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AC Losses and Transient Voltage Effects in Electric Machines

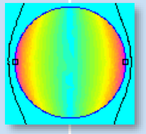
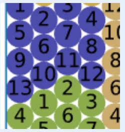
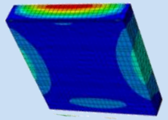
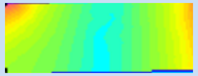
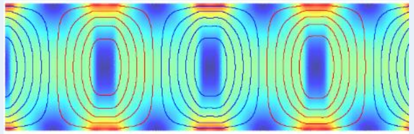
Efficient Simulation Methods

1

AC Losses and Simulation Methods

Overview of Additional Losses

Efficient simulation method

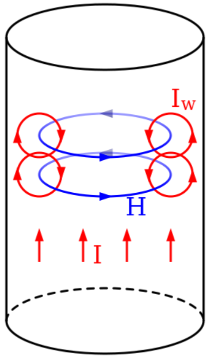
Based on magnetostatic FEM $f \leq \ f_{el} \ \frac{n_{Steps}}{2}$	Based on AC simulation with frozen permeability
Proximity and skin losses 	Proximity and skin losses
Losses in parallel wires 	
Magnet losses (slot harmonics, current distortion) 	 Magnetic losses due to PWM
Losses in rotating and stationary thin-walled sleeves 	
	Losses in solid materials

Skin and proximity losses

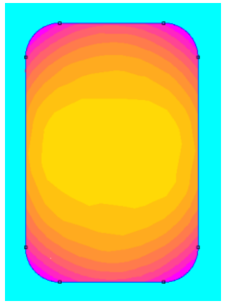
Losses due to skin effect

- Background
  - Alternating current in the conductor generates a magnetic field, which causes an electric field induced in the conductor.
  - Current density in the middle of the conductor is reduced and at the outer boundary increased.
- Calculation method
  - Increase of resistance as a function of frequency Ke
  - Analytical formula for round wire exists.
  - For conductors with arbitrary cross-sections Ke is calculated with FEA.

$$P_{skin} = m\left(K_e(f) - 1\right) R_{dc} I^2$$



Source: Wikipedia



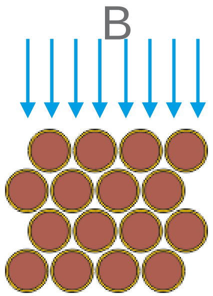
Current distribution in rectangular wire

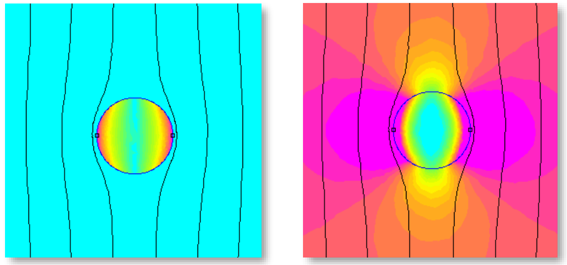
Skin and proximity losses

Proximity losses

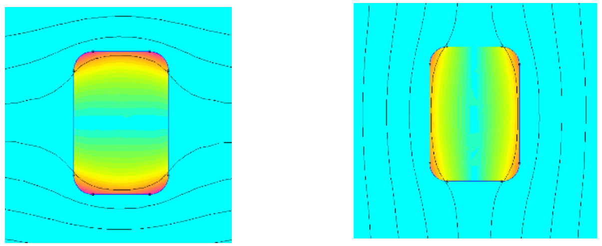
- Background
  - Losses due to the alternating magnetic fields, e.g. caused by leakage flux in the slots.
- Calculation method
  - Fourier spectrum of flux density is calculated with FEA for each conductor in slot.
  - Losses in the wire are calculated by means of a loss function Fp

$$P_{prox} = \sum_{N_s}\sum_{n_c}\sum_{\nu}\left(F_{px}B_{x\nu}^2 + F_{py}B_{y\nu}^2\right) f_1^2 l \nu^2$$

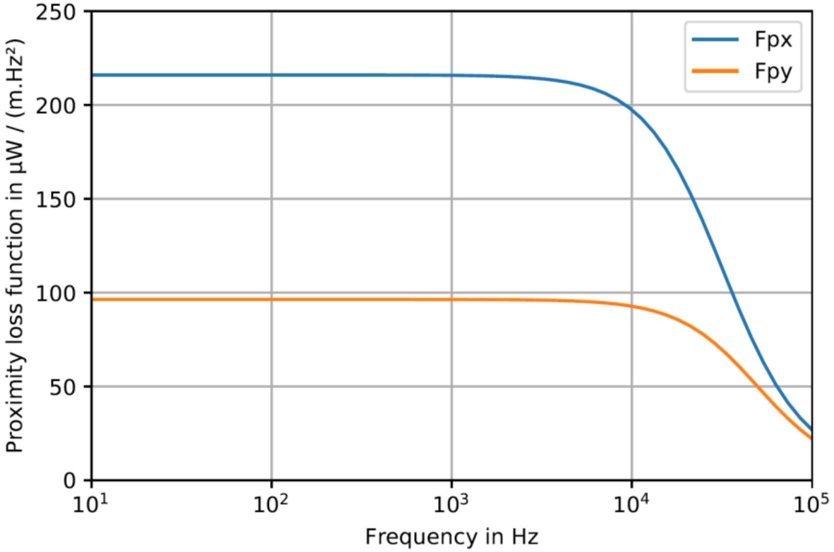




Flux density and current density distribution



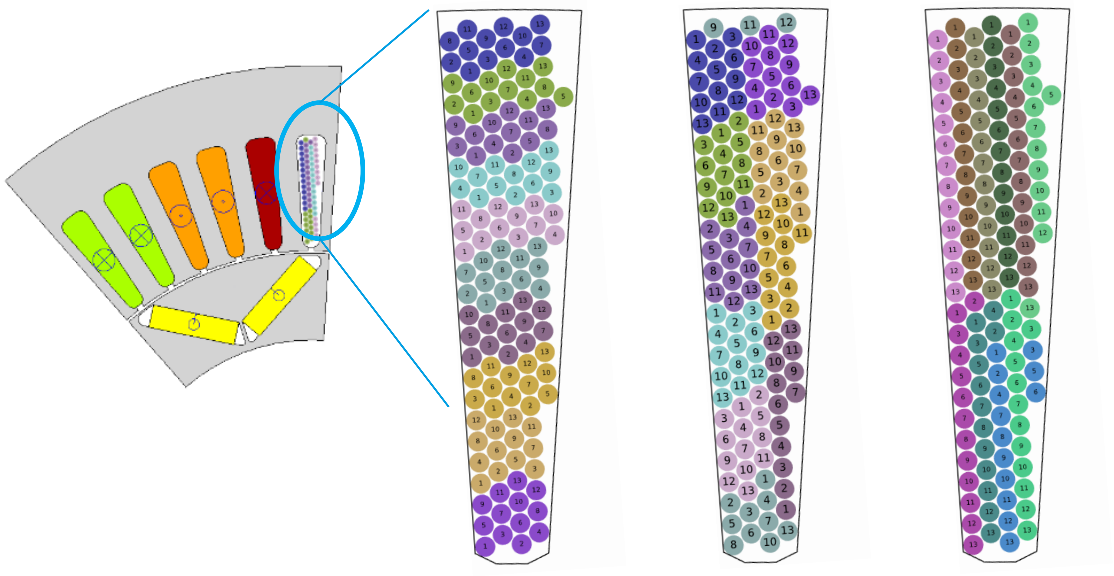
$$F_{px} = \frac{P_{px}}{f^2 B_x^2\, l} \qquad F_{py} = \frac{P_{py}}{f^2 B_y^2\, l}$$



Losses in stranded windings

Background

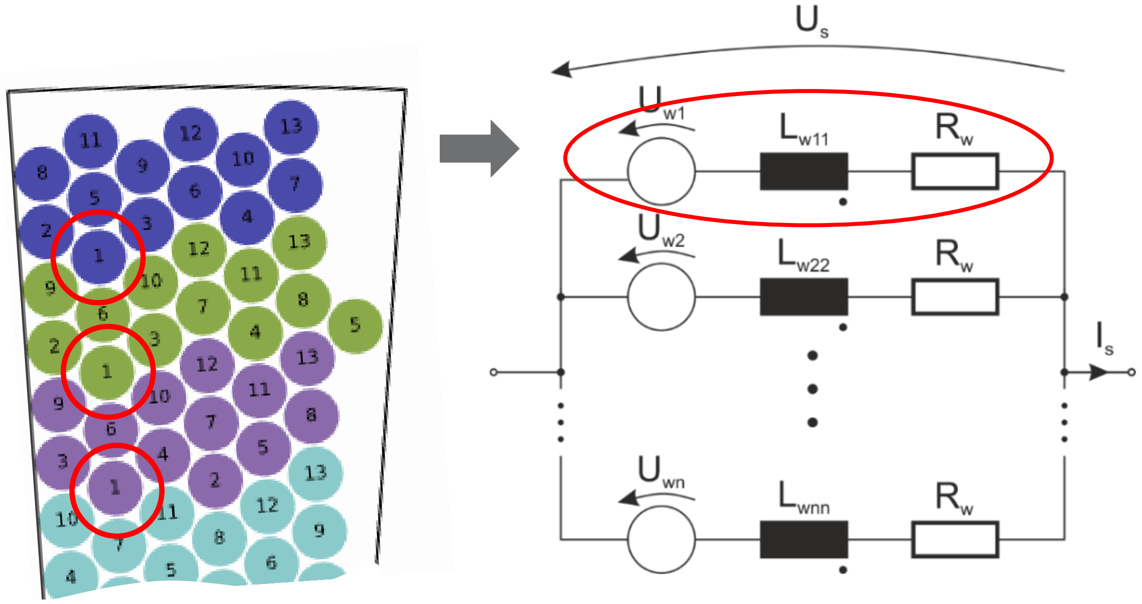
- Power density of electrical machines increases with speed.
- The number of turns decreases, and the wire cross-section increases with increasing speed.
- At low turn count, winding conductors are often subdivided into multiple insulated strands.
- The arrangement of the wires in the slot depends on the manufacturing process.

