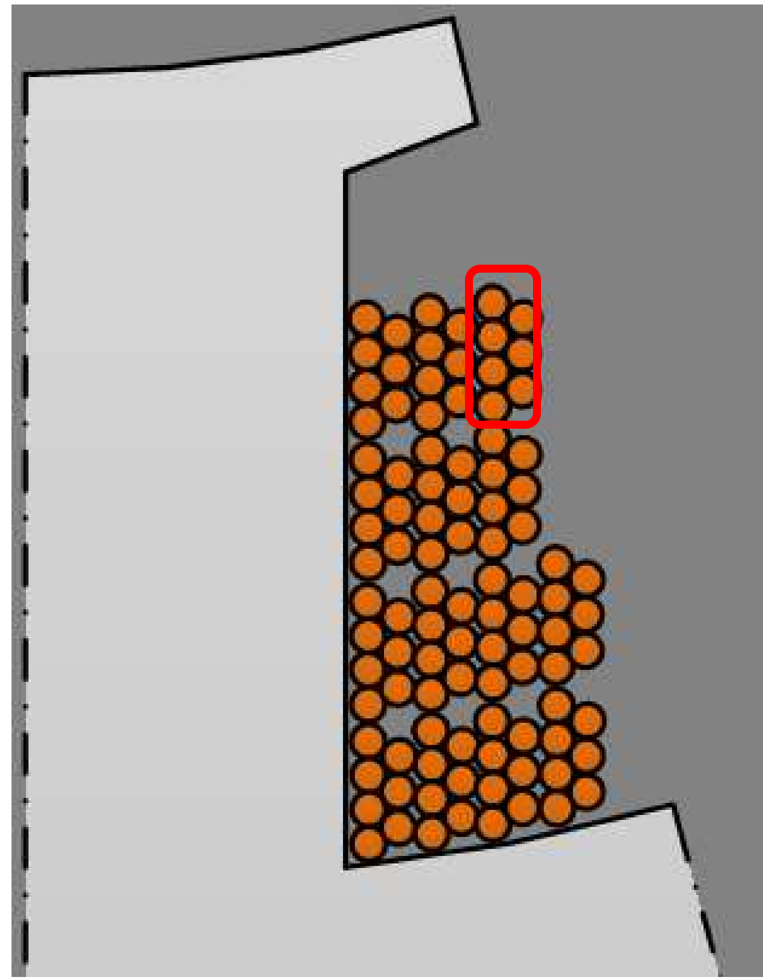
Test results for winding Version II



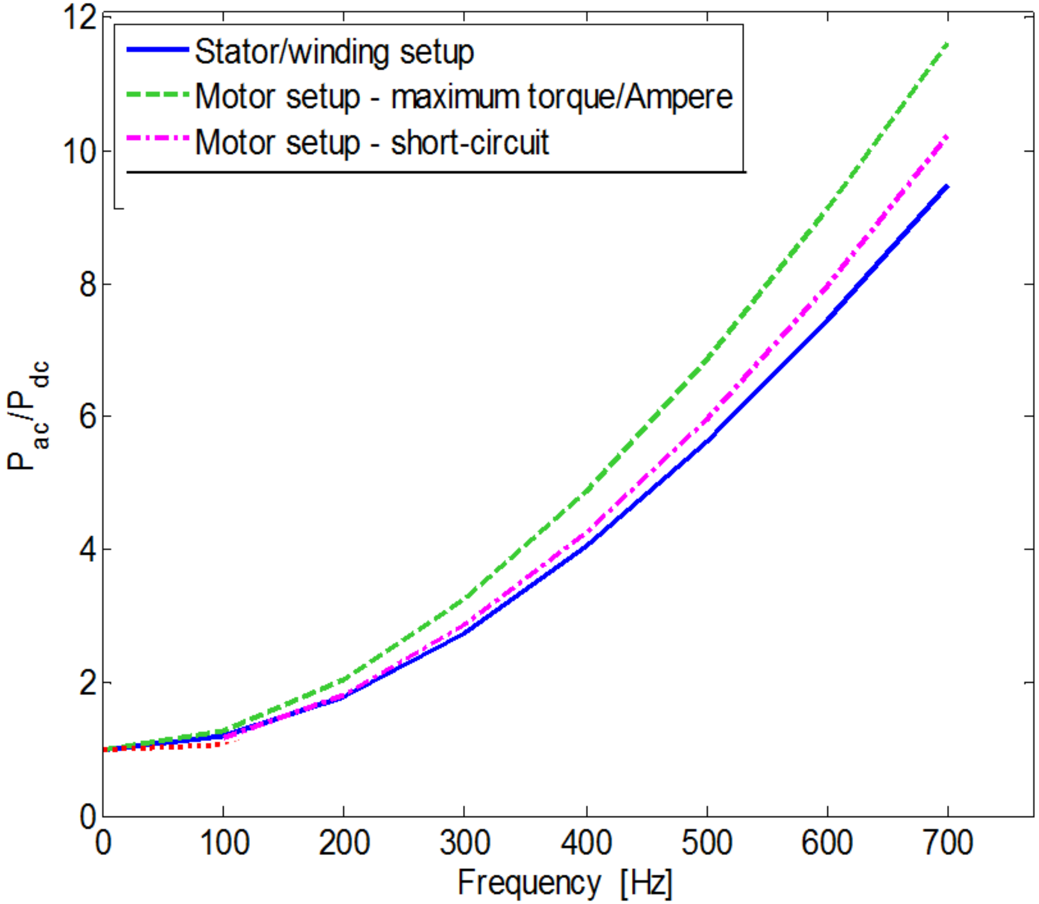


Comparison between two versions

- AC loss effect is much greater in winding Version I
- Grouping of 7 strand conductor bundle behave as a large single rectangular conductor
- AC loss effects are therefore equivalent to a 14 turn 4 layer