Common-Mode Impedance of an Electric Motor and the Impact of Material and Geometry Uncertainties

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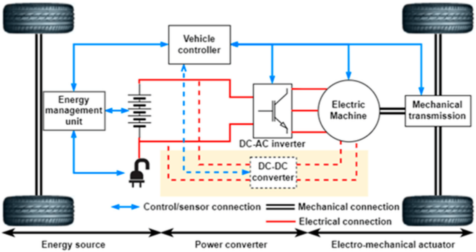
Overview

Introduction

Background

Electrification of automotive industry together with increased connectivity and focus on autonomous vehicles means challenges with respect to EMC



Source: [2]

- Modern efficient electric propulsion systems contain rapidly switching high-voltage power electronics
- Shorter rise/fall times of PWM signals $\implies$ high-frequency radiated and conducted emissions
- Electromagnetic Interference (EMI) decreases reliability of systems and sensors

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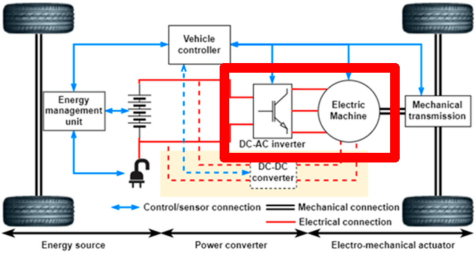

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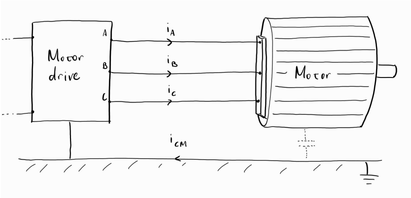
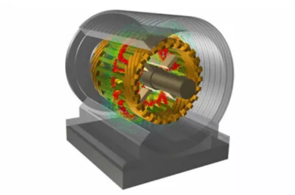
Why common-mode impedance?



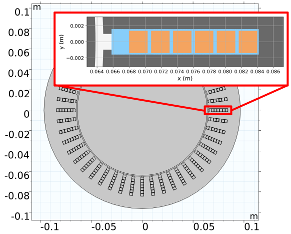
- Currents can be decomposed into Differential-Mode (DM) and Common-Mode (CM) currents
- CM currents are particularly problematic with respect to EMC
- For a three-phase electric motor with phase currents i_A, i_B and i_C, the CM current is the imbalance between phases: $i_\mathrm{CM} = i_\mathrm{A} + i_\mathrm{B} + i_\mathrm{C}$.
- CM current passes through CM impedance $\implies$ must determine CM impedance to predict CM current

Electric motor model

- Interested in frequencies between 10 kHz and 100 MHz
- Full 3D model: time-consuming and difficult to set up, costly in terms of computational resources
- Our approach: 2D model of motor cross-section + 1D transmission-line model along the motor axis
- We consider electric motors with hairpin conductors that have rectangular cross-sections and well defined locations



Courtesy of: *Ansys*



Method

Model concept

The main steps in the model are:

1. Assume the motor to have a constant cross-section along its axis
2. Use a 2D model of the cross-section to compute all capacitive and inductive couplings between the conductors of the motor
3. Use a 1D transmission-line model along the motor axis to determine the voltages and currents along all phase windings
4. Determine the motor admittance matrix which relates the phase voltages and phase currents
5. Compute the CM impedance from the elements of the motor admittance matrix

Computation of impedance and admittance matrices

Consider a 2D cross-section of the motor.

- Compute capacitive couplings and associated losses from the electro-quasistatic problem

$$-\nabla \cdot ((\sigma + j\omega\epsilon)\nabla\phi) = 0, \qquad (1)$$

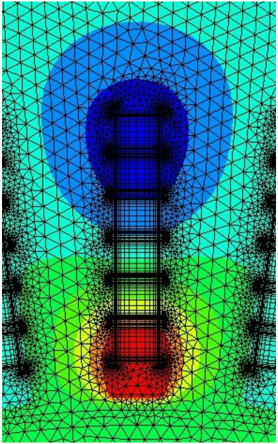
  to form the admittance matrix $\mathbf{Y} = \mathbf{G} + j\omega\mathbf{C}$

- Compute inductive couplings and associated losses from the magneto-quasistatic problem

$$-\nabla \cdot \left(\frac{1}{\mu}\nabla A_z\right) + j\omega\sigma A_z = J_z^{\mathrm{src}}, \qquad (2)$$

  to form the impedance matrix $\mathbf{Z} = \mathbf{R} + j\omega\mathbf{L}$

Here, we use the Finite Element Method to solve problems (1) and (2).