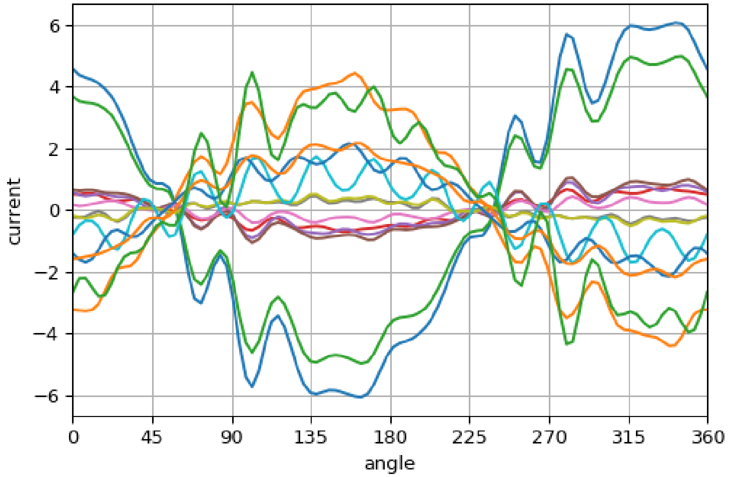


Losses in stranded windings

Calculation method

- Parameters of the equivalent circuit are calculated with FEA in the frequency domain
- Circulating currents and additional copper losses are evaluated

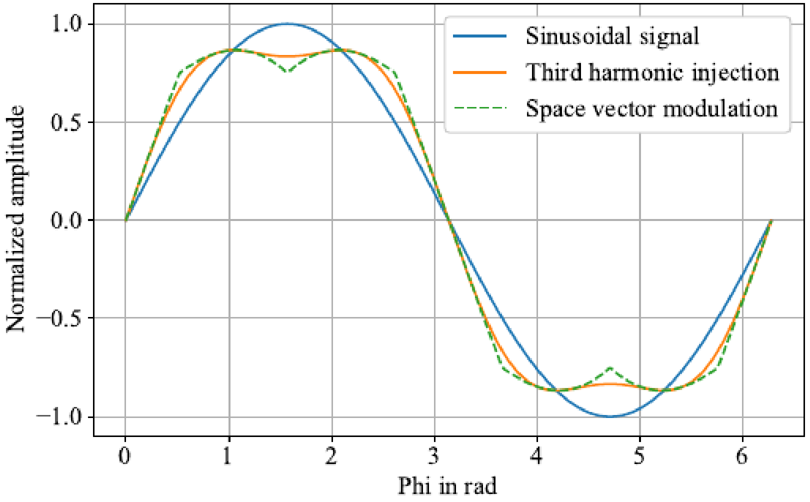


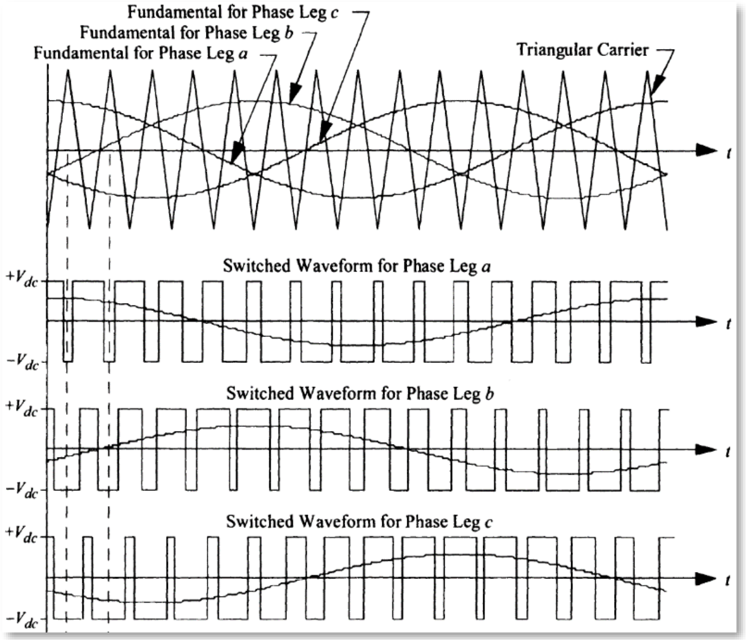


Losses due to PWM Harmonics

Calculation of PWM signal

- Calculation is carried out in the frequency domain.
- Intersection of modulated voltage with triangular carrier.
- Calculation of the Fourier coefficients for each switching cycle of the voltage signal for
    - Third harmonic injection
    - Space vector modulation
    - Discontinuous PWM min
    - Discontinuous PWM max
    - 2- or 3-level PWM

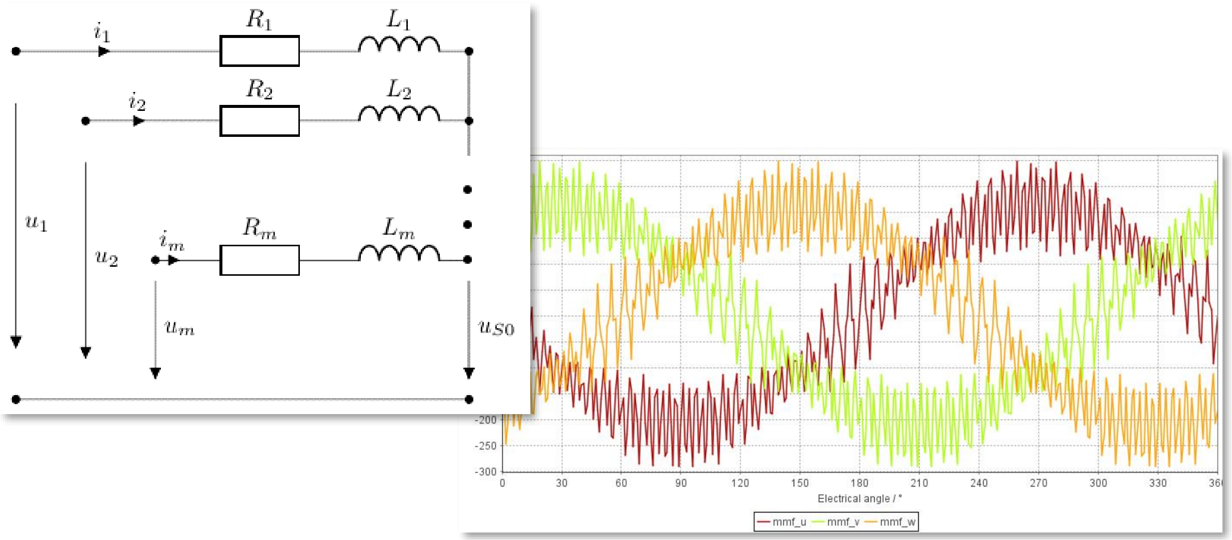


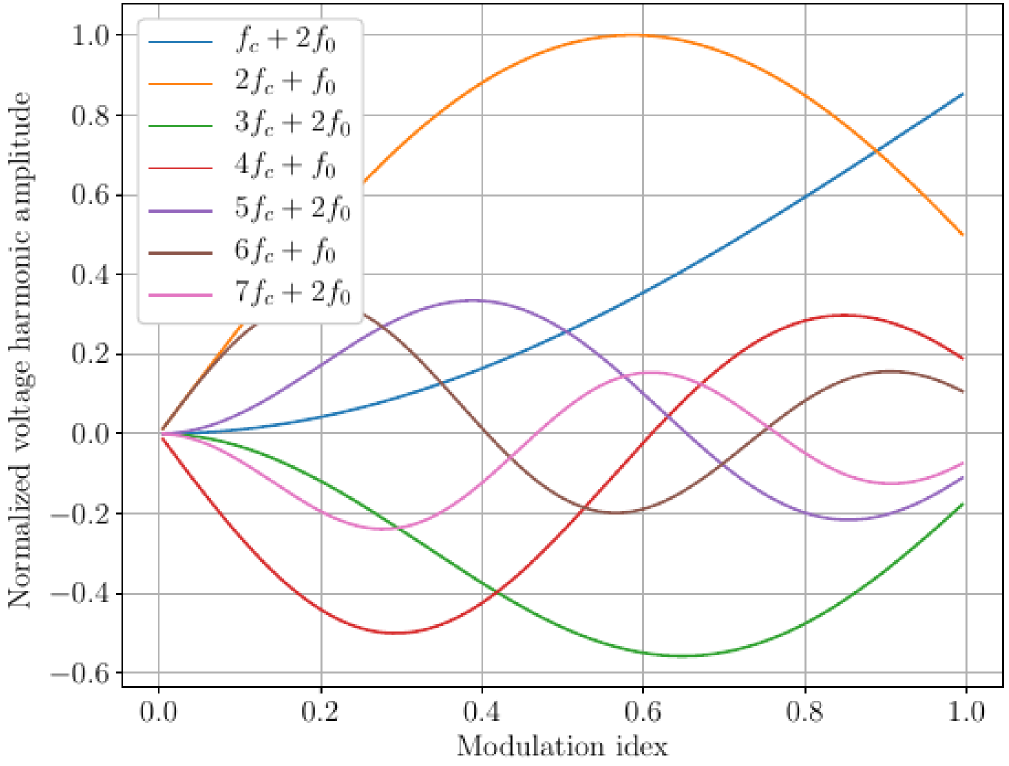


Losses due to PWM Harmonics

Calculation of PWM signal

- Evaluation of the currents for a symmetrical m phase system with floating star connection.
- Frequency dependent inductances and resistances are used for current calculation.

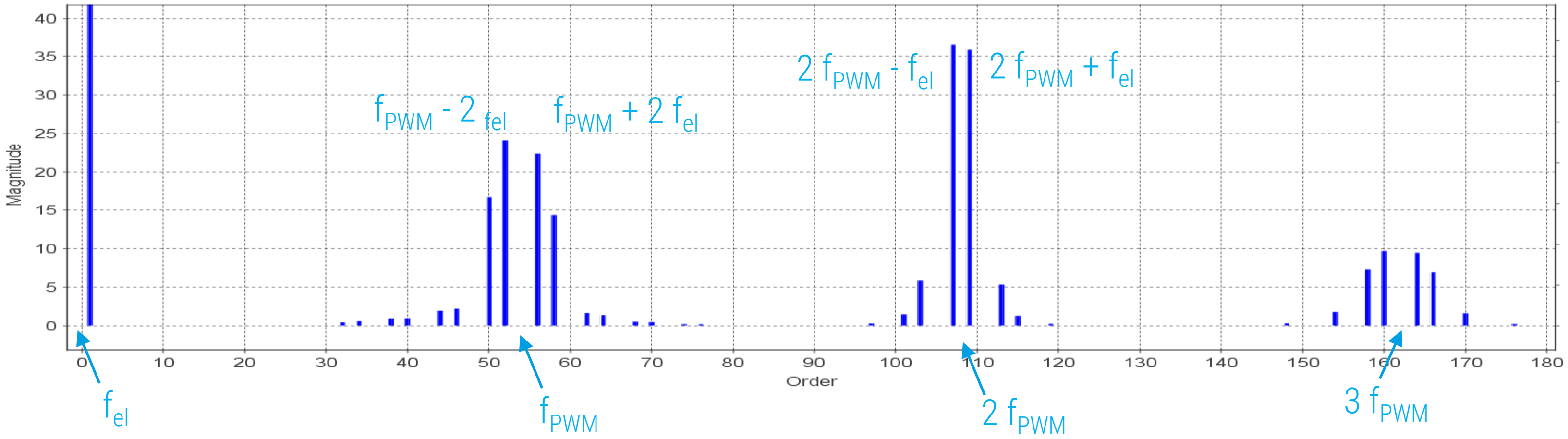




Losses due to PWM Harmonics

Loss calculation

- Simulation of the permeability distribution in the laminated core for the considered load point.
- Calculation of losses as a function of frequency with AC FE Solver at "frozen" permeabilities.
- Evaluation of losses in solid and laminated components.
  - Wire and hair pins
  - Laminated stack
  - Magnet