strip winding with a relatively large conductor characteristic height. High proximity losses will occur in the uppermost layer of conductors

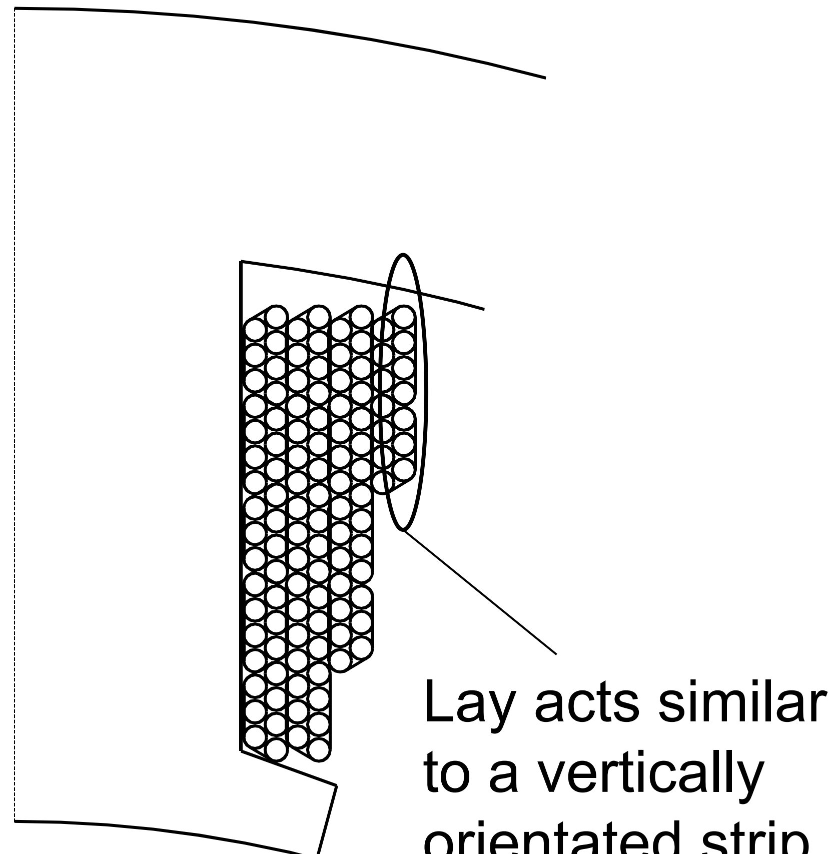


Test derived conductor losses from a second machine



Example of a poor winding lay

7 parallel round conductors ‘in hand’ wound uniformly around the tooth (50% slot fill)