Effective permeability of laminates

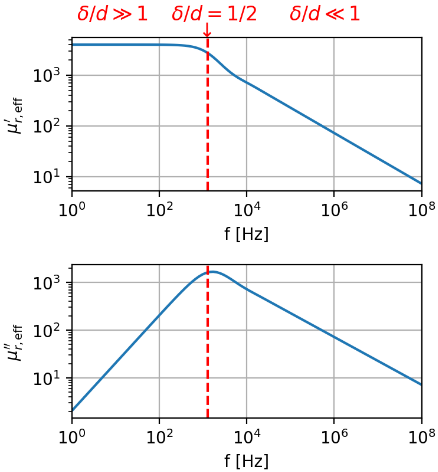
- To reduce losses due to eddy currents, the stator and rotor stacks are made up of thin metal sheets (laminates)
- At sufficiently high frequencies, the skin effect causes fields to only partially penetrate the laminate sheets
- Average associated magnetic flux density over the sheets to obtain the effective permeability [1]

$$\mu_{\mathrm{eff}} = \mu_{\mathrm{b}} \frac{2}{\kappa d} \tanh\left(\frac{\kappa d}{2}\right) \tag{3}$$

where we have the laminate thickness d, the "bulk" permeability μ_{b} and $\kappa = (1 + j)/\delta$ for the penetration depth $\delta = \sqrt{\frac{2}{\sigma_{\mathrm{b}} \mu_{\mathrm{b}} \omega}}$

- Replace laminates with solid material with permeability μ_{eff}

Example of effective permeability



δ/d	f	$\mu'_{\mathrm{r,eff}}$	$\mu''_{\mathrm{r,eff}}$
5	13 Hz	4000	27
1/2	1.3 kHz	2700	1600
1/20	130 kHz	200	200
1/50	3.2 MHz	40	40

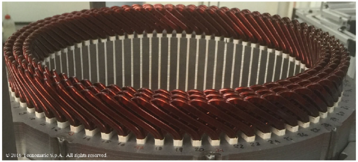
- Laminate thickness $d = 0.3$ mm, bulk permeability $\mu_{\mathrm{b}}/\mu_0 = 4000$, conductivity $\sigma_{\mathrm{b}} = 2.17 \cdot 10^6$ S/m
- $\mu_{\mathrm{eff}} = \mu_0(\mu'_{r,\mathrm{eff}} - j\mu''_{r,\mathrm{eff}})$
- Dashed line: $\delta/d = 1/2$
- Large variation across frequency range

Transmission-line equations

Wish to solve the multi-conductor Transmission Line (TL) equations

$$\frac{\mathrm{d}\mathbf{u}}{\mathrm{d}z} = -(\mathbf{R} + j\omega\mathbf{L})\mathbf{i} = -\mathbf{Z}\mathbf{i} \qquad (4)$$

$$\frac{\mathrm{d}\mathbf{i}}{\mathrm{d}z} = -(\mathbf{G} + j\omega\mathbf{C})\mathbf{u} = -\mathbf{Y}\mathbf{u} \qquad (5)$$



Courtesy of: *Tecnomatic Groups*

for the interval $0 \leq z \leq l$

- $\mathbf{u} = \mathbf{u}(z)$ and $\mathbf{i} = \mathbf{i}(z)$: voltages and currents for all conductors
- Use finite differences to discretize and solve the TL equations
- Must complement Eqs. (4) and (5) with boundary conditions that describe how conductors connect to each other
  - Here, we consider all connections between conductors to be short circuits