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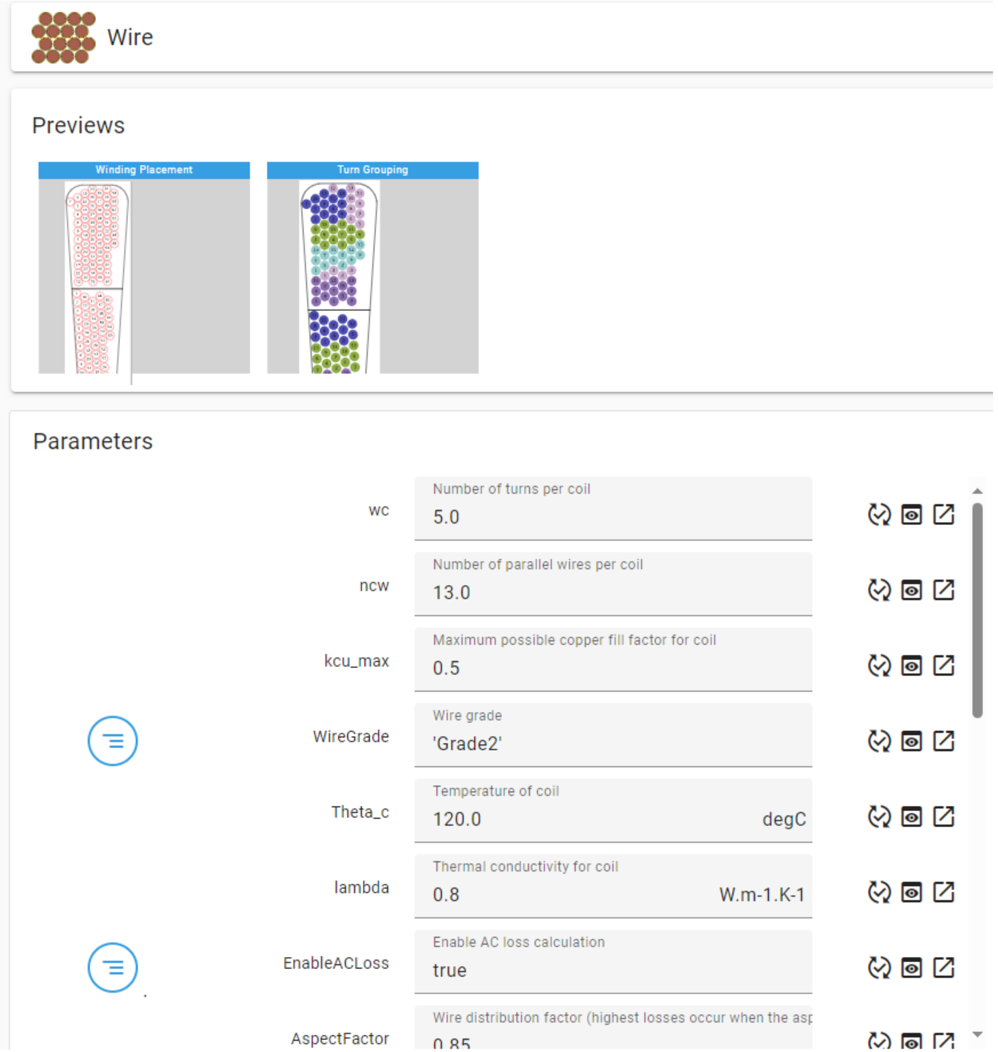
AC losses – Loadpoint and dq Grid

Usage in SyMSpace

AC losses in dq Grid in SyMSpace

Add AC losses to WebGUI project

- Add Component „PMSM AClosses FEMM“ to PMSM Simulation
- Settings in Geometry.Stator.Coil:
    - *EnableACloss* is set automatically to true after inserting AClosses
    - Set *wc*, *ncw*, *WireGrade* and *AspectFactor*
    - Check Preview of WireDiameter
- Further checks:
    - Preview of PMSM_Model (check if the wires are drawn in the correct slots, especially for double layer windings)
    - Check if all materials have a field *rho_el* or *kappa_20*
    - Check if laminated materials have a field *tlam*



Wire

Previews

Parameters

wc	Number of turns per coil	5.0
ncw	Number of parallel wires per coil	13.0
kcu_max	Maximum possible copper fill factor for coil	0.5
WireGrade	Wire grade	'Grade2'
Theta_c	Temperature of coil	120.0 degC
lambda	Thermal conductivity for coil	0.8 W.m-1.K-1
EnableACLoss	Enable AC loss calculation	true
AspectFactor	Wire distribution factor (highest losses occur when the asp	0.85

AC losses in dq Grid in SyMSpace

Postprocessing - PWM Settings

- Usage in Postprocessing (RBF) Components
  - AC losses are automatically evaluated according to settings in Postprocessing_Settings
- Master PWM Settings in Postprocessing_Settings.Power_Supply
  - Constant PWM frequency or speed-dependent vector
  - *enable_PWM*: default is false → set to true
  - *ModulationType*: sine, space vector, third harmonic, DPWM min, DPWM max
  - *InverterLevels*: 2 or 3
  - *MaxLossError*: default is 6 %, maximum order of PWM harmonics is automatically calculated from *MaxLossError*

enable_PWM — Enable PWM evaluation: false

InverterLevels — Number of inverter levels (only used for PWM): 2.0

MaxLossError — Maximum error of simulated PWM losses in percent: 6.0 %

nl_vector — Speed vector: [0.0 3000.0 4500.0 6000.0] rpm

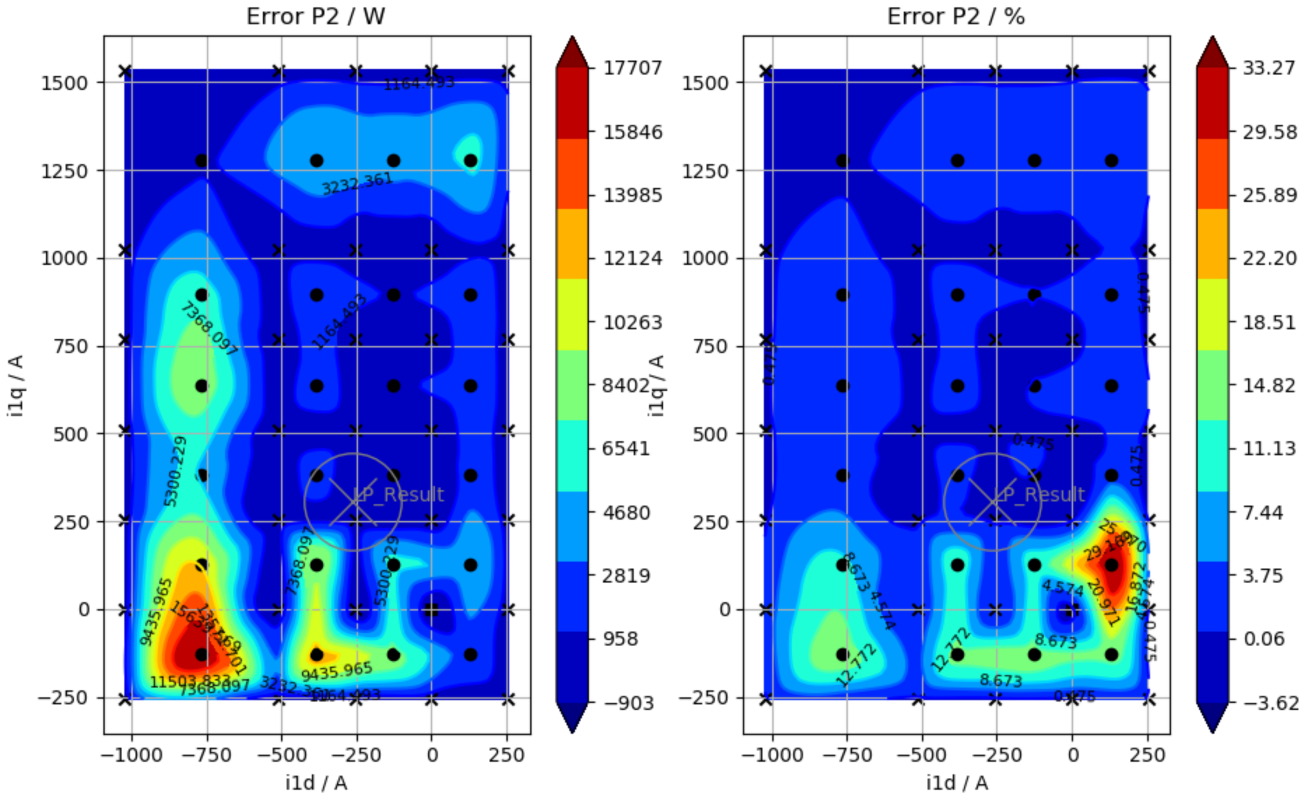
[0, nl_max / 2, nl_max * 3/4, nl_max]

ItpKind — Specifies the kind of interpolation (Default: next): 'next'

AC losses in dq Grid in SyMSpace

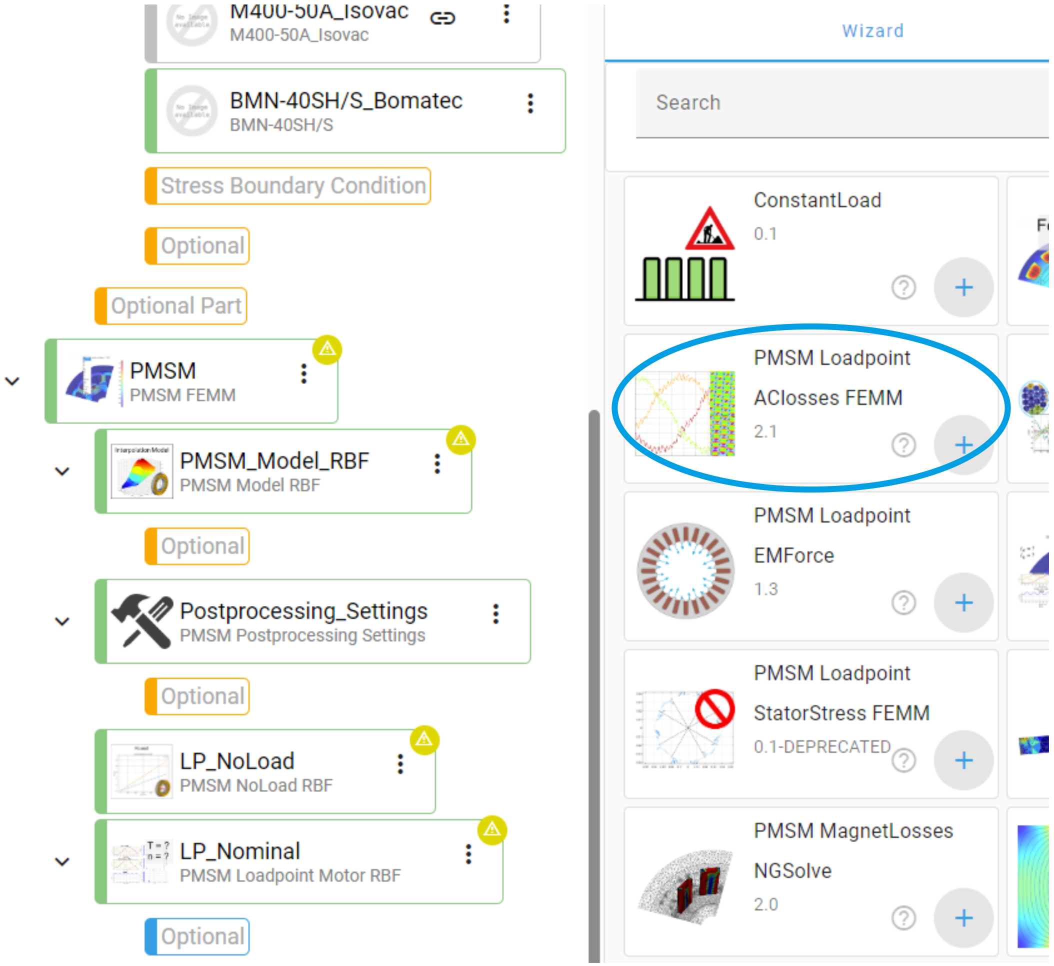
Verification of Interpolation Quality

- First: check quality of load point interpolation
  - Add PMSM_Model_Verification_FEMM component to your project
  - In general (also for basic models without AC losses) **highly recommended**
- Check interpolated AC loss results
  - Add a PMSM_Loadpoint_AClosses_FEMM component to your project and link *ild*, *ilq* and *nl* to the RBF load point for comparison