PM loss mapping methodology

$$P_{PM} = \boxed{P_{PM-SE}} + \boxed{P_{PM-AR}}$$

Slotting effect

$$P_{PM-SE}(n^2)$$

Armature reaction effect

$$P_{PM-AR}(n^2, I^2)$$

Functional relationship for Maximum Torque per Ampere operation

$$P_{PM} = a\frac{n^2}{n_R^2} + bI_q^2\frac{n^2}{n_R^2}$$

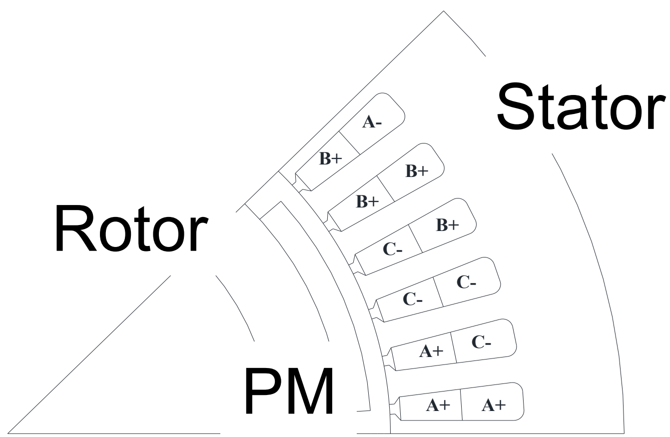
Parameters a, b found from two AC FEA analyses

PM loss mapping example

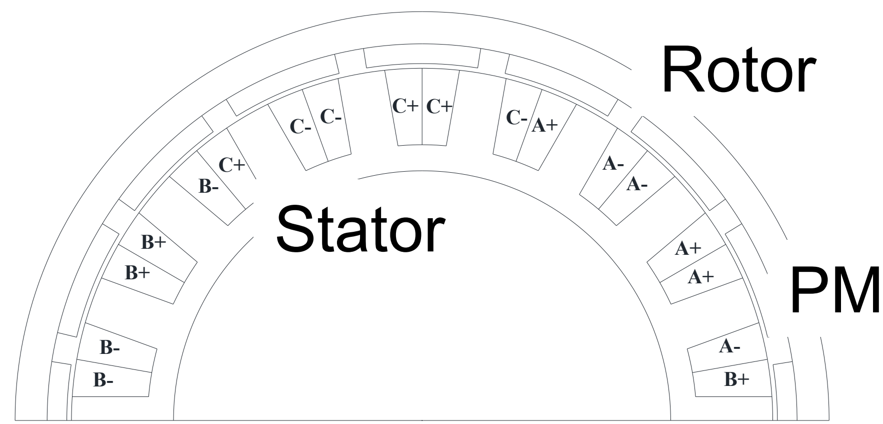
Non segmented magnets

Three phase, balanced sinusoidal currents

Motor version A



Motor version B



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PM loss mapping example

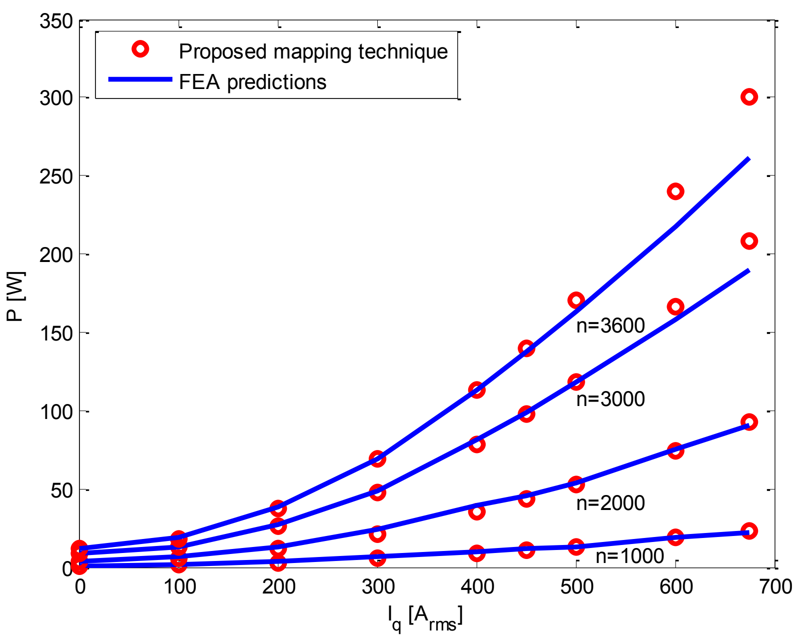
Machine parameters

Motor version	A	B
Number of poles	8	16
Number of slots	48	18
Rated speed	3600rpm	4000rpm
Rated torque	928Nm	35Nm
Rated power	350kW	14.7kW
Maximum speed	6000rpm	6000rpm
PM material	SmCo	NdFeB
Electrical resistivity of PM	86μΩ·cm	180μΩ·cm

