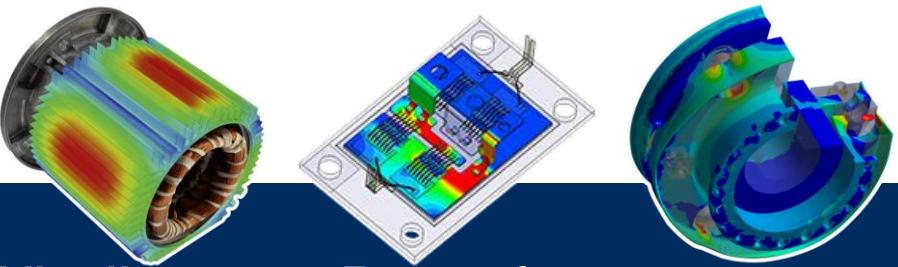




Simulation ist mehr als Software®



Eddy Current Losses in End Windings as Part of
Development Process for Electric Drives

Martin Hanke, Kleinmaschinenkolloquium Ilmenau 2019

Zusammenfassung

Im Zuge der Entwicklung von elektrischen Antrieben steigt einerseits die Breite der Simulation: von der elektromagnetischen Auslegung der Maschine für einen Lastzyklus unter Berücksichtigung der Temperaturrentwicklung über die detaillierte Untersuchung der Wechselwirkung der elektromagnetischen Domäne mit der Leistungselektronik, der Kühlung und der Vibration des Systems bis hin zur Systemsimulation.

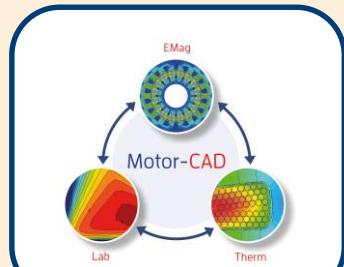
Andererseits ist die Erwartung an die Genauigkeit und damit die Anforderung an eine realistische Abbildung des Systems immer höher.

Für die Berechnung des Wickelkopfes von Maschinen mit Haarnadel-Wicklung wird die Geometrie beider Enden komplett abgebildet, statt hier eine verteilte Stromdichte über den Wickelkopfbereich anzunehmen. Aus dem Modell für ein periodisches Segment kann die Matrix der Induktivitäten und die der ohmschen Widerstände berechnet werden. Dabei sind Nichtdiagonalelemente für die Induktivitätsmatrix signifikant und daher zu berücksichtigen. Die Widerstandsmatrix hingegen ist in sehr guter Näherung diagonal. Mit der sich daraus ergebenden Schaltung kann die Berechnung in vielen Fällen in 2D erfolgen. Zur Bestimmung der lokalen Verluste im Wickelkopf kann dann wieder auf das 3D-Modell zurückgegriffen werden. Weiterhin wird zur Untersuchung der Verluste durch das Streufeld des Rotors eine Methode zur magnetischen Submodell-Berechnung vorgestellt.

Workflow Overview

Preliminary Design

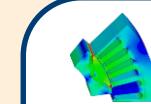
dunando optiSLang® Workflow Handling, Optimization, Sensitivity and MOP



Component Development

dunando optiSLang®

Workflow Handling, Optimization, Sensitivity, Robustness and MOP



MAXWELL
(Electromagnetic)

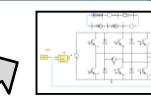


CFD
(Thermal)

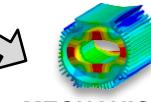
ANSYS



WORKBENCH
(Multi Physics)



TWIN BUILDER
(Power Electronics)



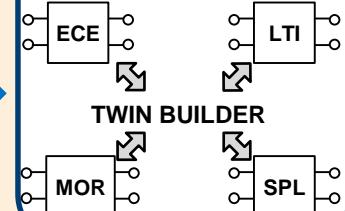
MECHANICAL
(Structural)

System Engineering

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Optimization and Sensitivity

ANSYS



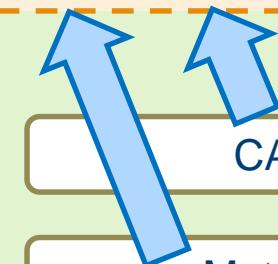
fmi FUNCTIONAL MOCK-UP INTERFACE

C/C++

SPICE

VHDL-AMS

MODELICA



CADFEM Extension

Electric Drive Acoustics inside ANSYS



Unheißt effizient

CADFEM Extension

Model Reduction inside ANSYS



Macht aus Goliath David

100 100

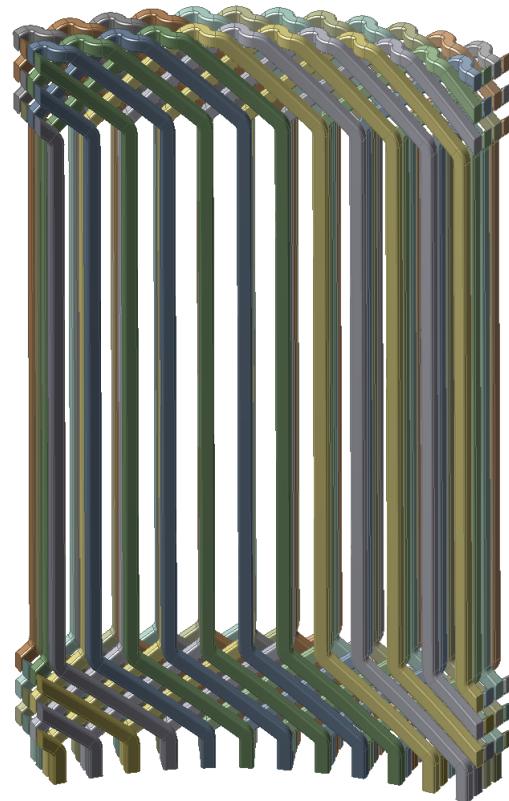
End Winding: Impedance Matrix, Losses, Submodel

- 1) End winding impedance matrix
- 2) End winding local losses
- 3) End winding in stray field from rotor



WeberStateU automotive youtube channel

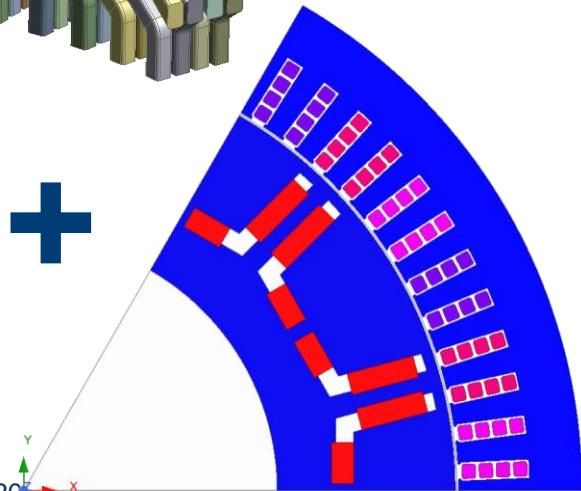
1) Impedance Matrix: End Winding Separation