Computation of common-mode impedance

We find the elements of a matrix $\mathbf{Y}_{\mathrm{mot}}$ which relates phase potentials and currents as

$$\begin{bmatrix} i_{\mathrm{A}} \\ i_{\mathrm{B}} \\ i_{\mathrm{C}} \end{bmatrix} = \mathbf{Y}_{\mathrm{mot}} \begin{bmatrix} u_{\mathrm{A}} \\ u_{\mathrm{B}} \\ u_{\mathrm{C}} \end{bmatrix} \tag{6}$$

We then consider a situation where

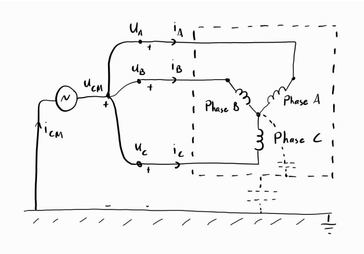
$$u_{\mathrm{CM}} = u_{\mathrm{A}} = u_{\mathrm{B}} = u_{\mathrm{C}} \tag{7}$$

$$i_{\mathrm{CM}} = i_{\mathrm{A}} + i_{\mathrm{B}} + i_{\mathrm{C}} \tag{8}$$

which gives the common-mode impedance

$$Z_{\mathrm{CM}} = \frac{u_{\mathrm{CM}}}{i_{\mathrm{CM}}} \tag{9}$$

from the elements of $\mathbf{Y}_{\mathrm{mot}}$.

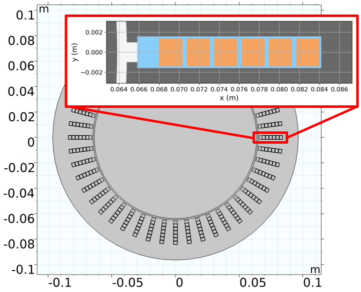


Advantages of our approach

- A 2D model of the motor cross-section uses much fewer elements than a full 3D model of the entire motor
  - The system of equations that result from the 1D TL equations is comparatively cheap to solve
- Easy to modify and exchange parts of the model - end winding model, geometry of cross-section, et cetera

Numerical example

Three-phase electric motor with 48 slots that each contain 6 hairpin conductors. The slots are filled with a dielectric filler material.



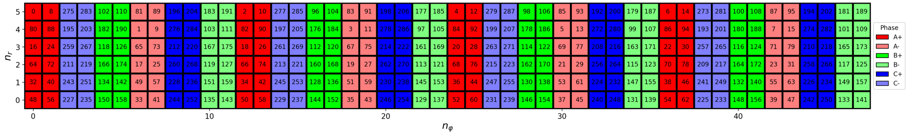


Figure: Winding scheme of the electric motor. Each square corresponds to a hairpin conductor.

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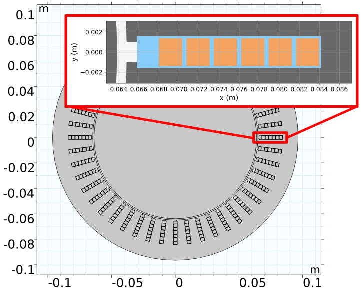

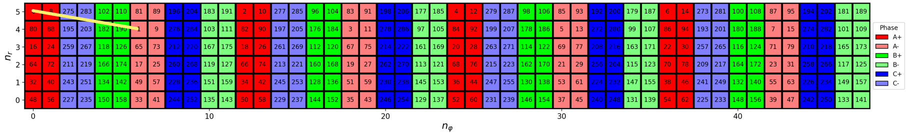

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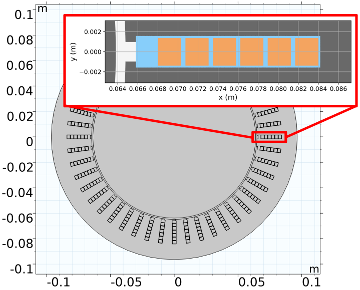