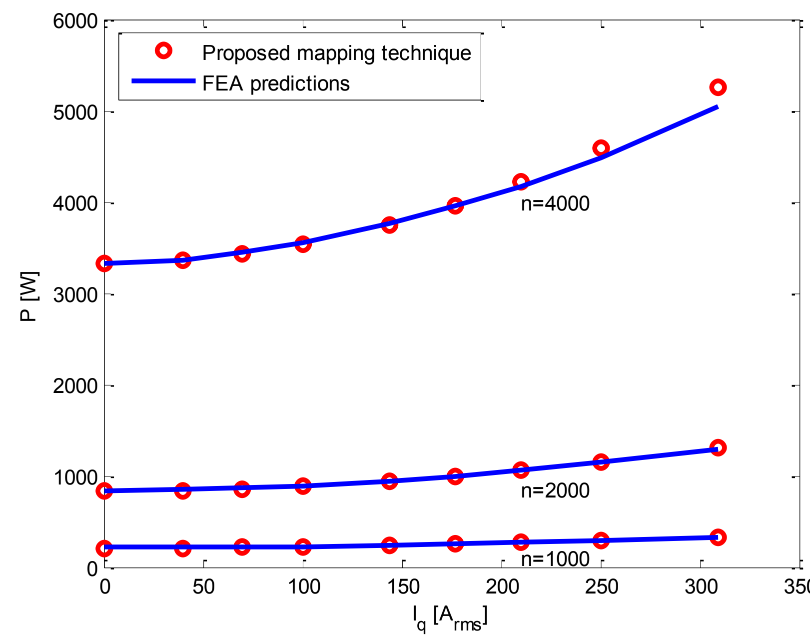
PM loss mapping example

Comparison between loss estimated using functional trend with parameters obtained from two time-stepping FEAs and loss determined from separate FEAs at every working point