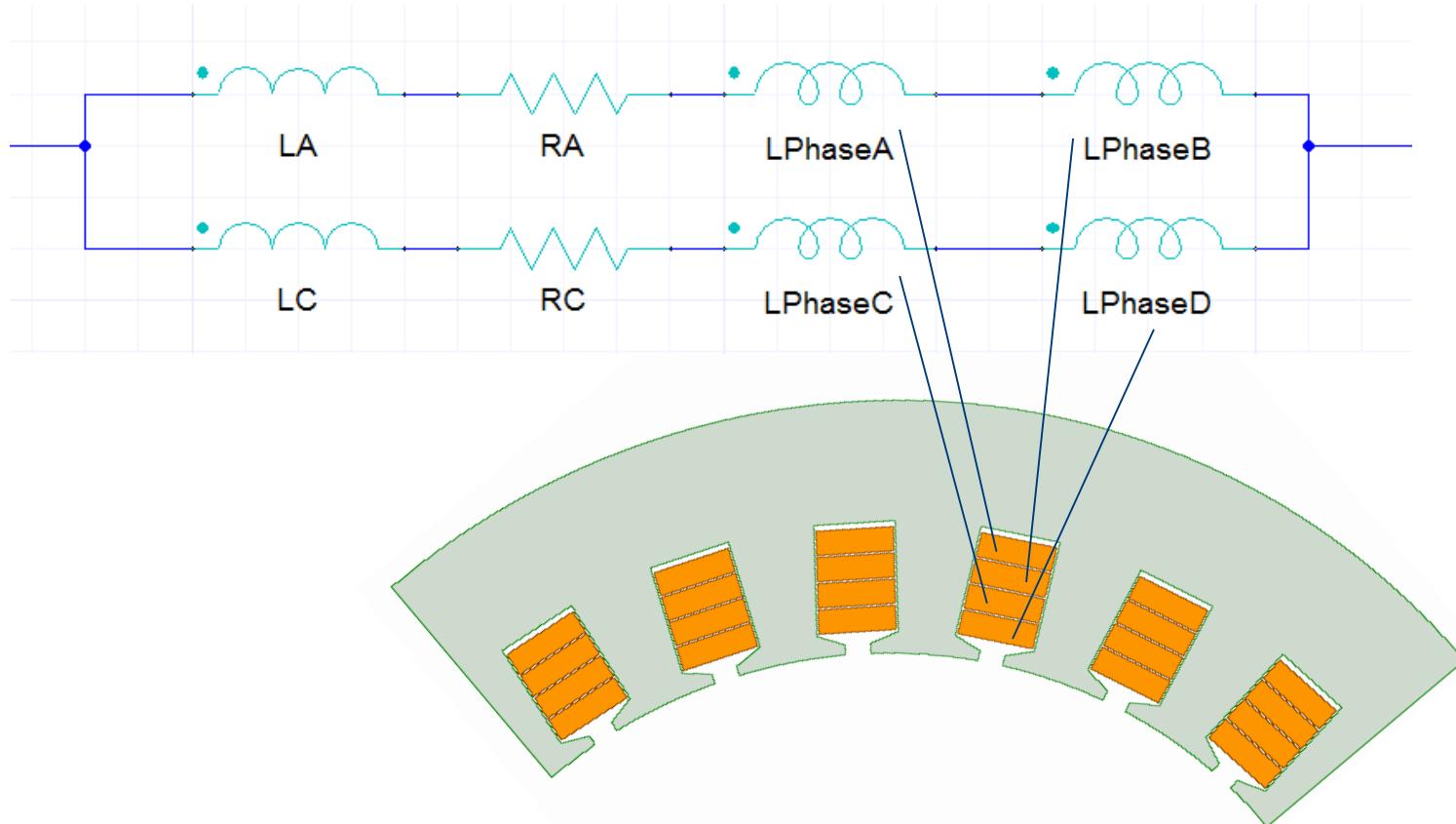
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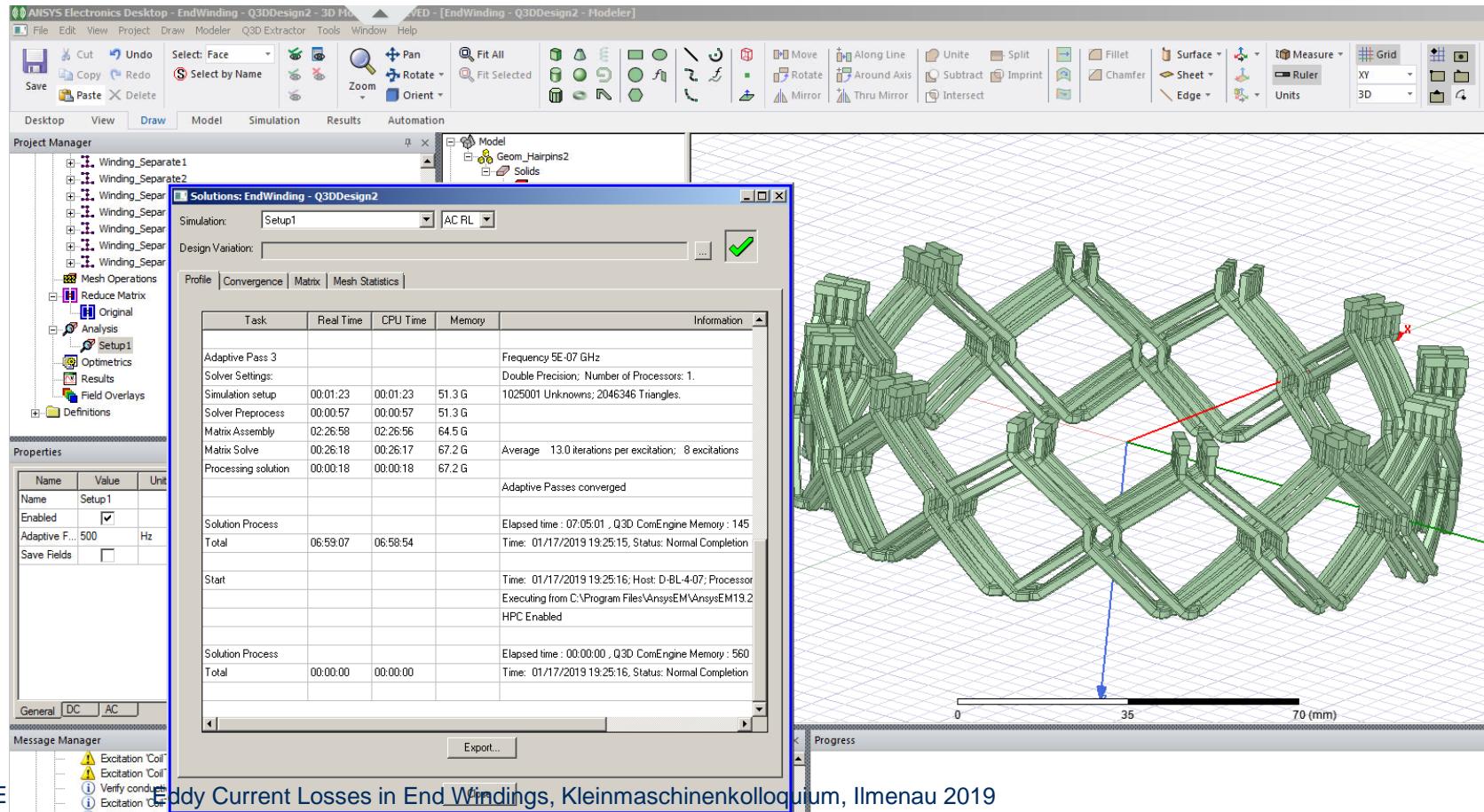
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1) Impedance Matrix: Hairpins, Parallel and in Series



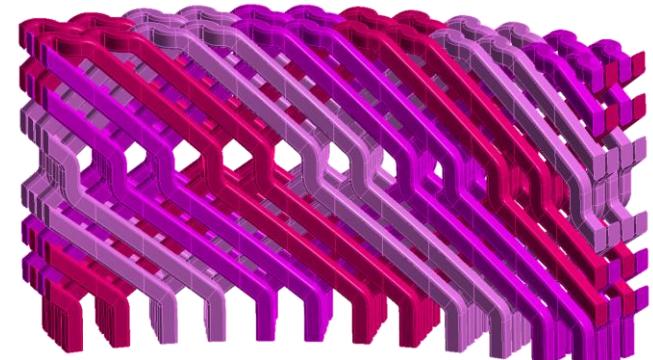
1) Impedance Matrix: Q3D Requires Full Model



1) Impedance Matrix: Feed one Conductor with 1A, Measure Harmonic Voltages

- $VOLT = \int U \cdot dt$ time integrated voltage (236,1,2)
- $U = R \cdot I + L \cdot \dot{I}$
- $i \cdot \omega \cdot VOLT = R \cdot I + i \cdot \omega \cdot L \cdot I$
- $Re(Volt) = L \cdot I$
- $\omega \cdot Im(VOLT) = -R \cdot I$

| L/nH | U | 1 | 2 | 3 | 4 | -W | 5 | 6 | 7 | 8 | 9 | 10 | 11 | -U | 12 | 13 | 14 | 15 | 16 | 17 | W | 18 | 19 | 20 | 21 | 22 | 23 | -V | 24 |
|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|-----|----|----|----|
| 1 | 55.9 | 22.7 | 26.1 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.2 | 19.0 | | | | | |
| 2 | 22.7 | 55.9 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.8 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 | 5.0 | 5.6 | 8.0 | 9.3 | 12.4 | 15.3 | 18.5 | 27.0 | | | | | |
| 3 | 26.1 | 19.0 | 55.9 | 22.7 | 26.3 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 | 0.5 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | | | | |
| 4 | 12.4 | 27.0 | 22.7 | 55.9 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.7 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 | 5.0 | 5.6 | 8.0 | 9.3 | 12.4 | 15.3 | | | | | |
| 5 | 14.4 | 12.6 | 26.2 | 10.0 | 56.0 | 22.7 | 26.2 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | | | | | |
| 6 | 12.4 | 15.3 | 27.0 | 12.6 | 22.7 | 55.9 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.7 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 | 5.3 | 4.9 | 8.7 | 8.0 | | | | | |
| 7 | 8.7 | 8.0 | 14.4 | 12.6 | 26.2 | 19.0 | 55.9 | 22.7 | 26.1 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | | | | |
| 8 | 8.0 | 9.3 | 12.4 | 15.3 | 18.5 | 27.0 | 22.7 | 55.0 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.8 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 | 5.0 | 5.6 | | | | | |
| 9 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.1 | 19.0 | 55.9 | 22.7 | 26.2 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | | | | | |
| 10 | 5.0 | 5.6 | 8.0 | 9.3 | 12.4 | 15.3 | 18.5 | 27.0 | 22.7 | 55.0 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.7 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 | | | | | |
| 11 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.2 | 19.0 | 56.0 | 22.7 | 26.2 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | | | | | |
| 12 | 2.8 | 2.9 | 5.0 | 5.6 | 8.0 | 9.3 | 12.4 | 15.3 | 18.5 | 27.0 | 22.7 | 55.0 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.7 | 2.9 | 1.5 | 1.0 | | | | | |
| 13 | 0.5 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.1 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.7 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 | | | | |
| 14 | 1.5 | 1.0 | 2.8 | 2.9 | 5.0 | 5.6 | 8.0 | 8.3 | 12.4 | 15.3 | 18.5 | 27.0 | 22.7 | 55.0 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.7 | 2.9 | 1.5 | 1.0 | | | |
| 15 | 2.8 | 2.8 | 6.1 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.1 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.7 | 2.9 | 1.5 | 1.0 | | | | |
| 16 | 2.7 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 | 5.0 | 5.6 | 8.0 | 8.3 | 12.4 | 15.3 | 18.5 | 27.0 | 22.7 | 55.0 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.7 | 2.9 | | | |
| 17 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.2 | 19.0 | 56.0 | 22.7 | 26.2 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 | | | | | |
| 18 | 4.9 | 5.6 | 2.7 | 2.9 | 1.5 | 1.2 | 2.8 | 2.9 | 5.0 | 5.6 | 8.0 | 9.3 | 12.4 | 15.3 | 18.5 | 27.0 | 22.7 | 55.0 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | | | | | |
| 19 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.2 | 19.0 | 55.9 | 22.7 | 26.1 | 18.5 | 14.4 | 12.4 | | | | | |
| 20 | 8.0 | 9.3 | 4.9 | 4.6 | 5.6 | 2.8 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 | 5.0 | 5.6 | 8.0 | 9.3 | 12.4 | 15.3 | 18.5 | 27.0 | 22.7 | 22.7 | 55.0 | 19.0 | 27.0 | | | | | |
| 21 | 14.4 | 12.4 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.1 | 19.0 | 55.9 | 22.7 | 26.2 | 18.5 | | | | | |
| 22 | 12.6 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.2 | 19.0 | 56.0 | 22.7 | | | | | |
| 23 | 26.2 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.2 | 19.0 | 55.9 | 22.7 | | | | | |
| 24 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.7 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 | 5.0 | 5.6 | 8.0 | 9.3 | 12.4 | 15.3 | 18.5 | 27.0 | 22.7 | 55.0 | | | | | |