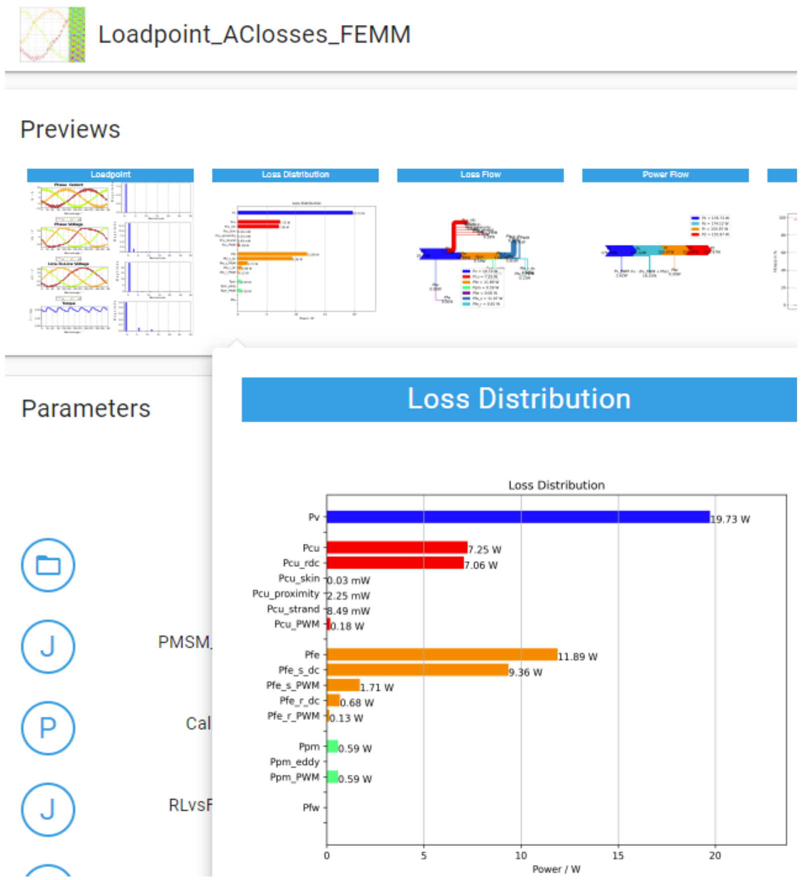


AC losses in dq Grid in SyMSpace

Add AC loss loadpoint to WebGUI project



Add Component „PMSM Loadpoint AClosses FEMM“ to a loadpoint



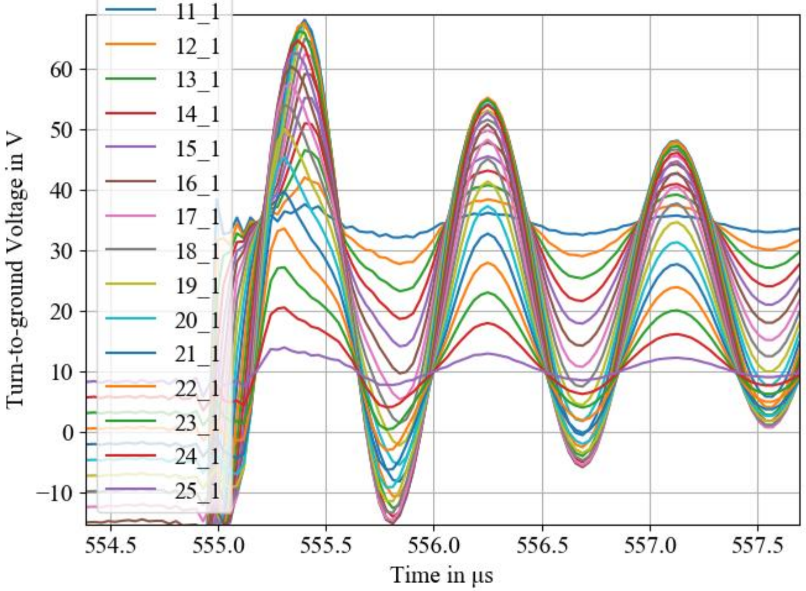
2

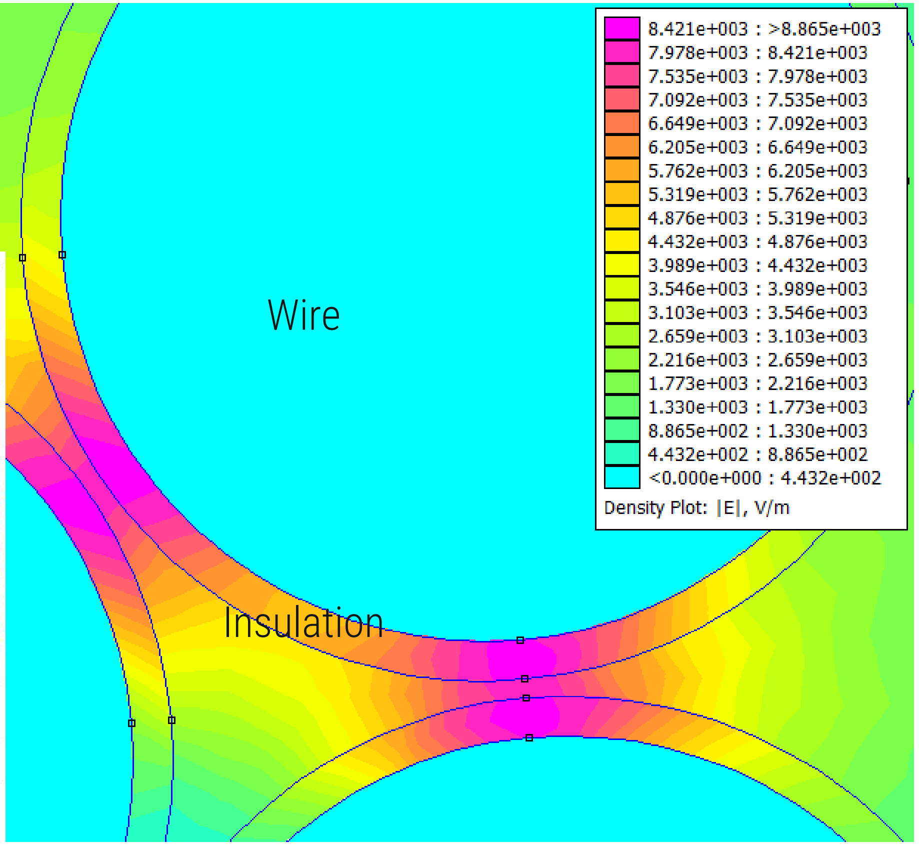
Transient Voltage Effects

Introduction

Transient Voltage Effects in Electric Machines

- Increasing switching frequencies and slew rates → electric stress on winding insulation in electric machines rises
- Distribution of voltage within winding is not uniform
- Transient overvoltages
  → damages in wire and slot insulation, partial discharge (PD)

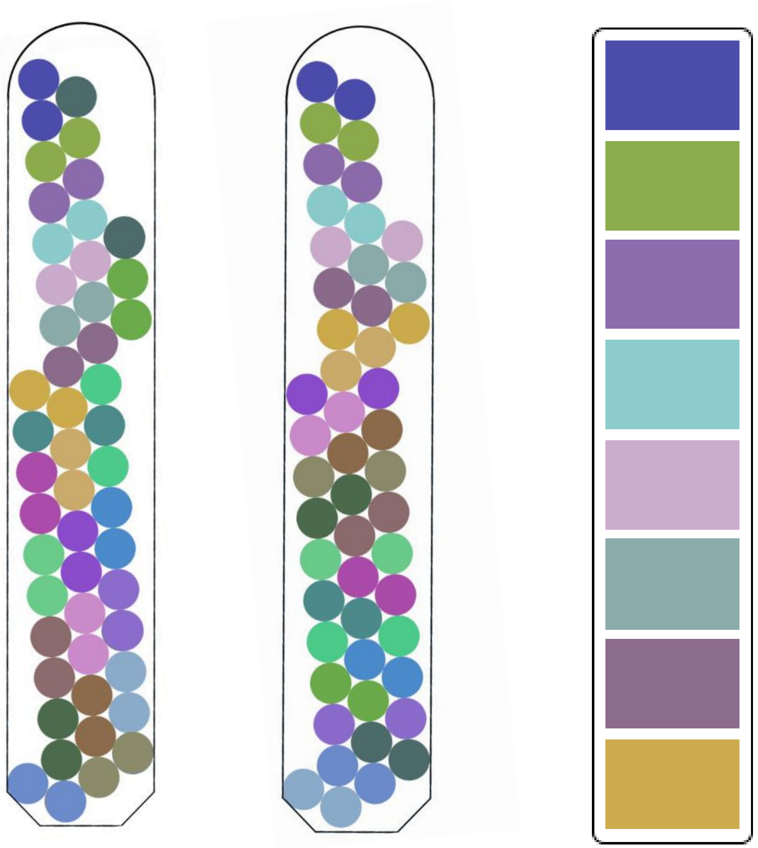




Introduction

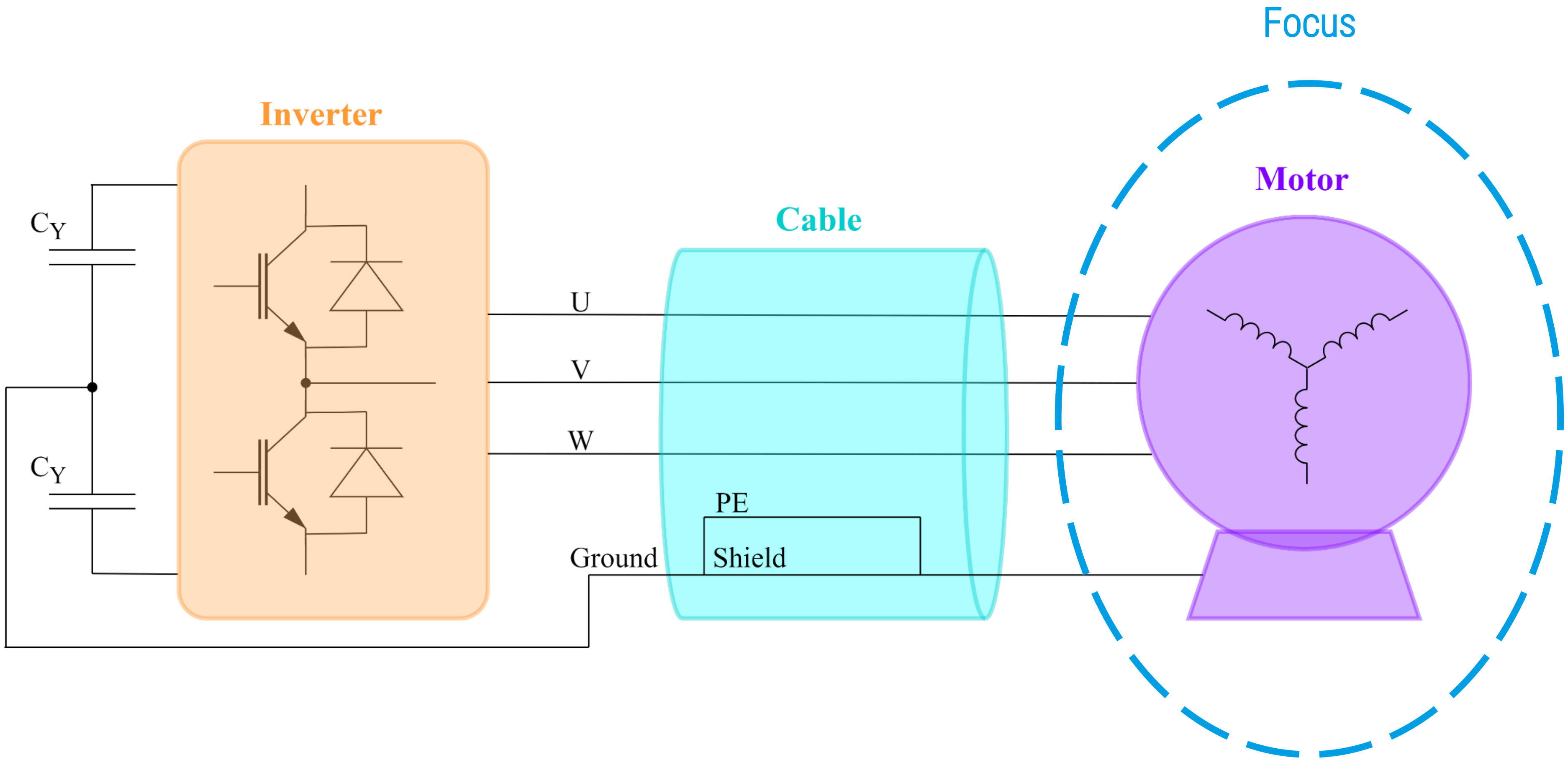
Transient Voltage Effects in Electric Machines