Motor version A



Motor version B

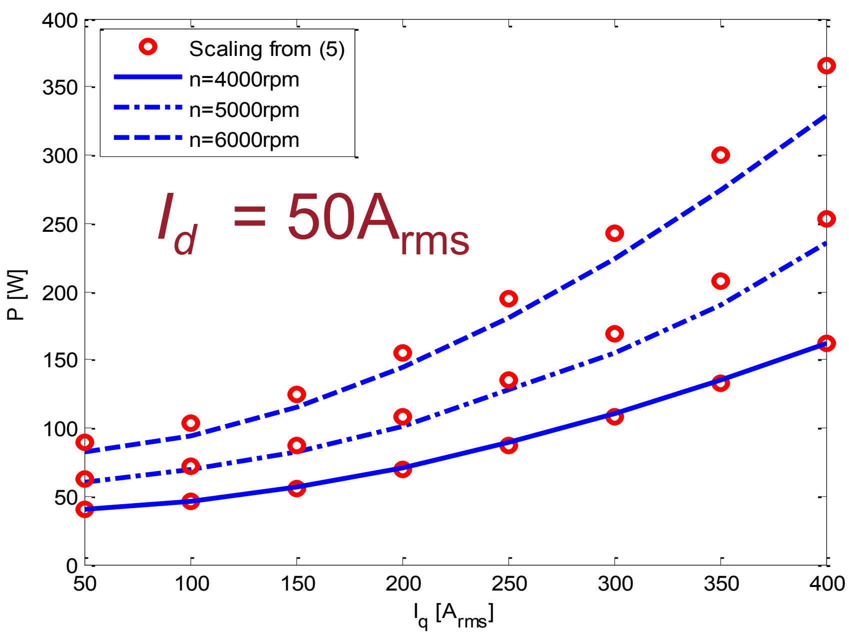


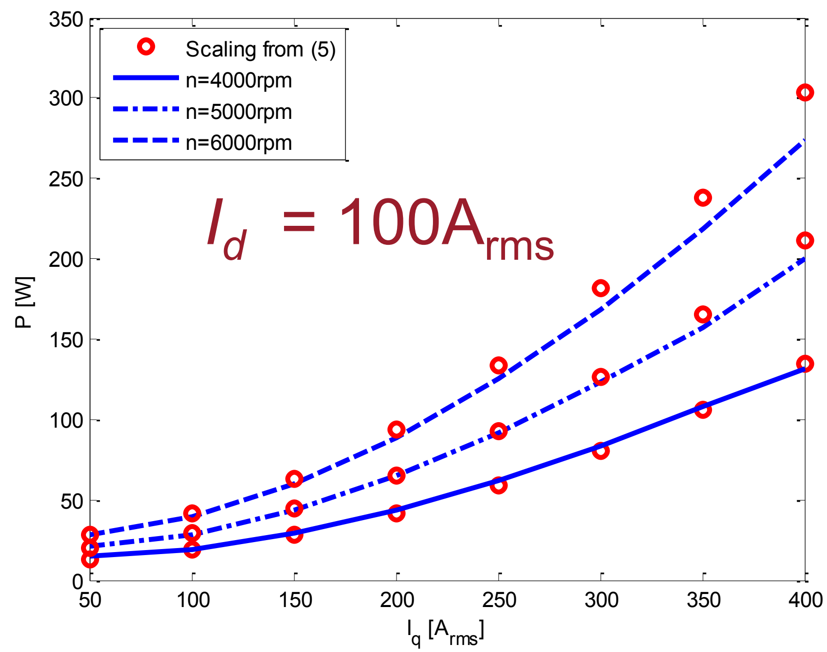
Field weakening operation

Method can be extended to cater for field weakening operation

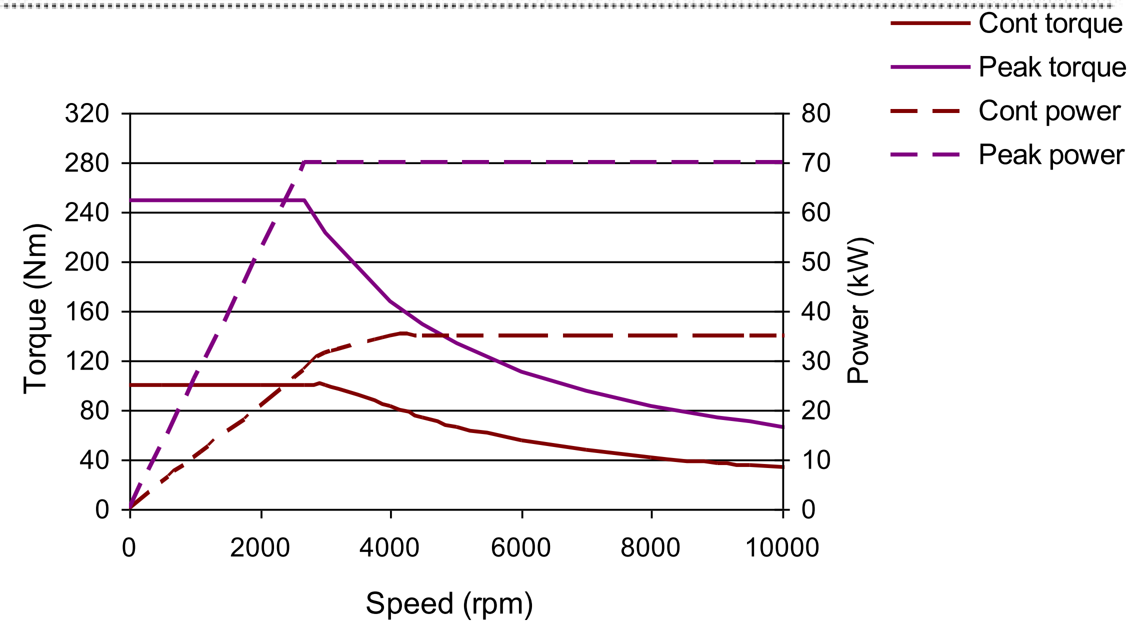
$$P_{PM} = P_{PM-SE}(n^2) + P_{PM-AR}\left(n^2, f(I_q, I_d)\right)$$

A further two FEAs required to obtain map parameters





EV propulsion motor example



Peak capability: 250Nm, 70kW
Continuous capability: >90Nm, 35kW
Constant power region: ~3:1