L

R

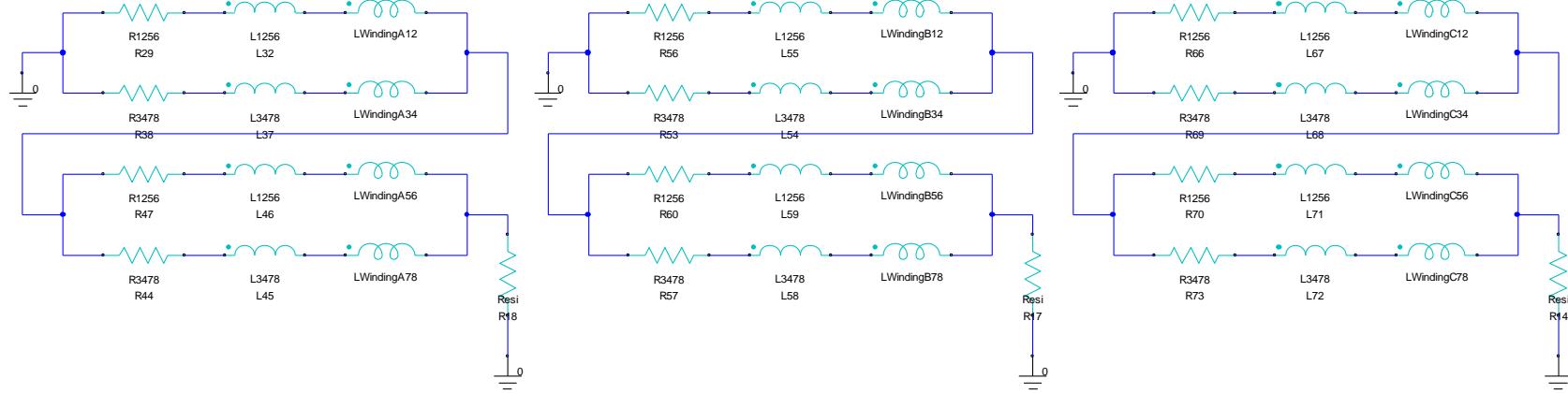
1) Impedance Matrix: Inductivity Matrix

| | U | | | | -W | | | | V | | | | -U | | | | W | | | | -V | | | | |
|--------|----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| L / nH | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | |
| U | 1 | 55.9 | 22.7 | 26.1 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.2 | 19.0 |
| | 2 | 22.7 | 55.0 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.8 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 | 5.0 | 5.6 | 8.0 | 9.3 | 12.4 | 15.3 | 18.5 | 27.0 |
| | 3 | 26.1 | 19.0 | 55.9 | 22.7 | 26.2 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 |
| | 4 | 18.5 | 27.0 | 22.7 | 55.0 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.7 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 | 5.0 | 5.6 | 8.0 | 9.3 | 12.4 | 15.3 |
| -W | 5 | 14.4 | 12.6 | 26.2 | 19.0 | 56.0 | 22.7 | 26.2 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 |
| | 6 | 12.4 | 15.3 | 18.5 | 27.0 | 22.7 | 55.0 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.7 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 | 5.0 | 5.6 | 8.0 | 9.3 |
| | 7 | 8.7 | 8.0 | 14.4 | 12.6 | 26.2 | 19.0 | 55.9 | 22.7 | 26.1 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 |
| | 8 | 8.0 | 9.3 | 12.4 | 15.3 | 18.5 | 27.0 | 22.7 | 55.0 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.8 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 | 5.0 | 5.6 |
| V | 9 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.1 | 19.0 | 55.9 | 22.7 | 26.2 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 |
| | 10 | 5.0 | 5.6 | 8.0 | 9.3 | 12.4 | 15.3 | 18.5 | 27.0 | 22.7 | 55.0 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.7 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 |
| | 11 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.2 | 19.0 | 56.0 | 22.7 | 26.2 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 |
| | 12 | 2.8 | 2.9 | 5.0 | 5.6 | 8.0 | 9.3 | 12.4 | 15.3 | 18.5 | 27.0 | 22.7 | 55.0 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.7 | 2.9 | 1.5 | 1.0 |
| -U | 13 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.2 | 19.0 | 55.9 | 22.7 | 26.1 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 |
| | 14 | 1.5 | 1.0 | 2.8 | 2.9 | 5.0 | 5.6 | 8.0 | 9.3 | 12.4 | 15.3 | 18.5 | 27.0 | 22.7 | 55.0 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.8 | 2.9 |
| | 15 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.1 | 19.0 | 55.9 | 22.7 | 26.2 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 | 5.3 | 5.0 |
| | 16 | 2.7 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 | 5.0 | 5.6 | 8.0 | 9.3 | 12.4 | 15.3 | 18.5 | 27.0 | 22.7 | 55.0 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 |
| W | 17 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.2 | 19.0 | 56.0 | 22.7 | 26.2 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 |
| | 18 | 4.9 | 5.6 | 2.7 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 | 5.0 | 5.6 | 8.0 | 9.3 | 12.4 | 15.3 | 18.5 | 27.0 | 22.7 | 55.0 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 |
| | 19 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.2 | 19.0 | 55.9 | 22.7 | 26.1 | 18.5 | 14.4 | 12.4 |
| | 20 | 8.0 | 9.3 | 4.9 | 5.6 | 2.8 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 | 5.0 | 5.6 | 8.0 | 9.3 | 12.4 | 15.3 | 18.5 | 27.0 | 22.7 | 55.0 | 19.0 | 27.0 | 12.6 | 15.3 |
| -V | 21 | 14.4 | 12.4 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.1 | 19.0 | 55.9 | 22.7 | 26.2 | 18.5 |
| | 22 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.7 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 | 5.0 | 5.6 | 8.0 | 9.3 | 12.4 | 15.3 | 18.5 | 27.0 | 22.7 | 55.0 | 19.0 | 27.0 |
| | 23 | 26.2 | 18.5 | 14.4 | 12.4 | 8.7 | 8.0 | 5.3 | 5.0 | 2.8 | 2.8 | 0.8 | 1.5 | 2.8 | 2.8 | 5.3 | 4.9 | 8.7 | 8.0 | 14.4 | 12.6 | 26.2 | 19.0 | 56.0 | 22.7 |
| | 24 | 19.0 | 27.0 | 12.6 | 15.3 | 8.0 | 9.3 | 4.9 | 5.6 | 2.7 | 2.9 | 1.5 | 1.0 | 2.8 | 2.9 | 5.0 | 5.6 | 8.0 | 9.3 | 12.4 | 15.3 | 18.5 | 27.0 | 22.7 | 55.0 |

1) Impedance Matrix: Resistance Matrix, Diagonal Dominant

| R / μOhm | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | |
|---------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|------|-------|------|-------|-------|
| 1 | 507.2 | 0.7 | 0.8 | 0.5 | 0.3 | 0.2 | 0.0 | 0.0 | -0.0 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | -0.0 | 0.0 | 0.0 | 0.2 | 0.2 | 0.9 | 0.5 | | |
| 2 | 0.7 | 488.7 | 0.5 | 0.9 | 0.2 | 0.3 | 0.0 | 0.1 | -0.1 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | -0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.5 | 0.9 | | |
| 3 | 0.8 | 0.5 | 507.4 | 0.7 | 0.8 | 0.5 | 0.2 | 0.2 | 0.0 | 0.0 | -0.0 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | 0.0 | 0.0 | 0.3 | 0.2 | | |
| 4 | 0.5 | 0.9 | 0.7 | 488.7 | 0.5 | 0.9 | 0.2 | 0.3 | 0.0 | 0.1 | -0.0 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | 0.0 | 0.1 | 0.2 | 0.3 | | |
| 5 | 0.3 | 0.2 | 0.8 | 0.5 | 507.4 | 0.7 | 0.8 | 0.5 | 0.2 | 0.2 | 0.1 | 0.0 | -0.0 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | -0.0 | 0.1 | 0.0 | |
| 6 | 0.2 | 0.3 | 0.5 | 0.9 | 0.7 | 488.7 | 0.5 | 0.9 | 0.2 | 0.3 | 0.0 | 0.1 | -0.1 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | -0.0 | 0.0 | 0.1 | |
| 7 | 0.0 | 0.0 | 0.2 | 0.2 | 0.9 | 0.5 | 507.2 | 0.7 | 0.8 | 0.5 | 0.3 | 0.2 | 0.0 | 0.0 | -0.0 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | -0.0 | |
| 8 | 0.0 | 0.1 | 0.2 | 0.3 | 0.5 | 0.9 | 0.7 | 488.7 | 0.5 | 0.9 | 0.2 | 0.3 | 0.0 | 0.1 | -0.1 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | -0.0 | |
| 9 | -0.0 | -0.0 | 0.0 | 0.0 | 0.3 | 0.2 | 0.8 | 0.5 | 507.4 | 0.7 | 0.8 | 0.5 | 0.2 | 0.2 | 0.0 | 0.0 | -0.0 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | |
| 10 | -0.0 | -0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.5 | 0.9 | 0.7 | 488.7 | 0.5 | 0.9 | 0.2 | 0.3 | 0.0 | 0.1 | -0.0 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | |
| 11 | -0.1 | -0.1 | -0.0 | -0.0 | 0.1 | 0.0 | 0.3 | 0.2 | 0.8 | 0.5 | 507.4 | 0.7 | 0.8 | 0.5 | 0.2 | 0.2 | 0.1 | 0.0 | -0.0 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | |
| 12 | -0.1 | -0.1 | -0.0 | -0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.5 | 0.9 | 0.7 | 488.7 | 0.5 | 0.9 | 0.2 | 0.3 | 0.0 | 0.1 | -0.1 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | |
| 13 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | -0.0 | 0.0 | 0.0 | 0.2 | 0.2 | 0.9 | 0.5 | 507.2 | 0.7 | 0.8 | 0.5 | 0.3 | 0.2 | 0.0 | 0.0 | -0.0 | -0.0 | -0.1 | -0.1 | |
| 14 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | -0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.5 | 0.9 | 0.7 | 488.7 | 0.5 | 0.9 | 0.2 | 0.3 | 0.0 | 0.1 | -0.1 | -0.0 | -0.1 | -0.1 | |
| 15 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | -0.0 | 0.0 | 0.0 | 0.3 | 0.2 | 0.8 | 0.5 | 507.4 | 0.7 | 0.8 | 0.5 | 0.2 | 0.2 | 0.0 | 0.0 | -0.0 | -0.0 | |
| 16 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | -0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.5 | 0.9 | 0.7 | 488.7 | 0.5 | 0.9 | 0.2 | 0.3 | 0.0 | 0.1 | -0.0 | -0.0 | |
| 17 | -0.0 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | -0.0 | 0.1 | 0.0 | 0.3 | 0.2 | 0.8 | 0.5 | 507.4 | 0.7 | 0.8 | 0.5 | 0.2 | 0.2 | 0.1 | 0.0 | |
| 18 | -0.1 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | -0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.5 | 0.9 | 0.7 | 488.7 | 0.5 | 0.9 | 0.2 | 0.3 | 0.0 | 0.1 | |
| 19 | 0.0 | 0.0 | -0.0 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | -0.0 | 0.0 | 0.0 | 0.2 | 0.2 | 0.9 | 0.5 | 507.2 | 0.7 | 0.8 | 0.5 | 0.3 | 0.2 | |
| 20 | 0.0 | 0.1 | -0.1 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | -0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.5 | 0.9 | 0.7 | 488.7 | 0.5 | 0.9 | 0.2 | 0.3 | |
| 21 | 0.2 | 0.2 | 0.0 | 0.0 | -0.0 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | -0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.5 | 0.9 | 0.7 | 0.8 | 0.5 | | |
| 22 | 0.2 | 0.3 | 0.0 | 0.1 | -0.0 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | -0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.5 | 0.9 | 0.7 | 488.7 | 0.5 | 0.9 | |
| 23 | 0.8 | 0.5 | 0.2 | 0.2 | 0.1 | 0.0 | -0.0 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | -0.0 | 0.1 | 0.0 | 0.3 | 0.2 | 0.8 | 0.5 | 507.4 | |
| 24 | 0.5 | 0.9 | 0.2 | 0.3 | 0.0 | 0.1 | -0.1 | -0.0 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.1 | -0.0 | -0.0 | 0.0 | 0.1 | 0.2 | 0.3 | 0.5 | 0.9 | 0.7 | 488.7 |