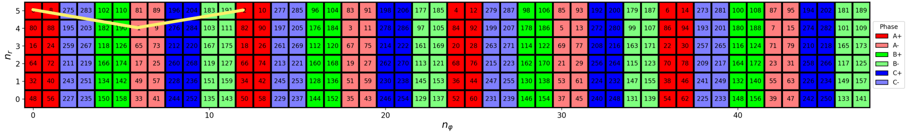

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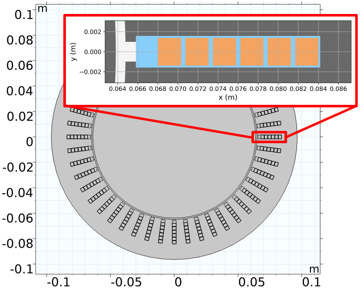

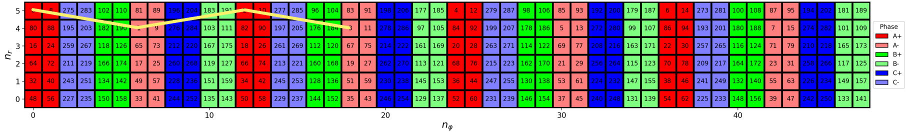

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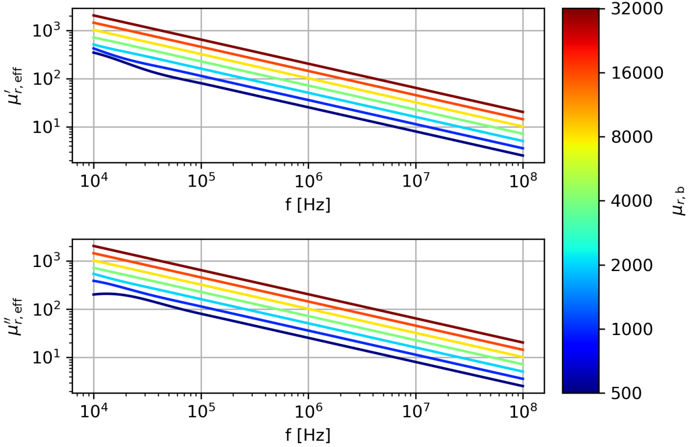
Bulk permeability – effective permeability

With $\sigma_\mathrm{b} = 2.17 \cdot 10^6$ S/m and $d = 0.3$ mm, we explore changes in the bulk permeability of the laminate sheets.



Bulk permeability – CM impedance

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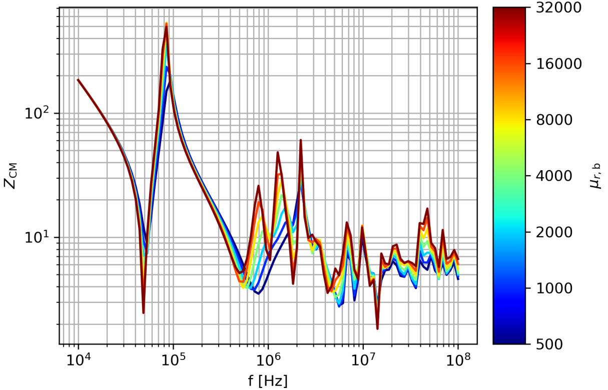
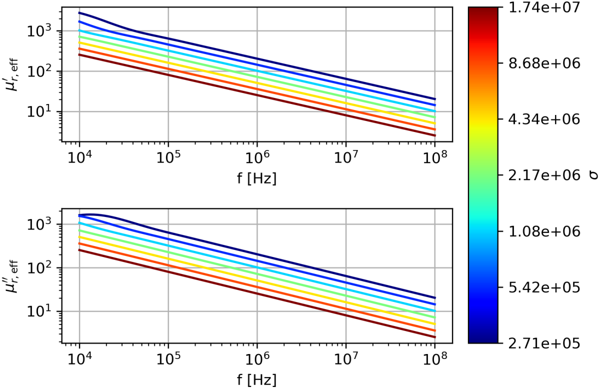


Conductivity of laminates – effective permeability

With $\mu_\mathrm{b}/\mu_0 = 4000$ and $d = 0.3$ mm, we explore changes in the bulk permeability of the laminate sheets.