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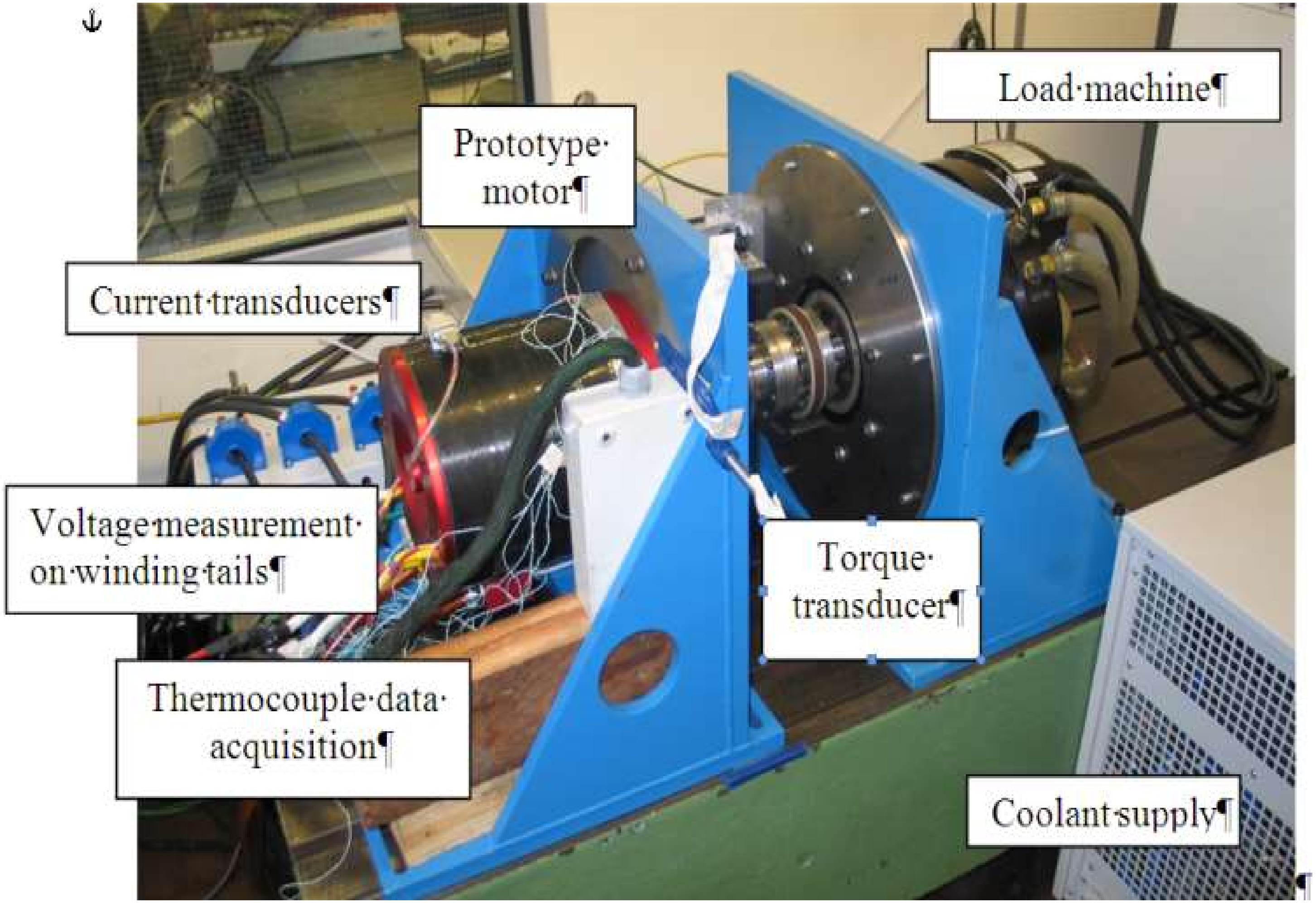
Test bench



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Loss model and separation

- Core loss from FE: $W_{Fe} = k_h B_m^2 f k_f + \sum_{\Delta T} \left[\sigma \frac{d^2}{12} \left(\frac{dB}{dt}(t) \right)^2 + k_e \left(\frac{dB}{dt}(t) \right)^{\frac{3}{2}} \right] \Delta t f k_f$