- Insulation design → model for prediction of transient overvoltages necessary
- Random wound winding: position of wires not exactly known → worst case estimation
- Hairpin / form wound winding: position of wires well defined → voltage distribution can be calculated considering winding scheme



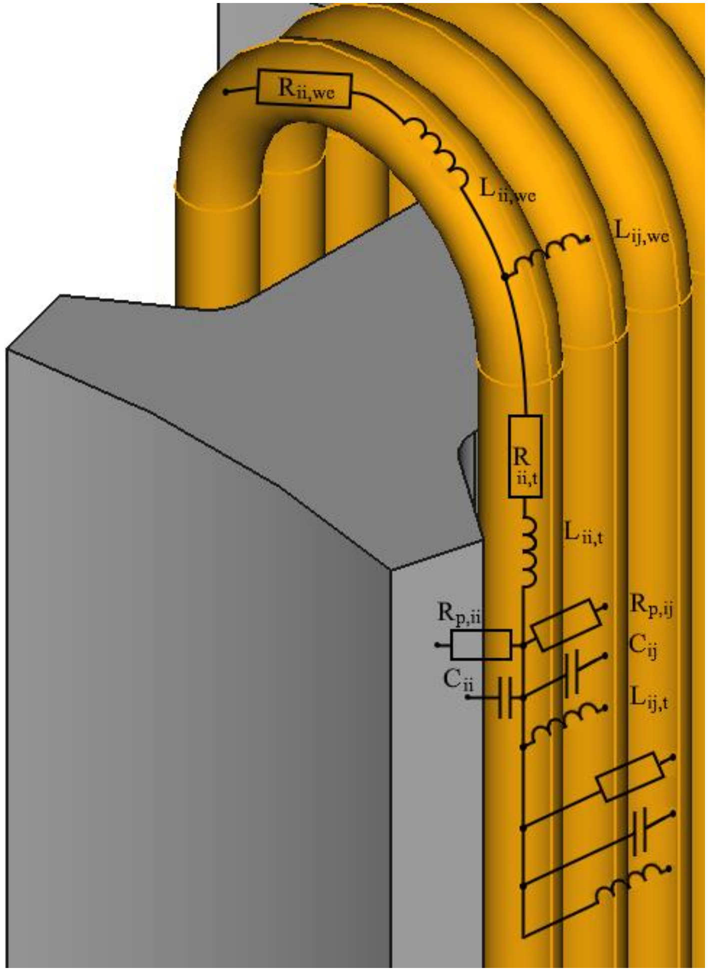
Overall model

Inverter – Cable – Motor

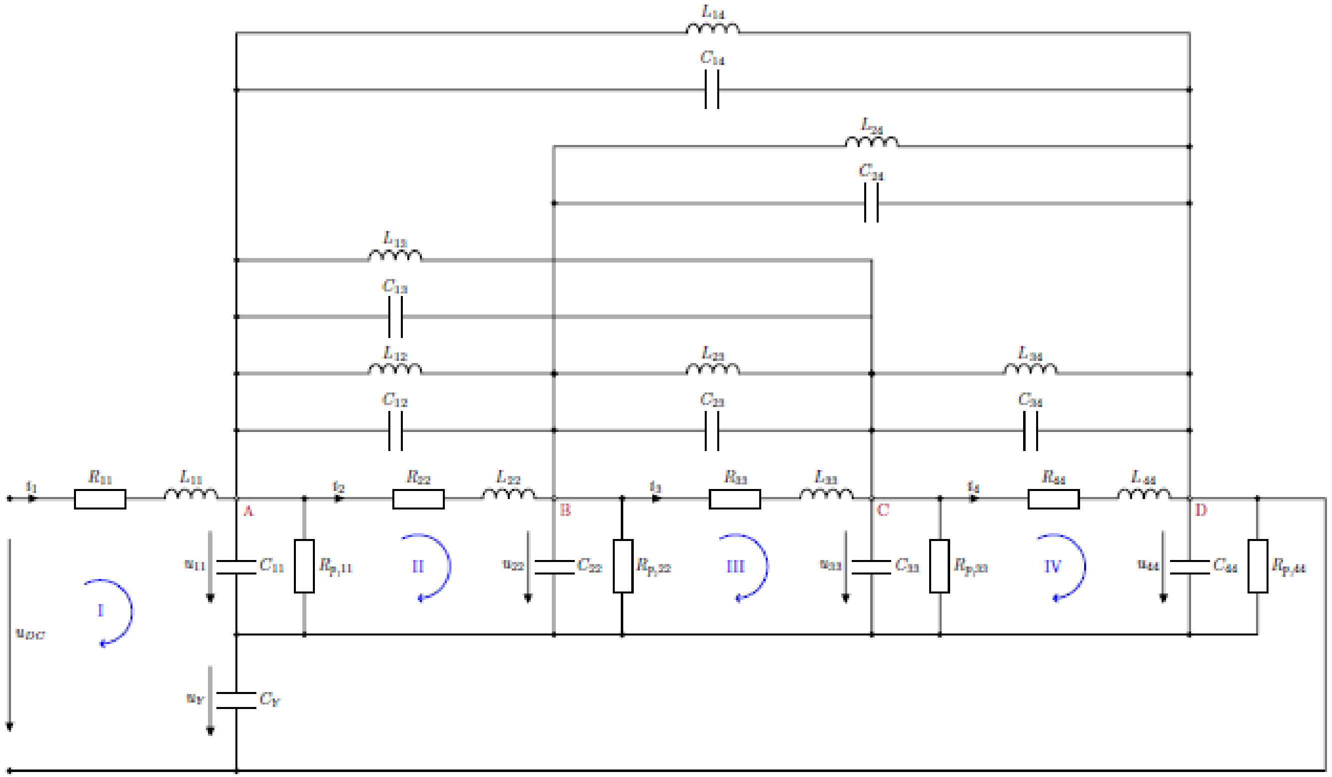


Overview

Model for transient voltage effects



- High-frequency motor model, evaluation of parameter in 2D FE or analytic
- Efficient computation in frequency domain → calculation of voltage overshoot

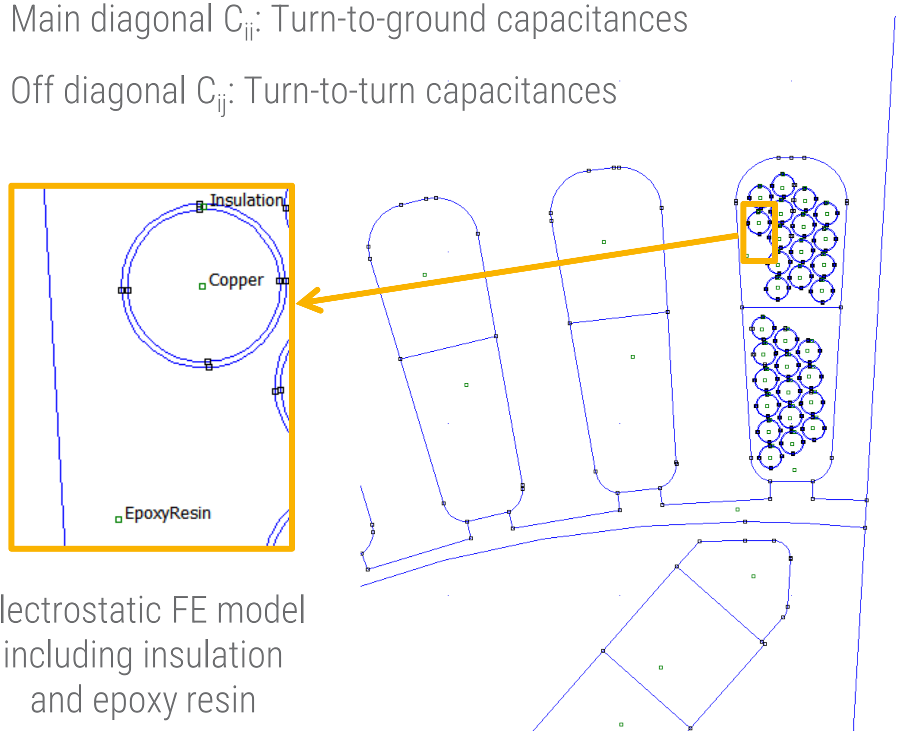


Capacitance Matrix

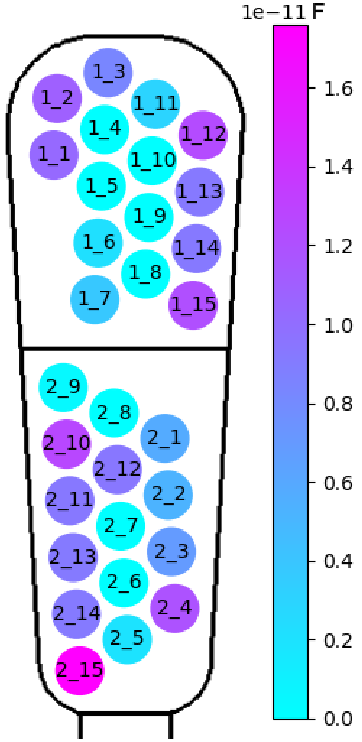
Simulation in FEMM electrostatic

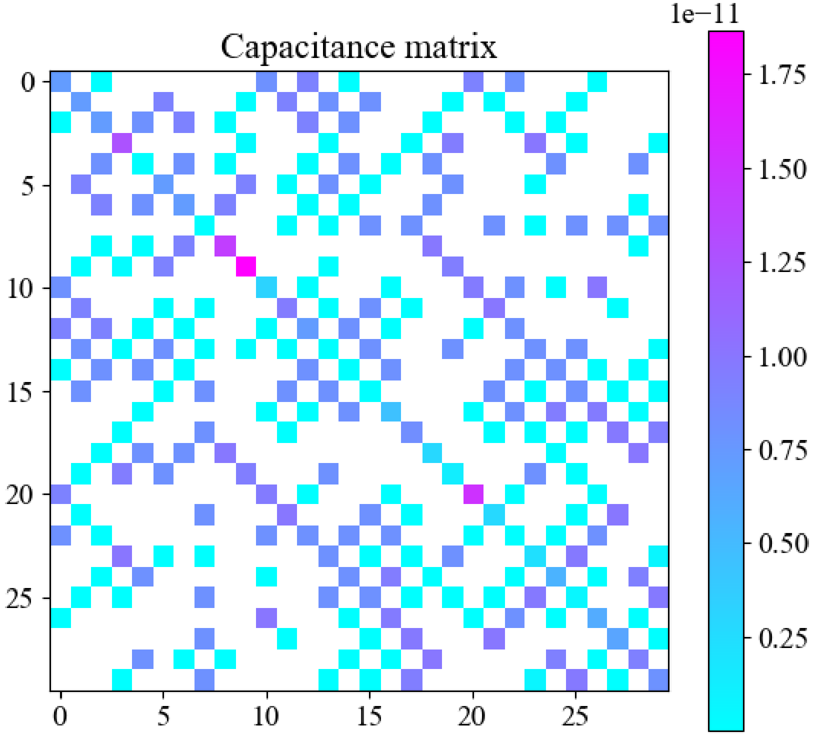
Resulting capacitance values

- Main diagonal C_{ii}: Turn-to-ground capacitances
- Off diagonal C_{ij}: Turn-to-turn capacitances