1) Impedance Matrix: External Circuit, Coupling Factors

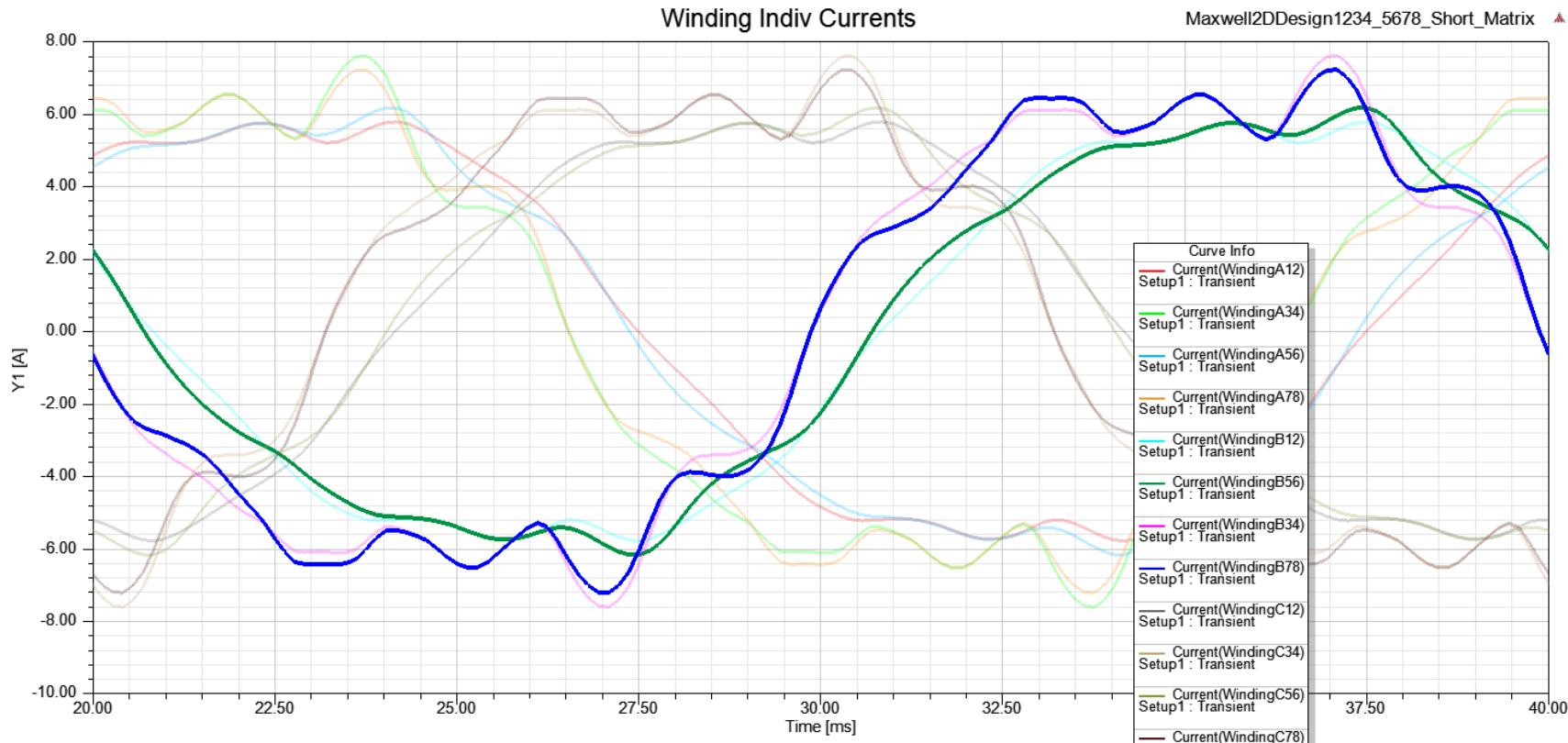


K75 LL32 LL37 0.409
 K76 LL32 LL46 0.468
 K77 LL32 LL45 0.333
 K78 LL32 LL55 -0.258
 K79 LL32 LL54 -0.223
 K80 LL32 LL59 -0.156
 K81 LL32 LL58 -0.144
 K82 LL32 LL67 0.094
 K83 LL32 LL68 0.090
 K84 LL32 LL71 0.050
 K85 LL32 LL72 0.051
 K86 LL37 LL46 0.343
 K87 LL37 LL45 0.491
 K88 LL37 LL55 -0.227
 K89 LL37 LL54 -0.278
 K90 LL37 LL59 -0.144
 K91 LL37 LL58 -0.168
 K92 LL37 LL67 0.088
 K93 LL37 LL68 0.101
 K94 LL37 LL71 0.050
 K95 LL37 LL72 0.052
 K96 LL46 LL45 0.409

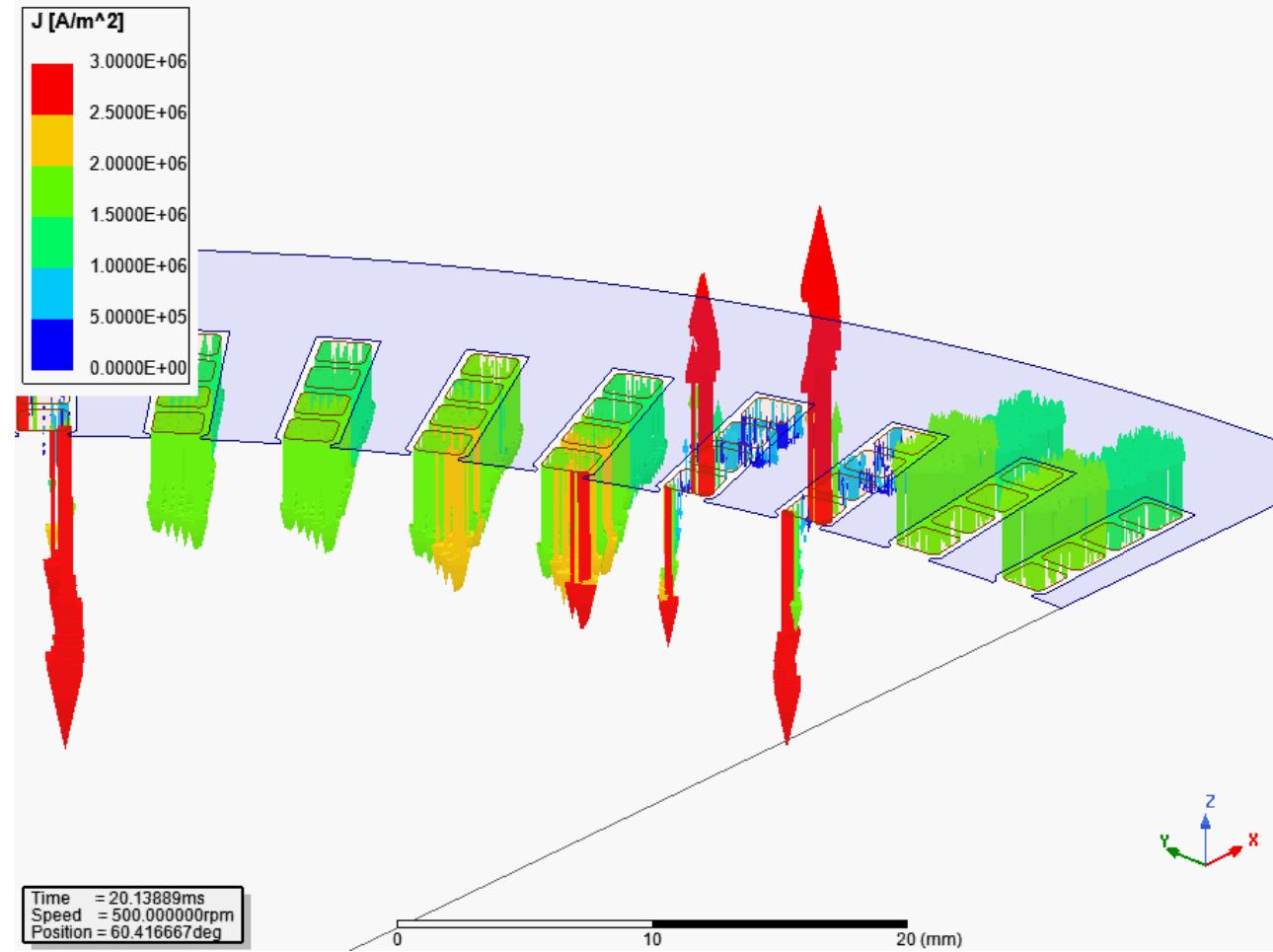
K97 LL46 LL55 -0.468
 K98 LL46 LL54 -0.333
 K99 LL46 LL59 -0.258
 K100 LL46 LL58 -0.223
 K101 LL46 LL67 0.156
 K102 LL46 LL68 0.144
 K103 LL46 LL71 0.094
 K104 LL46 LL72 0.090
 K105 LL45 LL55 -0.342
 K106 LL45 LL54 -0.491
 K107 LL45 LL59 -0.227
 K108 LL45 LL58 -0.278
 K109 LL45 LL67 0.144
 K110 LL45 LL68 0.168
 K111 LL45 LL71 0.088
 K112 LL45 LL72 0.101
 K113 LL55 LL54 -0.409
 K114 LL55 LL59 -0.468
 K115 LL55 LL58 -0.333
 K116 LL55 LL67 0.258
 K117 LL55 LL68 0.223
 K118 LL55 LL71 0.166