- Magnet loss from FE: $W_{PM} = \rho \iiint_V \mathbf{J}^2 dV$

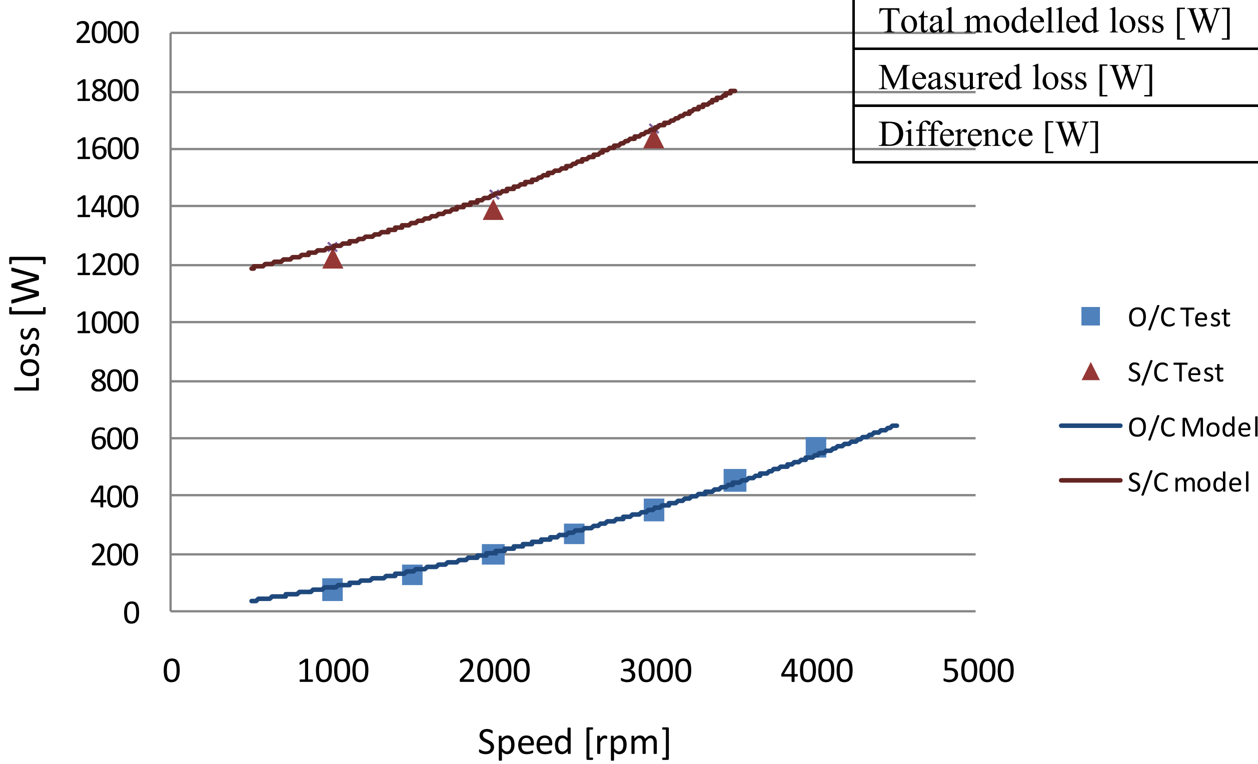
- Copper loss: $W_{Cu} = i^2 R_{dc}|_{T0} \left[\frac{f/f_{2ac}}{\sqrt{(1+\alpha(T-T_0))}} + (1+\alpha(T-T_0)) \right]$

  Separated between slot and endwinding regions

- Friction and windage: dominated by bearing loss

Loss estimates compared to test

3000rpm test		O/C	S/C
Stator	Copper	0	1212
	Iron	235	267
Rotor	Iron	31	101
	Magnet	0	9
Windage/friction		88	88
Total modelled loss [W]		354	1678
Measured loss [W]		350	1640
Difference [W]		4	38



FEA requirements for a complete loss mapping

- Core loss
  1. One open circuit discrete time step FEA
  2. One short circuit discrete time step FEA
- AC loss effects
  3. AC FEA with a single slot conductors meshed in detail. Evaluated at different frequency to establish conductor characteristic height and two set values of copper conductivity to establish temperature dependency
- Magnet loss effects
  4. One open circuit discrete time step FEA to obtain slotting effects
  5. One FEA at a known value of I_q
  6. Further two FEAs to obtain I_d dependency if required

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Thank you

Any questions?