Electrostatic FE model including insulation and epoxy resin



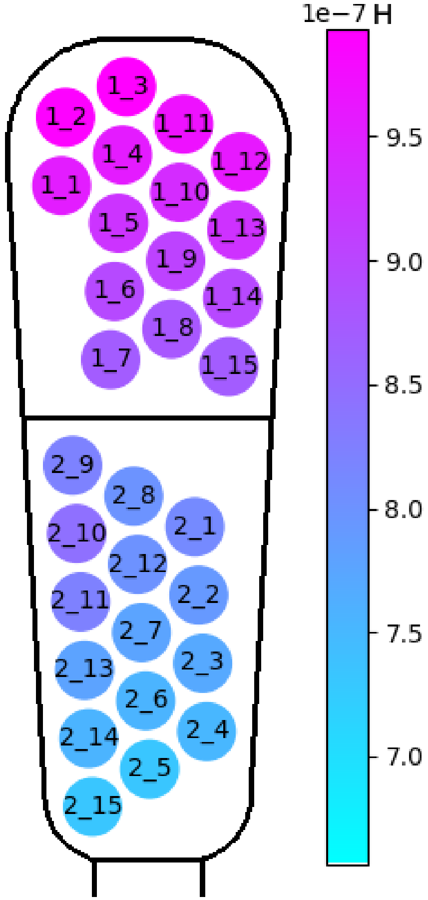


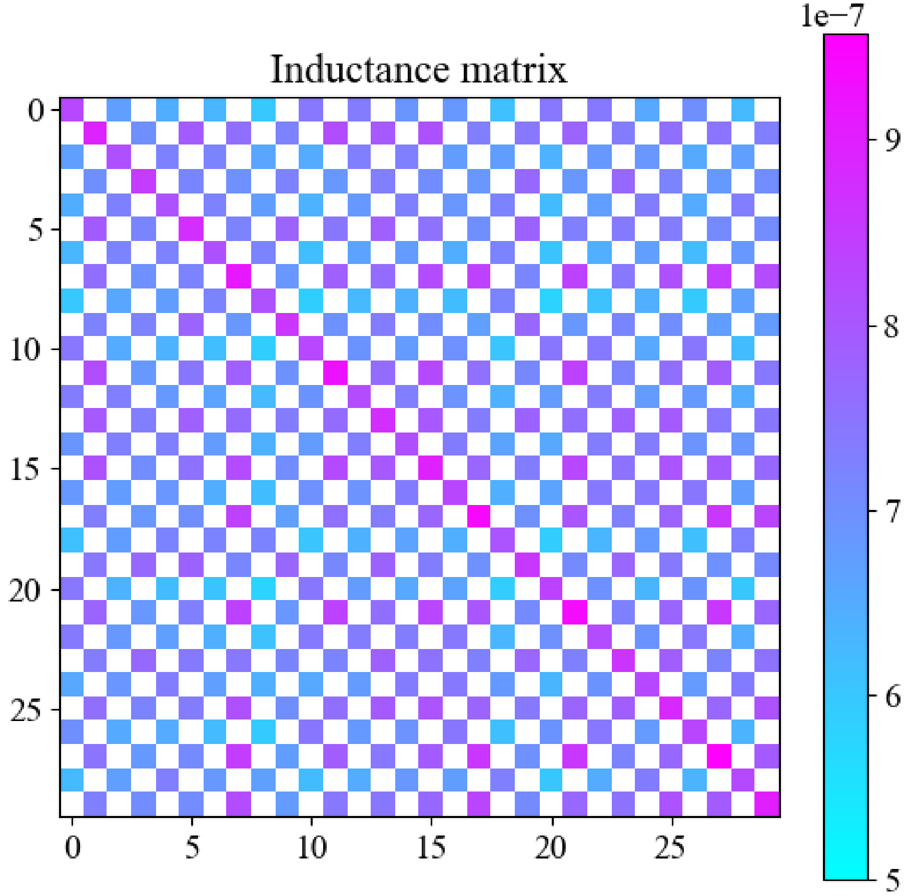
Inductance Matrix

Simulation in FEMM Magnetostatic

Resulting inductance values

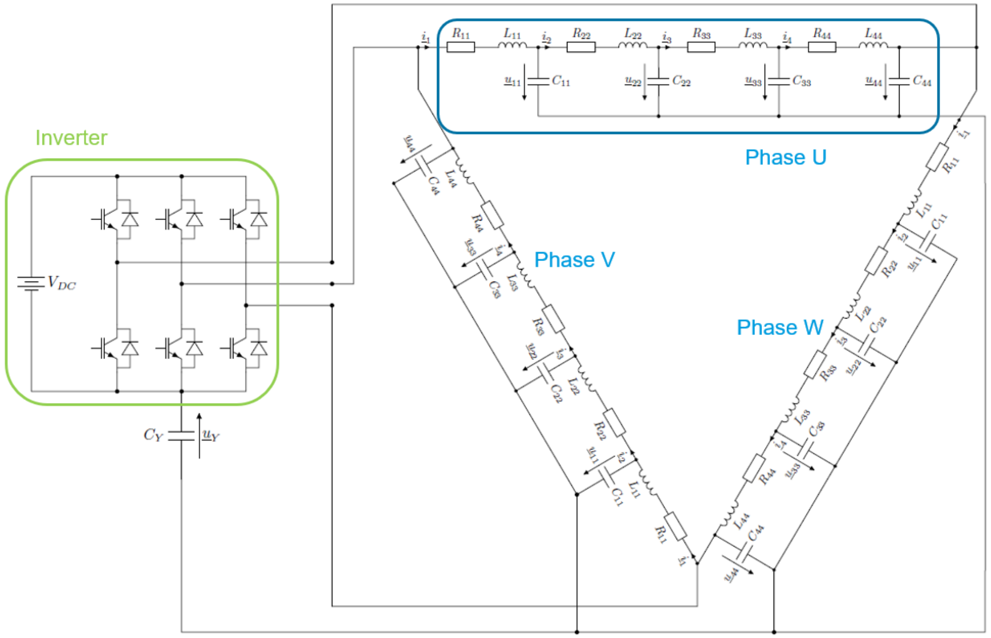
- Main diagonal L_{ii}: Self inductances
- Off diagonal L_{ij}: Mutual inductances

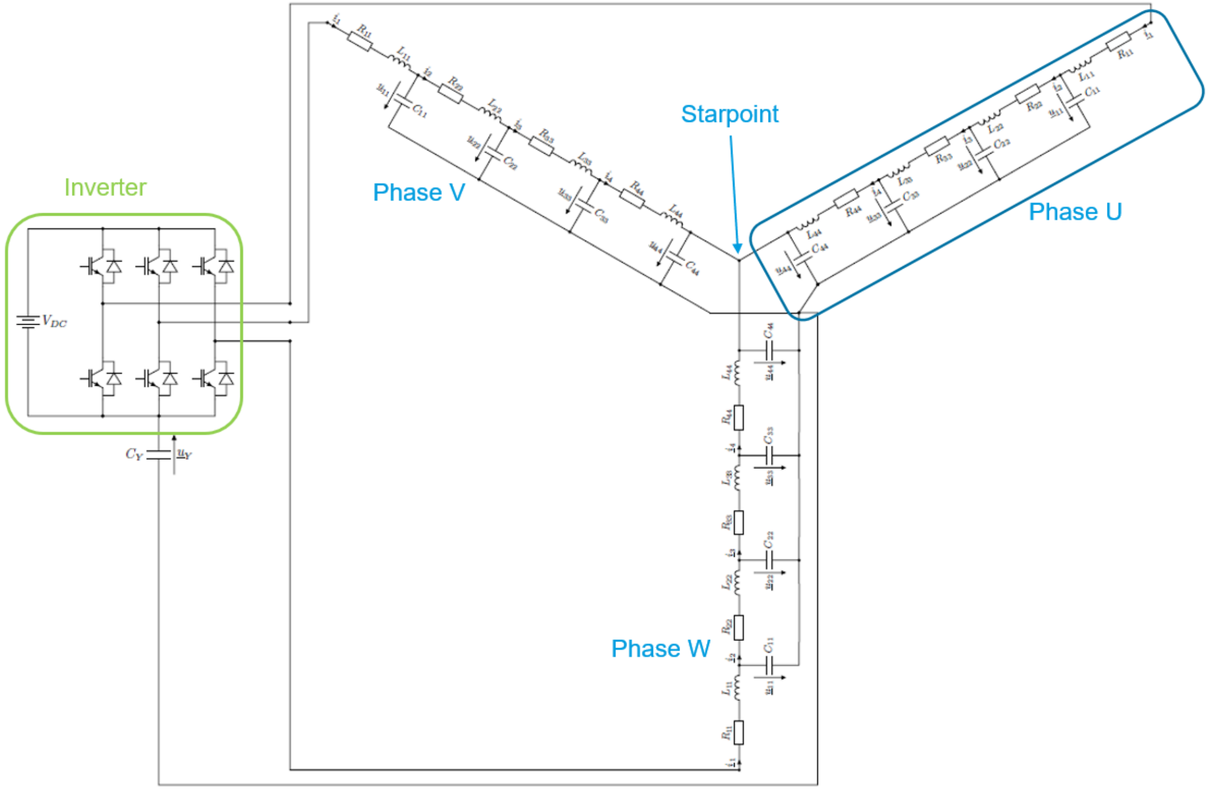




Coil → Phase → Motor model

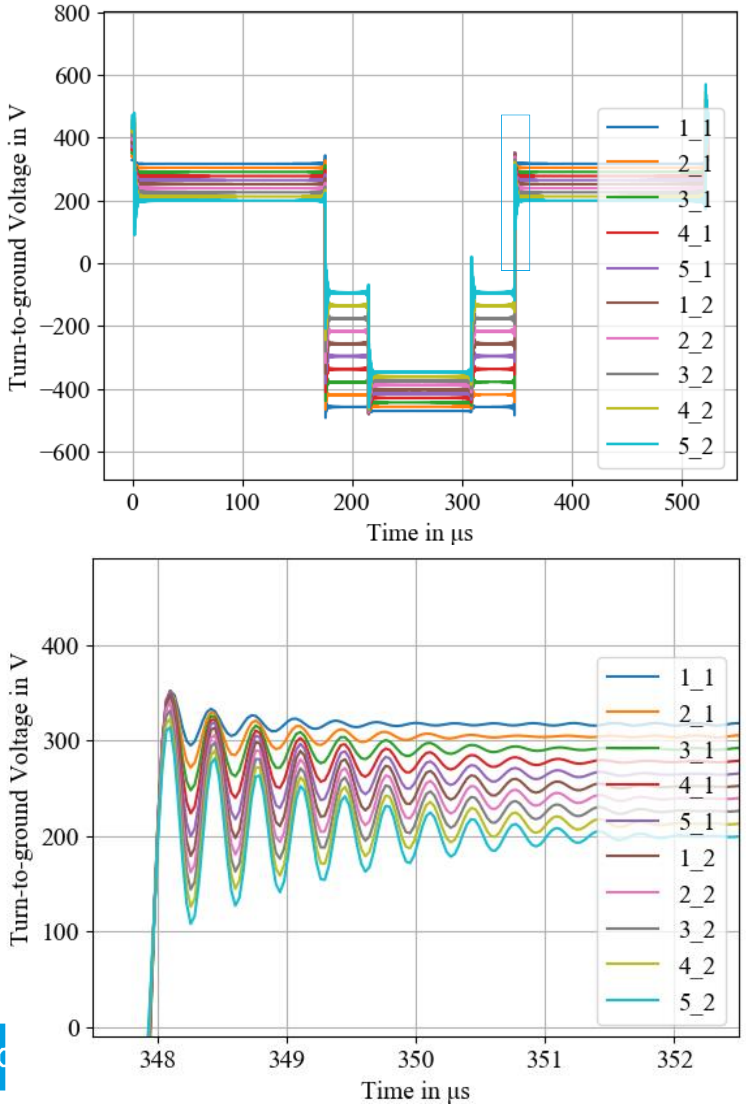
- Coils → Phase: winding scheme
- Delta and star connection including inverter



