Contactless Power and Data Transfer for Multiple Nonlinear Loads

H. –P. Schmidt, U. Vogl

HAW Amberg-Weiden,
University of Applied Sciences, Amberg
D-92224 Amberg, Germany

Excerpt from the Proceedings of the 2012 COMSOL Conference in Boston
Introduction

Contactless Power and Data Transfer Application in Industrial Automation
De-centralized automation with distributed sensors & actors (e.g. conveyer)
Introduction

Basic Layout

feed coupler(s) – controlled H-bridge – frequency inverter – adjustable speed drives

load coupler – distributed winding

power and data feed
Introduction

Multi-winding transformer with one “distributed” winding

- Power transfer
  - Feed < 10 kW
  - Load < 0.5 kW (typical)

- Data transfer
  - 500 kBit/s
  - Cycle time < 2ms

- Frequency range
  - 20-70 kHz power
  - 20-600 kHz data

- Extension
  - Length < 100 m / 300 ft
Objectives

AC/DC COMSOL for quasi-static conditions in 2D and 3D EM calculations AND eventually couple with “equation-based”

Realize design goals such as:

- Voltage must not vary too much at loads regardless of number of loads (resonances, variable loads …)
- Minimize losses while not increasing cost

Ongoing work utilizes version COMSOL 4.3

- Determination of lumped parameters such as
  - self and mutual inductances
  - capacitances (not dealt with here)
- Studies in frequency domain
- Time depended calculations (not yet…)
Objectives

Find Lumped Parameters

\[ U_F = Z_F \cdot I_F + j\omega M_{DFW} \cdot I_{DC} \]

\[ 0 = Z_{DW} \cdot I_{DW} + j\omega M_{DFW} \cdot I_{F} - j\omega \sum_{j=1}^{N_{load}} M_{DC Li} \cdot I_{Li} \]

\[ U_{Li} = Z_{Li} \cdot I_{Li} + j\omega M_{LWLi} \cdot I_{DW} + j\omega \sum_{j=1, j \neq i}^{N_{load}} M_{LiLj} \cdot I_{Lj} \]
COMSOL Usage

AC/DC Module

- Frequency domain
  - Linear transfer system: non saturation of ferrite E-cores
  - No-linear loads: input rectifier of inverters

- 2D Studies
  - Air-gap influence, some geometry
  - Losses (skin and proximity of distributed winding)

- 3D Studies
  - Air gap check
  - Self and mutual inductances
  - Transfer behavior

Coupling to heat transfer for distributed winding
COMSOL Usage

2D and 3D Air Gap Studies for one Coupler

We use quite small air gaps so variations influence fluxes considerably

- 3D Model
  - Mesh and solutions issues due to unfavorable geometric ratios

- 2D
  - Much easier to solve

Eventually applied for 3D studies
- 3D Model
  - permittivity layer feature
COMSOL Usage

3D Studies

- Simple geometry, but relevant narrow region are to be resolved

- Flux contained quite well in E–I ferrite but not in distributed winding

Relative large element number
COMSOL Usage

3D Studies AC/DC Module
Typical results
Lumped Parameters Extraction

- Self inductances
  Energize only relevant winding while other windings are “disabled” and determine magnetic energy

- Mutual inductances
  Fluxes across appropriate faces, ratio of flux and currents (accounting for number of turns) yields mutual inductances

- Coupling with circuit also yields inductances

- Results are reasonable accurate for the application
COMSOL Usage

3D Studies AC/DC Module:

Magnetic Field and Circuit Calculation

- Distributed winding is divided
  - one small section (e.g. 1m / 3ft) part of FEM
  - the large section (e.g. 100m/300ft) is modeled via an impedance within the circuit
Experimental Set Up

Test Stand

- Five adjustable speed drives
- Feed laboratory H-bridge with full control and access
- Distributed winding (app. 65 m / 200ft) is housed in a conduit which meanders along a wooden base plate.
- Distributed winding for data is attached to it
- Field and load couplers use standard E-Cores, bobbins are tailor made
Experimental Set Up

Measurement

Lumped parameters
• Precision impedance meter
• Frequency synthesizer and power amplifier
• Current sensor DC to 5Mhz

System behaviour
• Voltage and current sensors

Field
• Scanning device
• 3 perpendicular hall sensors
• DC- 300kHz
Results and Conclusion

Results

Lumped parameter
- Results are reasonable accurate to 10 % within the measurements
- Field levels (only one coupler)
  Results are reasonable accurate

Transfer behavior
- No and light load voltage transfer ok also within 10 %
- Heavy load conditions have to be re considered

Heating
- Temperature elevation reproduced with adjusted heat transfer coefficients
Results and Conclusion

Conclusion

• As expected results are quite sensitive to air gap spacing

• The presented work is on going and first results have been presented.

• This first results helped to build a working test stand in finding appropriate parameters. We have operated inverter driven motors, where power and data have been supplied contactless.

Next steps

• Heavy load conditions
• Transient behaviour.
Thank you for your attention!
Contents

• Introduction
• Objectives
• COMSOL Usage
• Experimental Set UP
• Results and Conclusion
Introduction

Contactless Power Transfer
“Battery” Charging

Source: Conductix-Wampfler, Source: Wire less Consortium

Source: Vahle
Introduction

System Configuration

Distributed Winding / Cable

Feed
Load 1
Load 2
Load 3
...
Load N

Energy
Data

10/03/2012
COMSOL Usage

3D Studies

Paint circuit  relative simple geometry

Results

+ MCAD
Design Considerations and Efficiency

Loss Considerations

Losses are assessed via analytical approximations:

- Skin effect

\[
\frac{R}{R_{DC}} = \text{Re} \left\{ \frac{r_w}{2} \sqrt{-j \cdot 2 \pi \cdot f \cdot \mu \cdot \sigma} \frac{J_0(\sqrt{-j \cdot 2 \pi \cdot f \cdot \mu \cdot \sigma \cdot r_w})}{J_1(\sqrt{-j \cdot 2 \pi \cdot f \cdot \mu \cdot \sigma \cdot r_w})} \right\}
\]

- Proximity effect as given by Nan and Sullivan,

\[
P_{v_{\text{Proximity}}} = G(r, f, ws, ls) \frac{H^2}{\sigma}
\]

\[
\bar{H}^2 = \frac{1}{3} \frac{N^2 \cdot I^2}{b_w^2} \left(1 - \frac{1}{4m^2}\right)
\]

- Core losses via a Steinmetz formula

\[
P_v = K \cdot f^{ef} B^{eb}
\]

- Eddy current losses of a thin back plate

\[
P_v = \frac{1}{2} B_{av}^2 \cdot \pi^{3/2} \cdot f^{3/2} \cdot \frac{\sqrt{\sigma \cdot \sinh(X) - \sin(X)}}{\mu \cdot \cosh(X) - \cos(X)}; \quad X = \frac{d}{\delta} = \sqrt{\pi \cdot f \cdot \mu \cdot \sigma \cdot d}
\]
Design Considerations and Efficiency

**Shielding**

Opera 3D Electra and 2D COMSOL

- Diffusion equation for the quasi static case and the harmonic Ansatz.

- Design of shield geometries for given damping requirements
- Minimizing incurred eddy current losses by altering conductivities, distances and thicknesses