Conductivity of laminates – CM impedance

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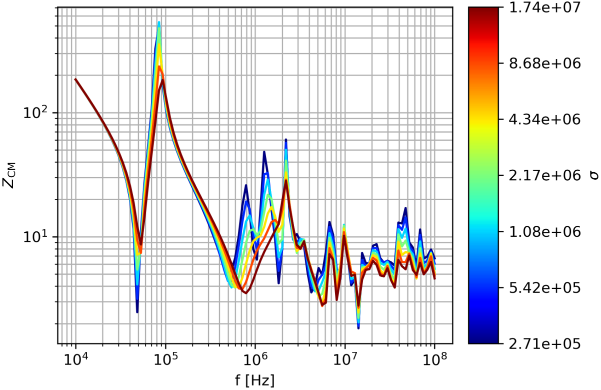


Very similar results – why?

CM impedance vs material parameters

Given the results, we find:

- At higher frequencies ($\delta \ll d$) we have

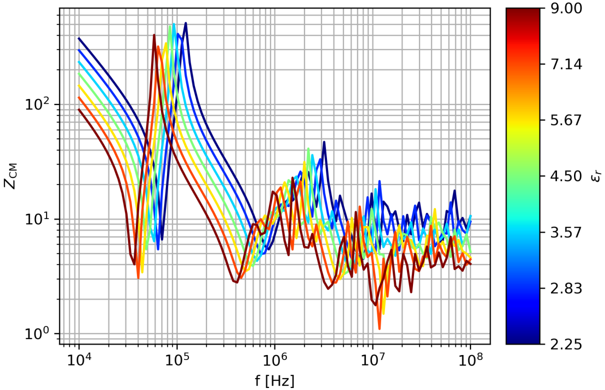
$$\mu_{\text{eff}} \approx \frac{2\sqrt{2}}{(1+j)d}\sqrt{\frac{\mu_{\text{b}}}{\sigma_{\text{b}}\omega}}$$

$\Longrightarrow$ effective permeability depends on the ratio $\mu_{\text{b}}/\sigma_{\text{b}}$
$\Longrightarrow$ doubling μ_b identical to halving σ_{b}

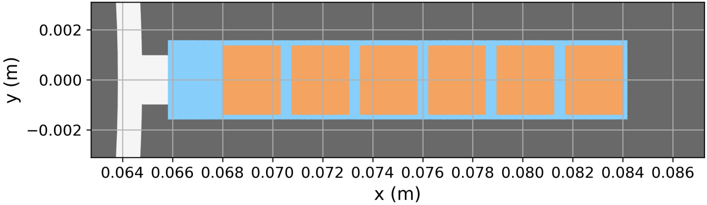
- At lower frequencies, capacitive couplings dominate and the results do not vary with μ_{b} and σ_{b}

Uncertainty in permittivity

With $\sigma_\mathrm{b} = 2.17 \cdot 10^6$ S/m, $\mu_\mathrm{b}/\mu_0 = 4000$ and $d = 0.3$ mm, we explore uncertainties in the permittivity of the dielectric filler material



Uncertainty in geometry



- We study the CM impedance under perturbation of the locations of the hairpin windings
- Random displacements of up to 40 µm applied simultaneously to all hairpin conductors
- No significant changes in the common-mode impedance

Conclusions

Conclusions

- Computationally attractive model that yields the common-mode (CM) impedance for an electric motor
  - Capacitive and inductive coupling computed by 2D finite-element method applied to the motor's cross section
  - Effective permeability accounts for the laminates in stator and rotor
  - Spatial variation in currents and voltages along the windings (and the motor axis) are modelled by a 1D transmission-line model discretized by finite differences
- Parameter study with respect to geometry and materials
  - Perturbations of the locations for hairpin windings have a negligible impact on the the CM impedance
  - Permittivity of the insulation material influences the CM impedance at all frequencies
  - Permeability and conductivity of the laminates influence the CM impedance at higher frequencies
  - Parameter μ_b/σ_b is important for the results when $\delta \ll d$

References

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PhD thesis, Technische Universität Darmstadt, 2015.

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Thank you!

Questions?