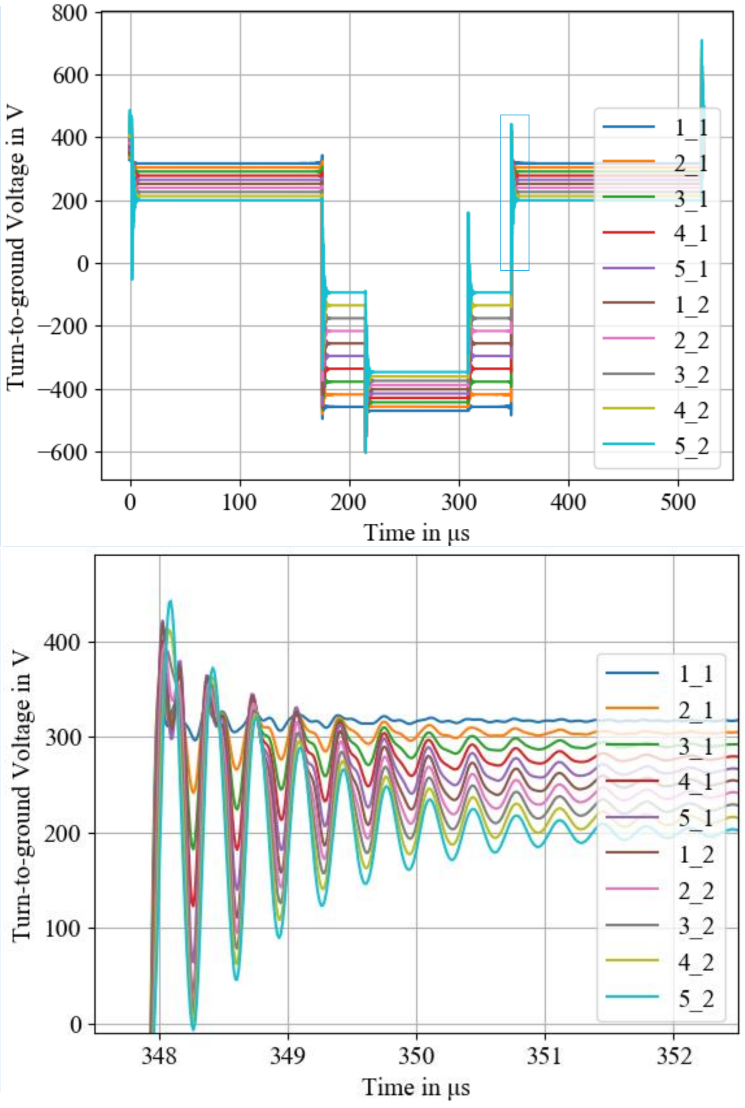


Motor model – Turn-to-ground Voltage at different Slew Rates

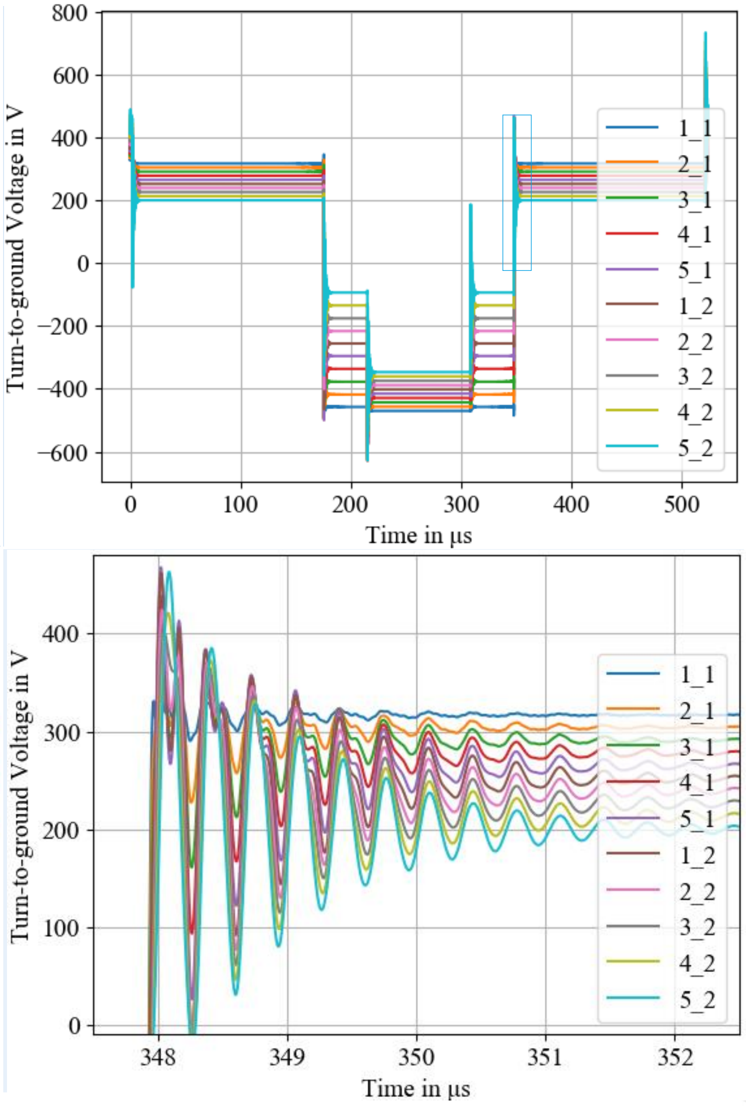
2 kV / µs



5 kV / µs



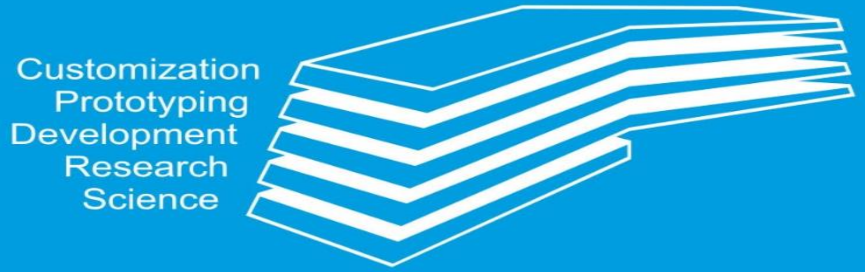
10 kV / µs



Solution in the Frequency Domain

Advantages

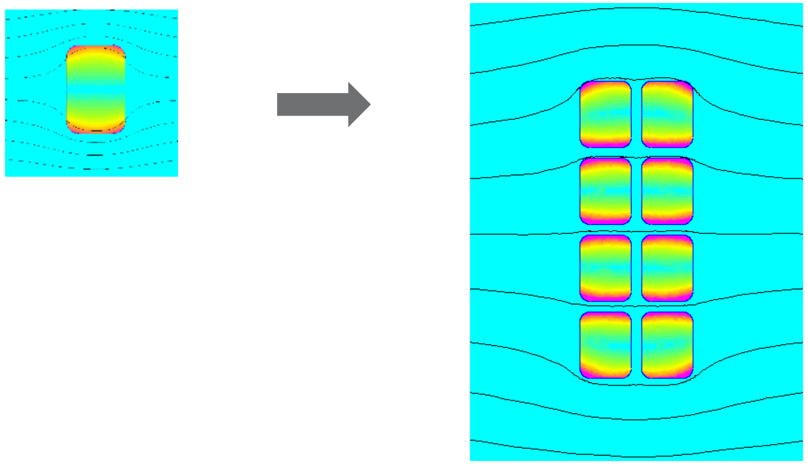
- Fast model evaluation, no time-consuming 3D or transient FEA
- Frequency dependency of parameters (resistances, inductances) - due to skin and eddy current effects - can be considered directly → higher accuracy, reduced number of network parameters compared to ladder network approximation
- Free software tools are used (Python, FEMM) → suitable for optimization

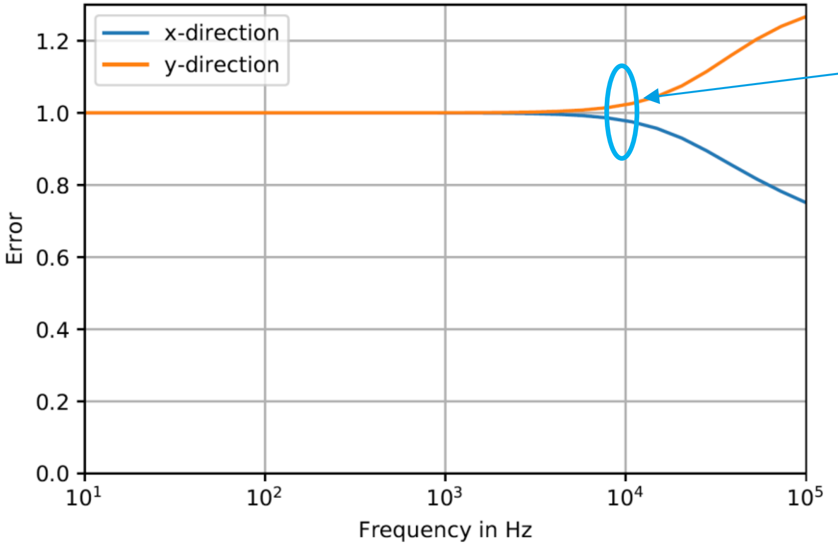

Customization
Prototyping
Development
Research
Science

Proximity Losses

Validation of losses

- Calculation method is based on single conductors.
- Is this method valid for a typical arrangement of conductors in the slot?