K119 LL55 LL72 0.144
 K120 LL54 LL59 -0.343
 K121 LL54 LL58 -0.491
 K122 LL54 LL67 0.227
 K123 LL54 LL68 0.278
 K124 LL54 LL71 0.144
 K125 LL54 LL72 0.168
 K126 LL59 LL58 -0.409
 K127 LL59 LL67 0.468
 K128 LL59 LL68 0.333
 K129 LL59 LL71 0.258
 K130 LL59 LL72 0.223
 K131 LL58 LL67 0.343
 K132 LL58 LL68 0.491
 K133 LL58 LL71 0.227
 K134 LL58 LL72 0.278
 K135 LL67 LL68 0.409
 K136 LL67 LL71 0.468
 K137 LL67 LL72 0.333
 K138 LL68 LL71 0.342
 K139 LL68 LL72 0.491
 K140 LL71 LL72 0.409

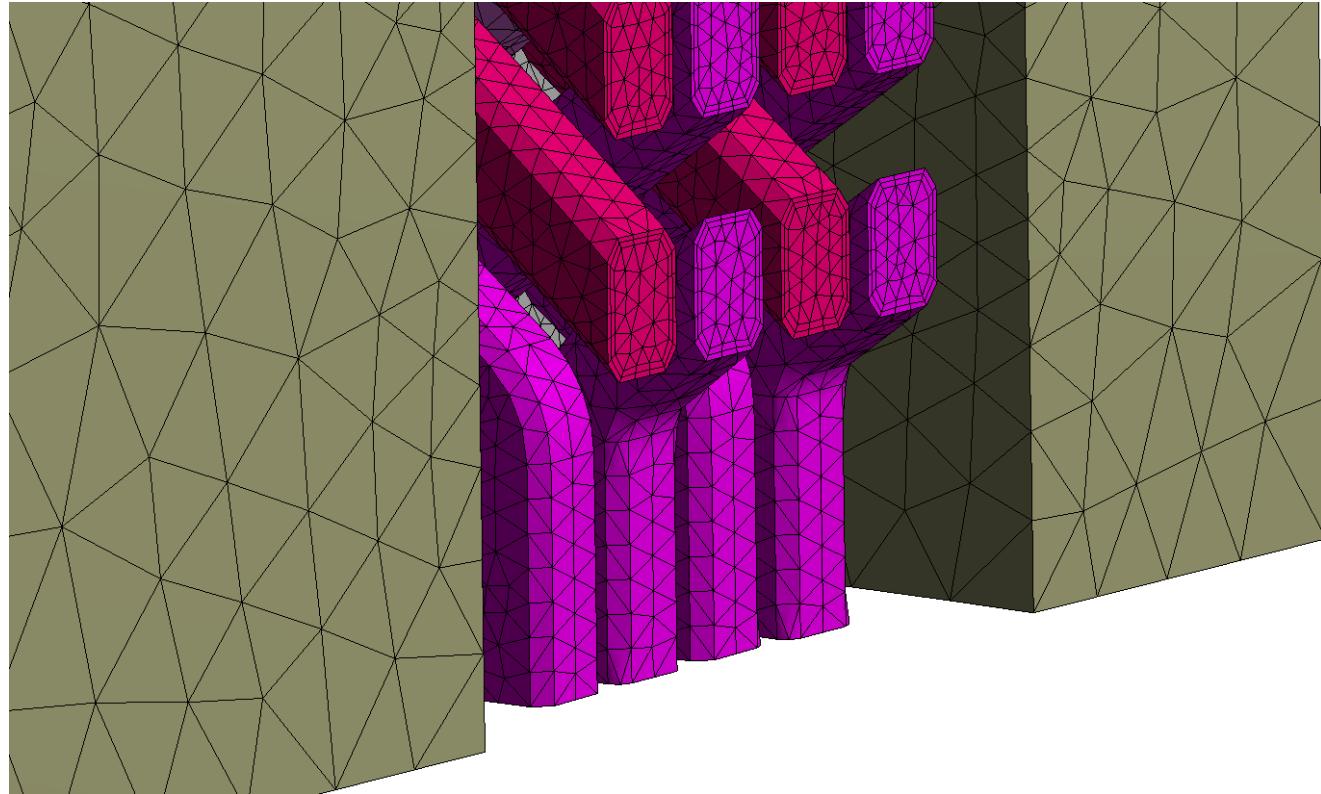
1) Impedance Matrix: Currents of Two Parallel Branches



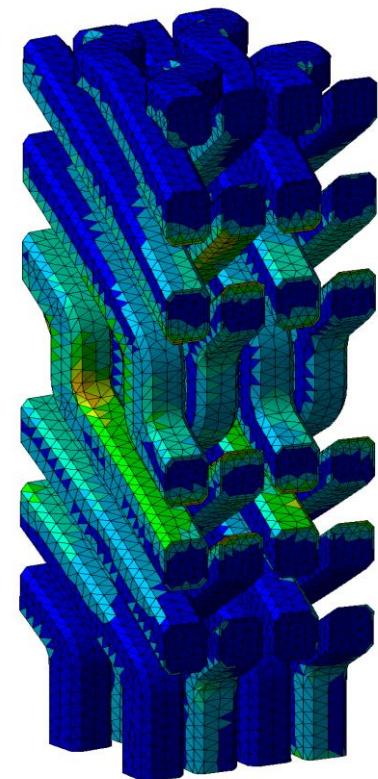
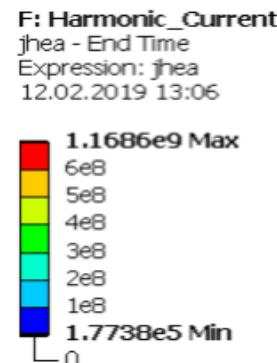
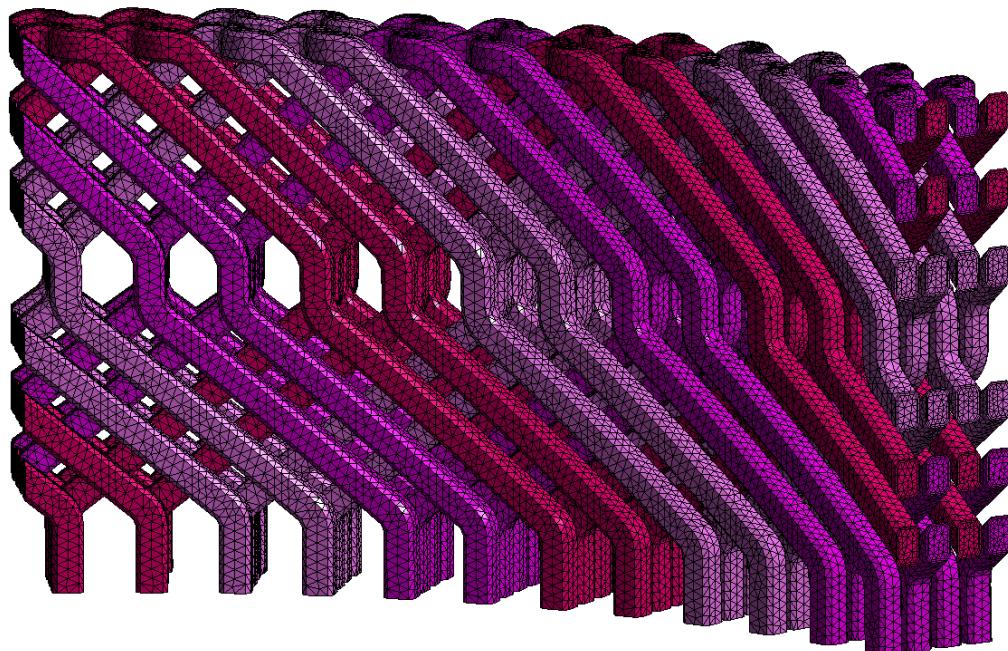
1) Impedance Matrix: Current Density in Conductors