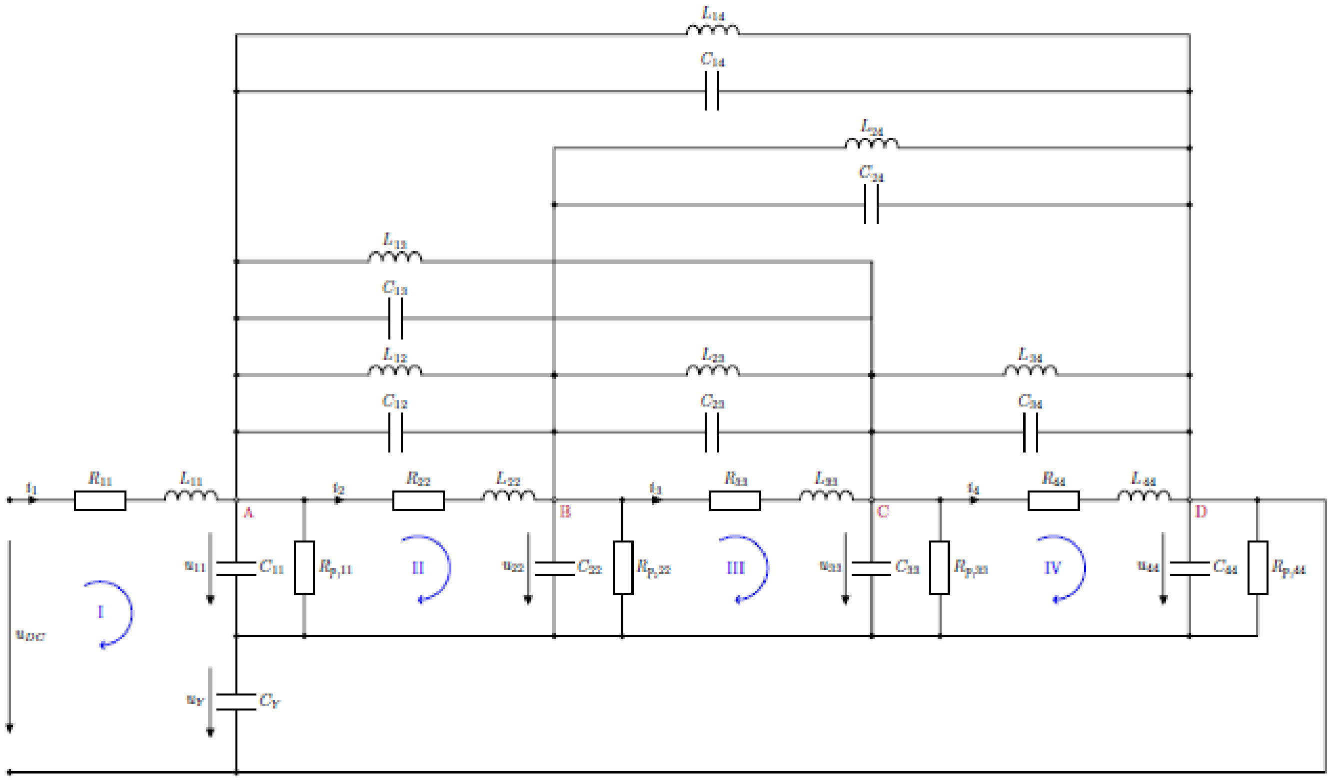


2.5% error at 10kHz

Error of the proximity losses for the array arrangement instead of single conductor

Multi-Conductor Transmission Line Motor Model

Network and equations



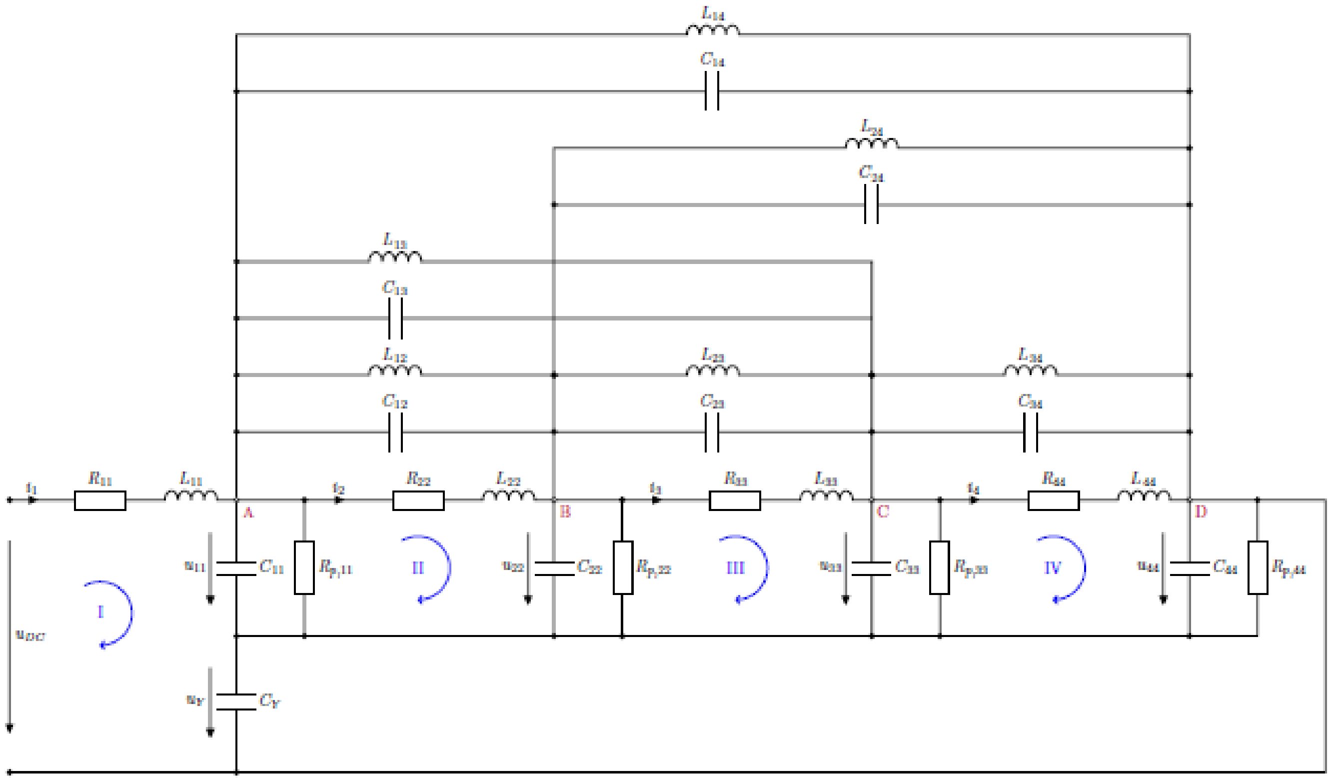
$$(A) \quad (C_{11}+C_{12}+C_{13}+C_{14})\frac{du_{11}}{dt} - C_{12}\frac{du_{22}}{dt} - C_{13}\frac{du_{33}}{dt} - C_{14}\frac{du_{44}}{dt} = -(\frac{1}{R_{p,11}}+\frac{1}{R_{p,12}}+\frac{1}{R_{p,13}}+\frac{1}{R_{p,14}})u_{11} + \frac{1}{R_{p,12}}u_{22} + \frac{1}{R_{p,13}}du_{33} + \frac{1}{R_{p,14}}u_{44} + i_1 - i_2$$

$$(B) \quad -C_{21}\frac{du_{11}}{dt} + (C_{21}+C_{22}+C_{23}+C_{24})\frac{du_{22}}{dt} - C_{23}\frac{du_{33}}{dt} - C_{24}\frac{du_{44}}{dt} = \frac{1}{R_{p,21}}u_{11} - (\frac{1}{R_{p,21}}+\frac{1}{R_{p,22}}+\frac{1}{R_{p,23}}+\frac{1}{R_{p,24}})u_{22} + \frac{1}{R_{p,23}}du_{33} + \frac{1}{R_{p,24}}u_{44} + i_2 - i_3$$

$$(C) \quad -C_{31}\frac{du_{11}}{dt} - C_{32}\frac{du_{22}}{dt} + (C_{31}+C_{32}+C_{33}+C_{34})\frac{du_{33}}{dt} - C_{34}\frac{du_{44}}{dt} = \frac{1}{R_{p,31}}u_{11} + \frac{1}{R_{p,32}}du_{22} - (\frac{1}{R_{p,31}}+\frac{1}{R_{p,32}}+\frac{1}{R_{p,33}}+\frac{1}{R_{p,34}})u_{33} + \frac{1}{R_{p,34}}u_{44} + i_3 - i_4$$

Multi-Conductor Transmission Line Motor Model

State-space model



$$\bar{\boldsymbol{A}} = \begin{pmatrix} -R_{11} & 0 & 0 & 0 & -1 & 0 & 0 & 1 \\ 0 & -R_{22} & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & -R_{33} & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & -R_{44} & 0 & 0 & 1 & -1 \\ 1 & -1 & 0 & 0 & -\sum\limits_{i=1}^{4} \frac{1}{R_{p,1i}} & \frac{1}{R_{p,12}} & \frac{1}{R_{p,13}} & \frac{1}{R_{p,14}} \\ 0 & 1 & -1 & 0 & \frac{1}{R_{p,21}} & -\sum\limits_{i=1}^{4} \frac{1}{R_{p,2i}} & \frac{1}{R_{p,23}} & \frac{1}{R_{p,24}} \\ 0 & 0 & 1 & -1 & \frac{1}{R_{p,31}} & \frac{1}{R_{p,32}} & -\sum\limits_{i=1}^{4} \frac{1}{R_{p,3i}} & \frac{1}{R_{p,34}} \\ -1 & 0 & 0 & 1 & \frac{1}{R_{p,41}} & \frac{1}{R_{p,42}} & \frac{1}{R_{p,43}} & -\sum\limits_{i=1}^{4} \frac{1}{R_{p,4i}} \end{pmatrix}$$

$$\bar{\boldsymbol{B}} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}^T$$

$$\boldsymbol{C} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ \vdots & & \ddots & & & & & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\boldsymbol{D} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}^T$$

Numerically Robust Solution of State-Space Model

$$\begin{aligned} F\dot{x} &= \bar{A}x + \bar{B}u, \\ y &= Cx + Du \end{aligned} \quad \rightarrow \quad \xcancel{\begin{aligned} A &= F^{-1}\bar{A}, \\ B &= F^{-1}\bar{B} \end{aligned} \quad \rightarrow \quad \begin{aligned} \dot{x} &= Ax + Bu, \\ y &= Cx + Du \end{aligned}}$$

Matrix *F* has a very high condition number
→ Inversion causes high numeric errors

$\downarrow$ Laplace transform

$$\begin{aligned} FX(s)s = \bar{A}X(s) + \bar{B}U(s), \\ Y(s) = CX(s) + DU(s) \end{aligned} \quad \rightarrow \quad \begin{aligned} X(s) = (Fs - \bar{A})^{-1}\bar{B}U(s), \\ Y(s) = CX(s) + DU(s). \end{aligned} \quad \xrightarrow{D = 0} \quad Y(s) = C(Fs - \bar{A})^{-1}\bar{B}U(s)$$

$$F = \begin{pmatrix} L_{11} & L_{21} & L_{31} & L_{41} & 0 & 0 & 0 & 0 \\ L_{12} & L_{22} & L_{32} & L_{42} & 0 & 0 & 0 & 0 \\ L_{13} & L_{23} & L_{33} & L_{43} & 0 & 0 & 0 & 0 \\ L_{14} & L_{24} & L_{34} & L_{44} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sum_{i=1}^{4} C_{1i} & -C_{12} & -C_{13} & -C_{14} \\ 0 & 0 & 0 & 0 & -C_{21} & \sum_{i=1}^{4} C_{2i} & -C_{23} & -C_{24} \\ 0 & 0 & 0 & 0 & -C_{31} & -C_{32} & \sum_{i=1}^{4} C_{3i} & -C_{34} \\ 0 & 0 & 0 & 0 & -C_{41} & -C_{42} & -C_{43} & \sum_{i=1}^{4} C_{4i} - C_Y \end{pmatrix}$$

$$\bar{A} = \begin{pmatrix} -R_{11} & 0 & 0 & 0 & -1 & 0 & 0 & 1 \\ 0 & -R_{22} & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & -R_{33} & 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & -R_{44} & 0 & 0 & 1 & -1 \\ 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\bar{B} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}^T$$

$$C = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ \vdots & & \ddots & & & & & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$D = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}^T$$