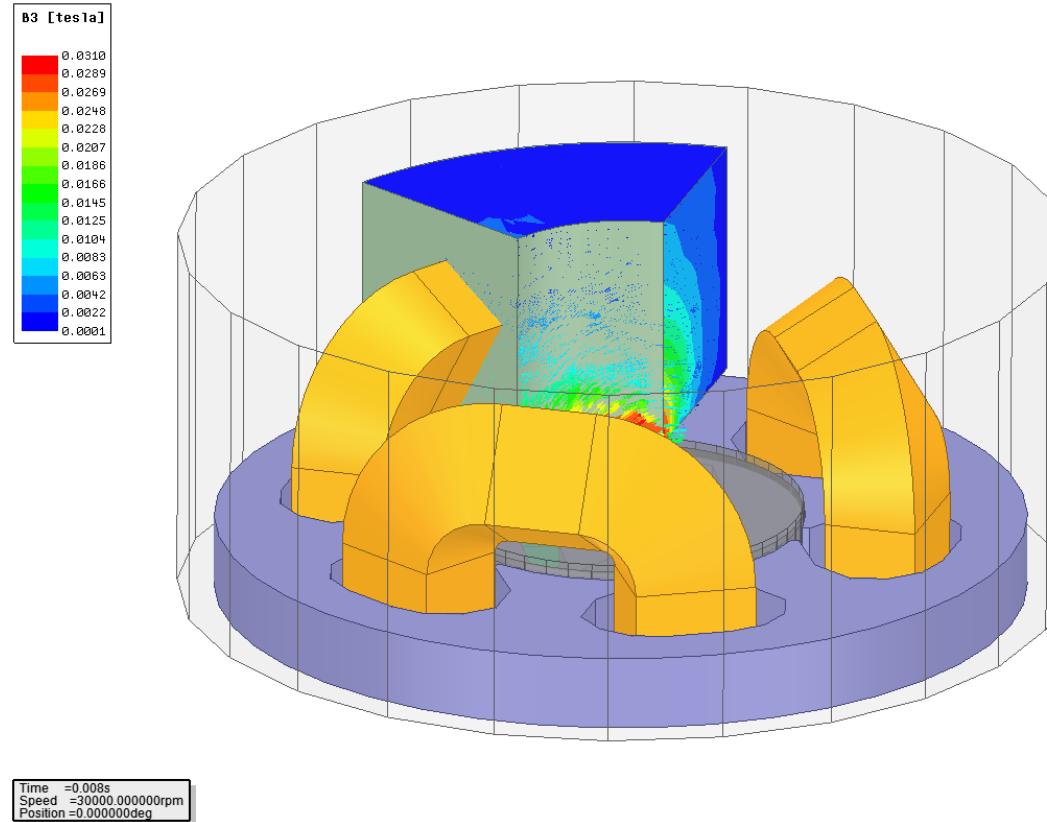
2) Local Losses: Inflation Mesh for Loss Analysis



2) Local Losses: Joule Heat from 200 A Harmonic Current



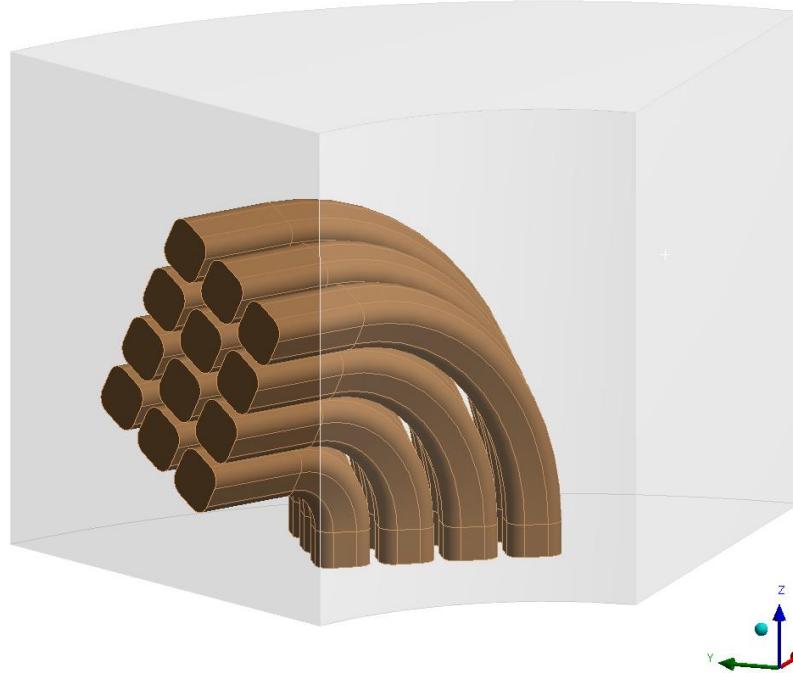
3) End Winding Submodel: Maxwell Model with Non-Model Cut Face



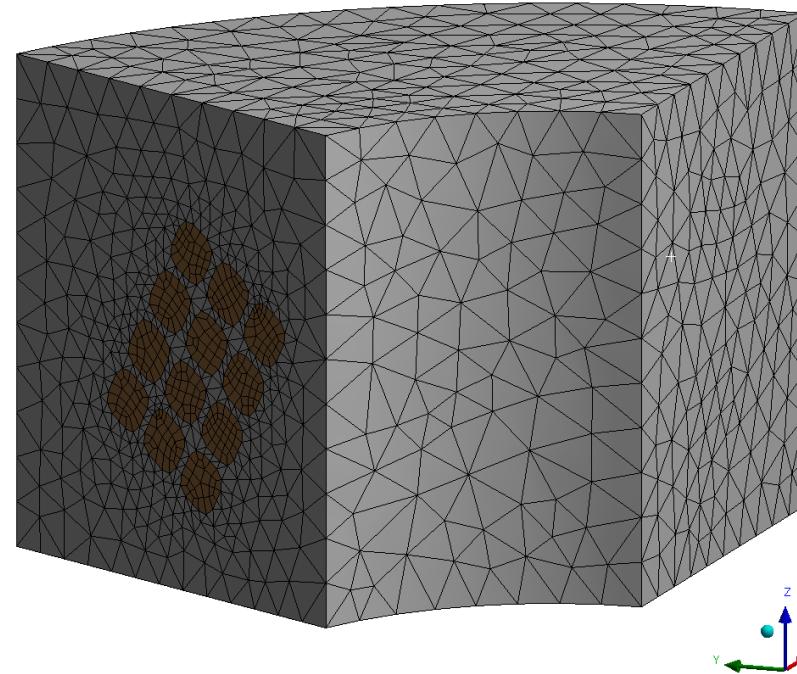
3) End Winding Submodel: Mechanical, Full Details for End Winding

Geometry
23.10.2018 09:53

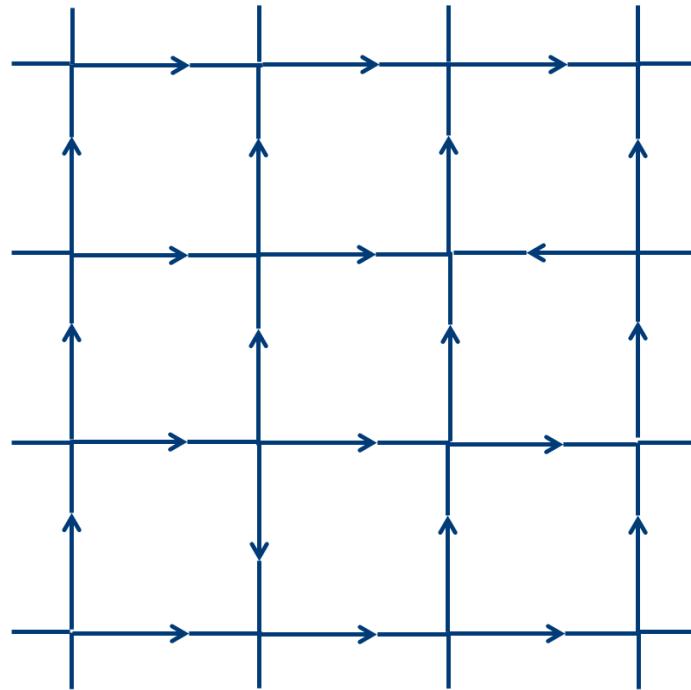
Air
Copper Alloy



3) End Winding Submodel: Mesh



3) End Winding Submodel: Magnetic BC: Surface of Magnetic Edge Elements



E, e – Corner (Eck) nodes

K, k – Edges (Kanten)

F, f – Faces

A – Edge flux

Φ – Face flux

Ψ – aux. Scalar Potential

$$\begin{aligned}\Phi_f &= \iint \vec{B} \cdot d^2 \vec{f} = \iint \vec{\nabla} \times \vec{A} \cdot d^2 \vec{f} \\ &= \oint \vec{A} \cdot d\vec{l} = \sum_k \pm A_k\end{aligned}$$

$$\begin{pmatrix} \Phi_1 \\ .. \\ \Phi_F \end{pmatrix} = \begin{pmatrix} v_{11} & .. & .. & v_{1K} \\ .. & .. & .. & .. \\ v_{F1} & .. & .. & v_{FK} \end{pmatrix} \cdot \begin{pmatrix} A_1 \\ .. \\ A_K \end{pmatrix}$$
$$v_{fk} \in \{0, 1, -1\}$$

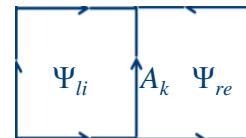
3) End Winding Submodel: Magnetic BC: Relations for Edge Fluxes

$$\Phi_f = \sum_k \pm A_k$$

$$\begin{pmatrix} \Phi_1 \\ .. \\ \Phi_F \end{pmatrix} = \begin{pmatrix} v_{11} & .. & .. & v_{1K} \\ .. & .. & .. & .. \\ v_{F1} & .. & .. & v_{FK} \end{pmatrix} \cdot \begin{pmatrix} A_1 \\ .. \\ A_K \end{pmatrix}$$



$$\Phi_e = \sum_k \pm A_k = 0$$



$$A_k = \Psi_{rechts} - \Psi_{links}$$

Face flux is sum of edge fluxes

System of F equations to find K edge fluxes ($K>F$)

Freedom to apply additional requirements
(gauging)

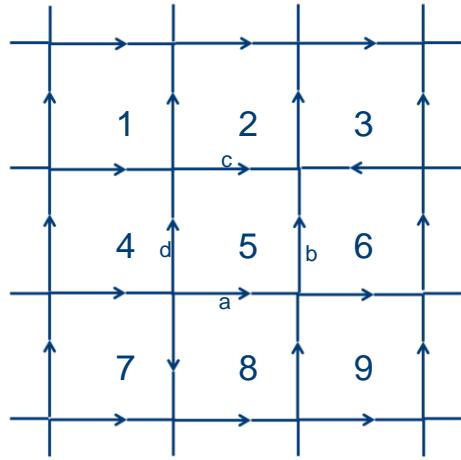
Euler Characteristic:

$$F+E-K=2 \text{ or } (F-1) + (E-1) = K$$

Using $(F-1)$ given values (sum of fluxes is zero) K edge fluxes shall be found. To find them uniquely $(E-1)$ conditions can be applied, e.g. sum of edge fluxes in a node is zero (discrete Coulomb gauge)

A_k potentials described as difference of an auxiliary scalar potential Ψ fulfill this condition

3) End Winding Submodel: Example, Flux into face 5



$$A_a = \Psi_8 - \Psi_5$$

$$A_b = \Psi_6 - \Psi_5$$

$$A_c = \Psi_5 - \Psi_2$$

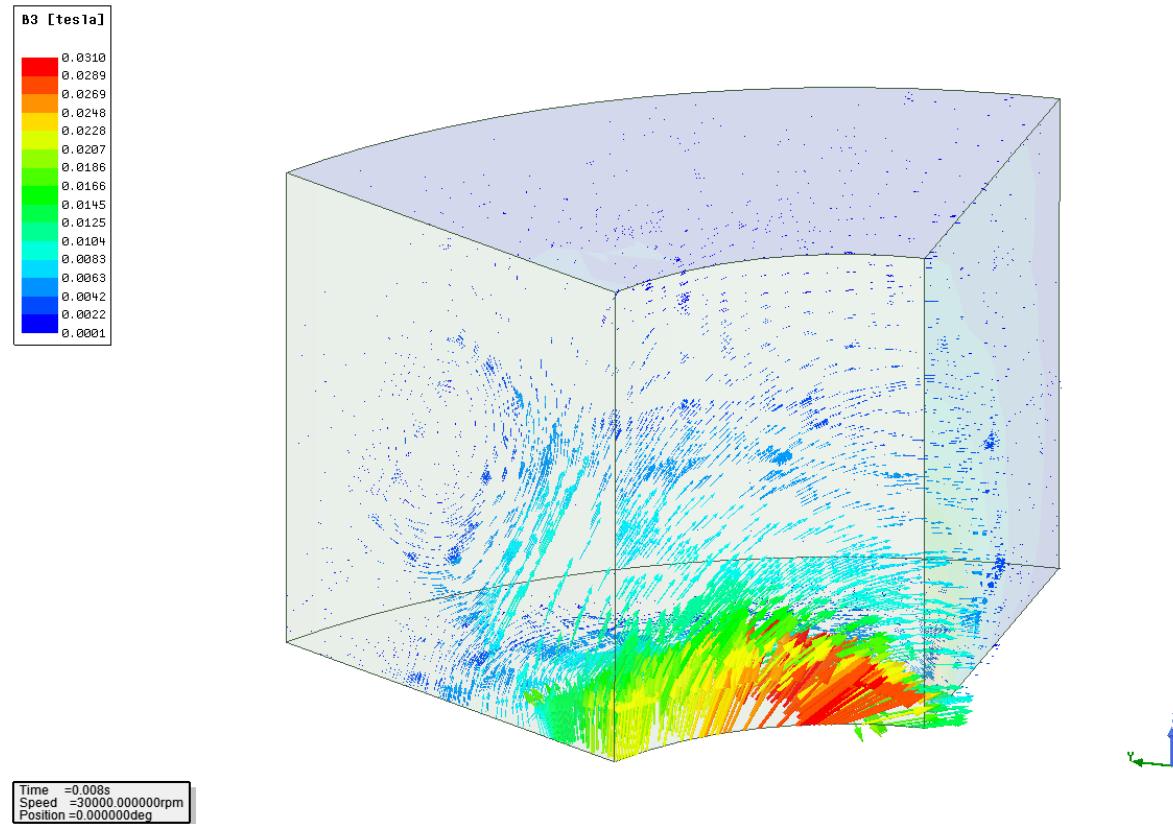
$$A_d = \Psi_5 - \Psi_4$$

$$\Phi_5 = A_a + A_b - A_c - A_d$$

$$\Phi_5 = \Psi_8 + \Psi_6 + \Psi_2 + \Psi_4 - 4 \cdot \Psi_5$$

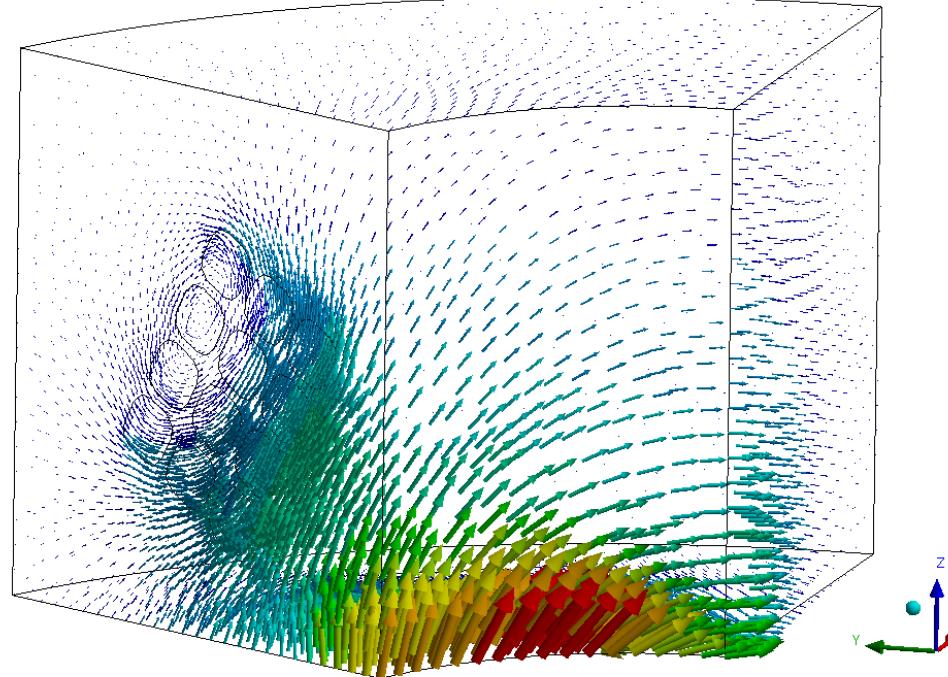
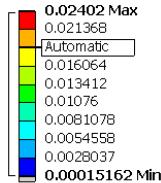
$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \\ \Phi_3 \\ \Phi_4 \\ \Phi_5 \\ \Phi_6 \\ \Phi_7 \\ \Phi_8 \\ \Phi_9 \end{pmatrix} = \begin{pmatrix} -4 & 1 & 1 & & & & & & \\ 1 & -4 & 1 & & & & & & \\ 1 & 1 & -4 & & & & & & \\ & & & -4 & 1 & 1 & & & \\ 1 & 1 & -4 & 1 & 1 & & & & \\ & 1 & 1 & -4 & 1 & 1 & & & \\ & & 1 & 1 & -4 & 1 & & & \\ & & & 1 & 1 & -4 & 1 & & \\ & & & & 1 & 1 & -4 & 1 & \end{pmatrix} \cdot \begin{pmatrix} \Psi_1 \\ \Psi_2 \\ \Psi_3 \\ \Psi_4 \\ \Psi_5 \\ \Psi_6 \\ \Psi_7 \\ \Psi_8 \\ \Psi_9 \end{pmatrix}$$

3) End Winding Submodel: Flux Density from 3D Maxwell Model

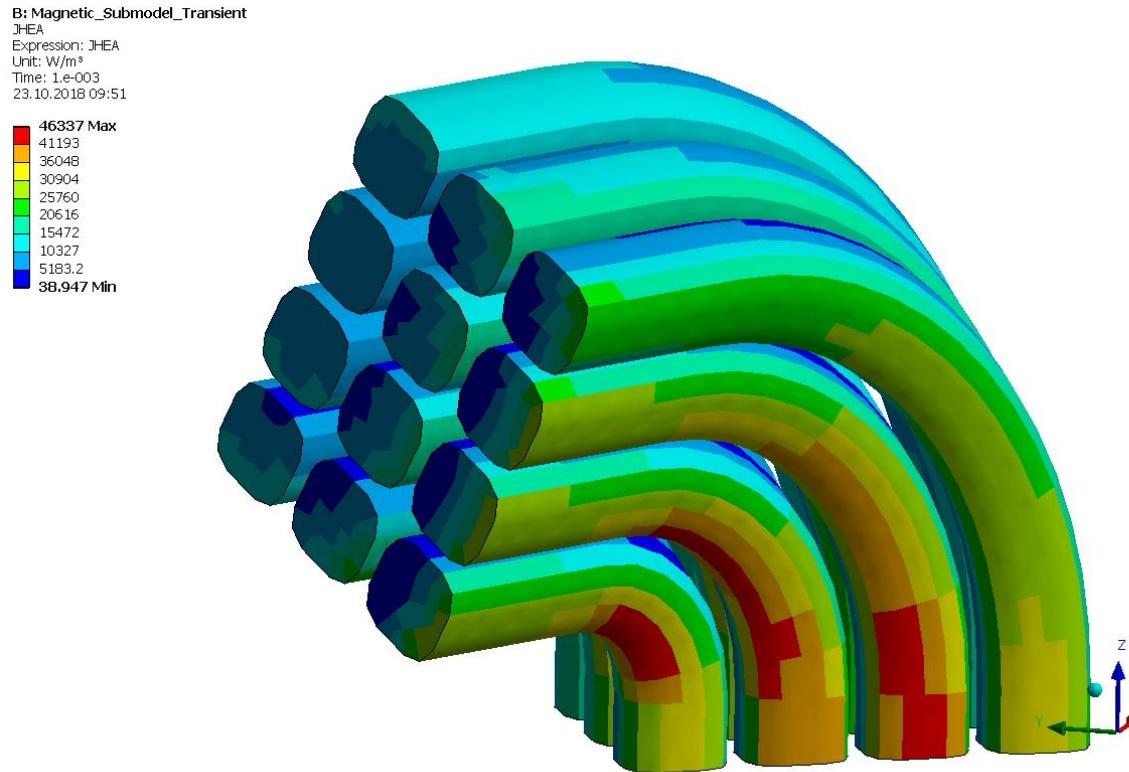


3) End Winding Submodel: Flux Density on Surface of Submodel

B: Magnetic_Submodel_Transient
Total Magnetic Flux Density Cut Face
Type: Total Magnetic Flux Density
Unit: T
Time: 1.e-03
23.10.2018 09:23



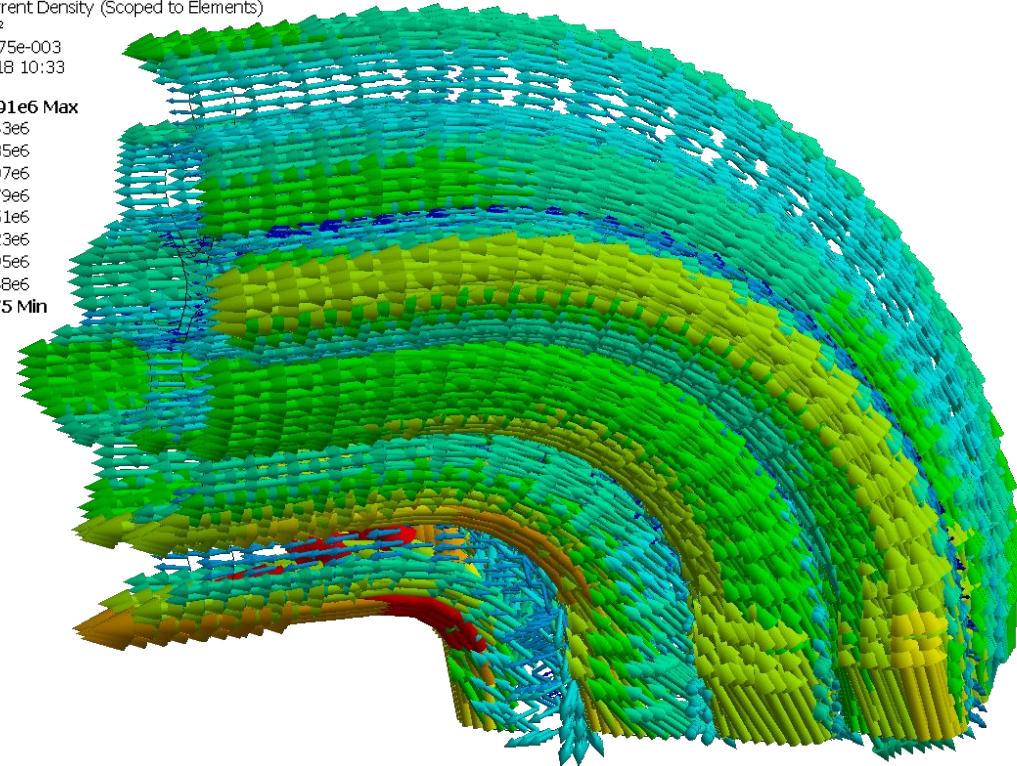
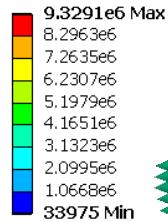
3) End Winding Submodel: Heat Generation Rate in End Winding



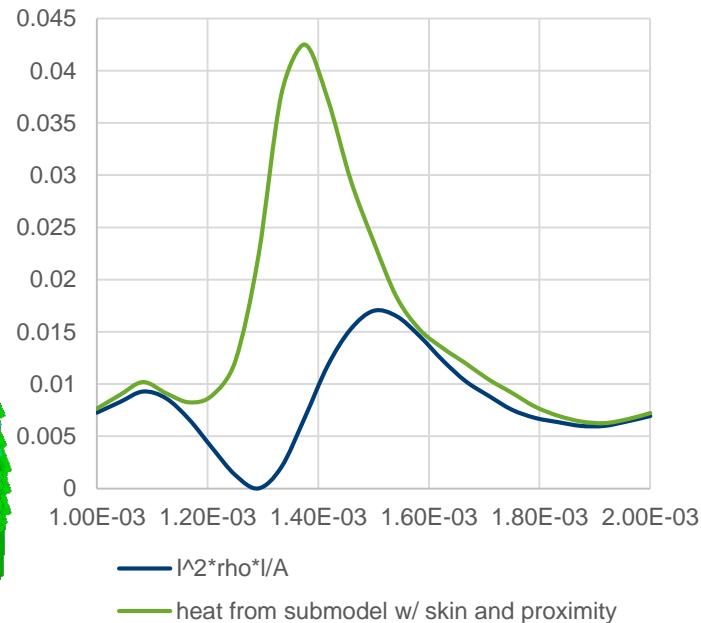
3) End Winding Submodel: Current Density in End Winding, Heat Generation

B: Magnetic_Submodel_Transient

Current Density
Type: Current Density (Scoped to Elements)
Unit: A/m²
Time: 1.375e-003
09.11.2018 10:33



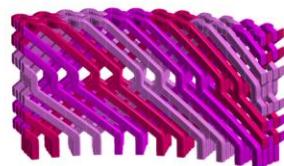
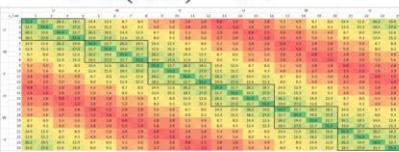
Joule Heat in Wire 1



End Winding Analysis

1) Impedance Matrix: Feed one Conductor with 1A, Measure Harmonic Voltages

- $VOLT = \int U \cdot dt$ time integrated voltage (236,1,2)
- $U = R \cdot I + L \cdot \dot{I}$
- $i \cdot \omega \cdot VOLT = R \cdot I + i \cdot \omega \cdot L \cdot I$
- $Re(Volt) = L \cdot I$
- $\omega \cdot Im(VOLT) = -R \cdot I$



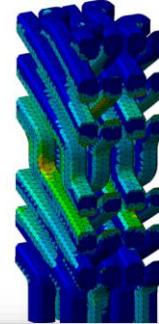
L

R

2) Local Losses: Joule Heat from 200 A Harmonic Current

F: Harmonic_Current
teta - End Time
Expression: ttheta
12.02.2019 13:06

| |
|-------------|
| 1.169e9 Max |
| 6e8 |
| 5e8 |
| 4e8 |
| 3e8 |
| 2e8 |
| 1e8 |
| 1.773e5 Min |



3) End Winding Submodel: Magnetic BC: Relations for Edge Fluxes

$$\Phi_f = \sum_k \pm A_k$$

$$\begin{pmatrix} \Phi_1 \\ \dots \\ \Phi_F \end{pmatrix} = \begin{pmatrix} v_{11} & \dots & \dots & v_{1K} \\ \dots & \dots & \dots & \dots \\ v_{F1} & \dots & \dots & v_{FK} \end{pmatrix} \cdot \begin{pmatrix} A_1 \\ \dots \\ A_K \end{pmatrix}$$

$$\Phi_e = \sum_k \pm A_k = 0$$



Face flux is sum of edge fluxes

System of F equations to find K edge fluxes (K>F)

Freedom to apply additional requirements (gauging)

Euler Characteristic:

$F+E-K=2$ or $(F-I) + (E-I) = K$

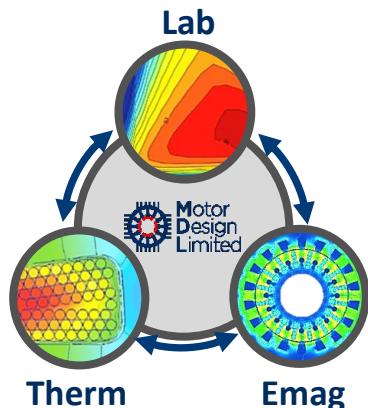
Using $(F-I)$ given values (sum of fluxes is zero) K edge fluxes shall be found. To find them uniquely, $(E-I)$ conditions can be applied, e.g. sum of edge fluxes in a node is zero (discrete Coulomb gauge)

A_k potentials described as difference of an auxiliary scalar potential Ψ fulfill this condition

Electric Motor Design Platform & Workflow

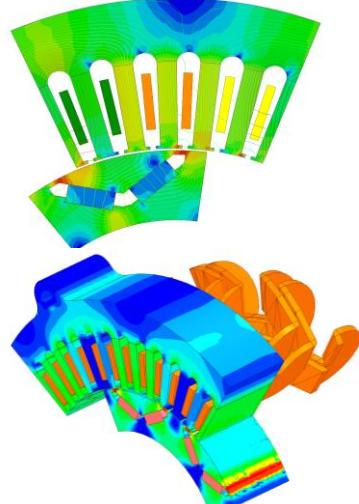
Design

Efficient Motor Design Toolkit



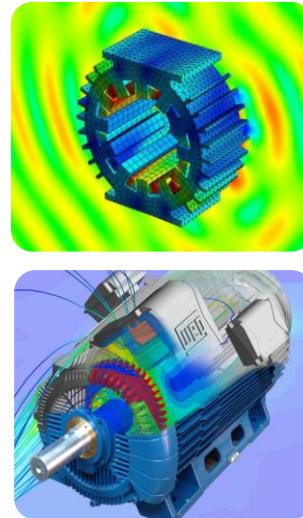
2D & 3D Analysis

Advanced Magnetics Modeling



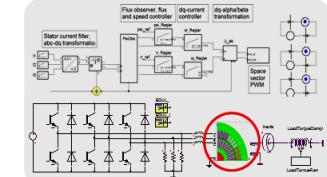
Coupled Analysis

NVH, Cooling...



System Validation

Control logic, software



Concept Design



System Validation



3D Physical Validation

Simplorer

