NPSC 2024

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Achieving Decarbonized, Digitalized Energy and Electric Transportation Systems

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Periodic Steady-state Computation for Coupled Field-Circuit Problems

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Presented By:

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Track 2: Power Electronics Applications and Drives

Madhya Pradesh Chapter

Motivation

1. Examples of “coupled-field circuit problems”

2. FOSS (free or open source software)
   - **Field computation packages**: OpenFOAM, Elmer, FEMM, Radia, etc.
   - **Circuit simulation**: LTSpice, GNU Octave, Python, etc.

3. Design of machines → optimizations in steady-state.

Outline

1. Modelling → "coupled-field circuit problems"
2. Transient simulation
3. Periodic steady-state computation
4. Summary

Coupled-field circuit problems

1. Co-simulation → model in the loop (MIL)
2. Field computation → look-up tables (LUT)
3. Interpolation.

Zhou, Ping, et al. "A general co-simulation approach for coupled field-circuit problems," *IEEE Transactions on Magnetics,* 2006.

Coupled-field circuit problems

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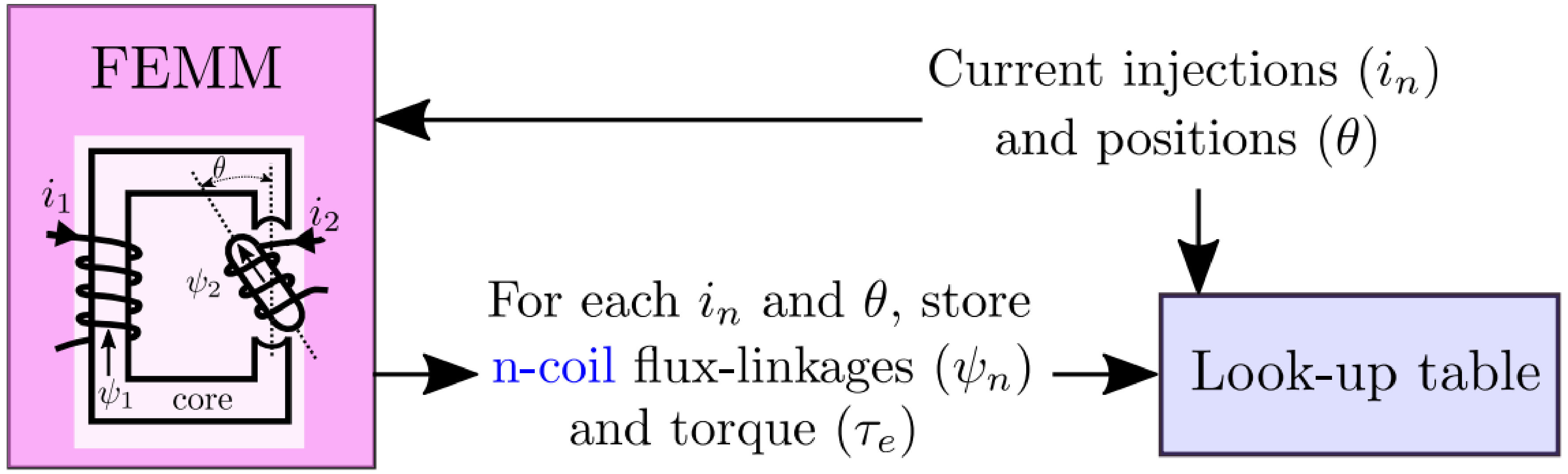

(Note: static relations are modelled for simplicity).

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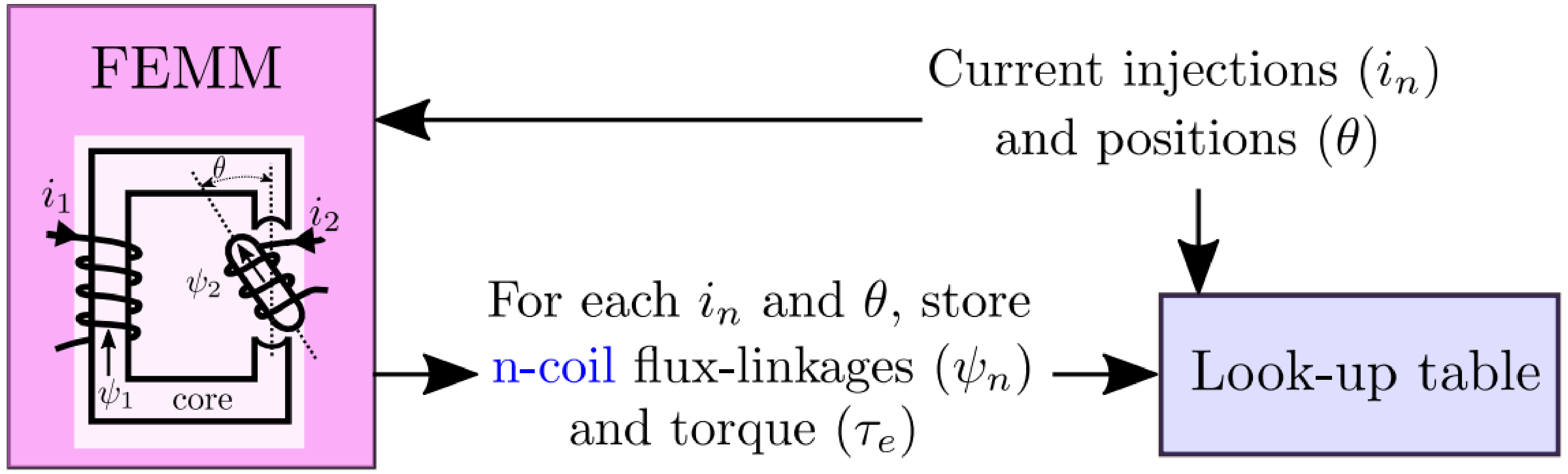

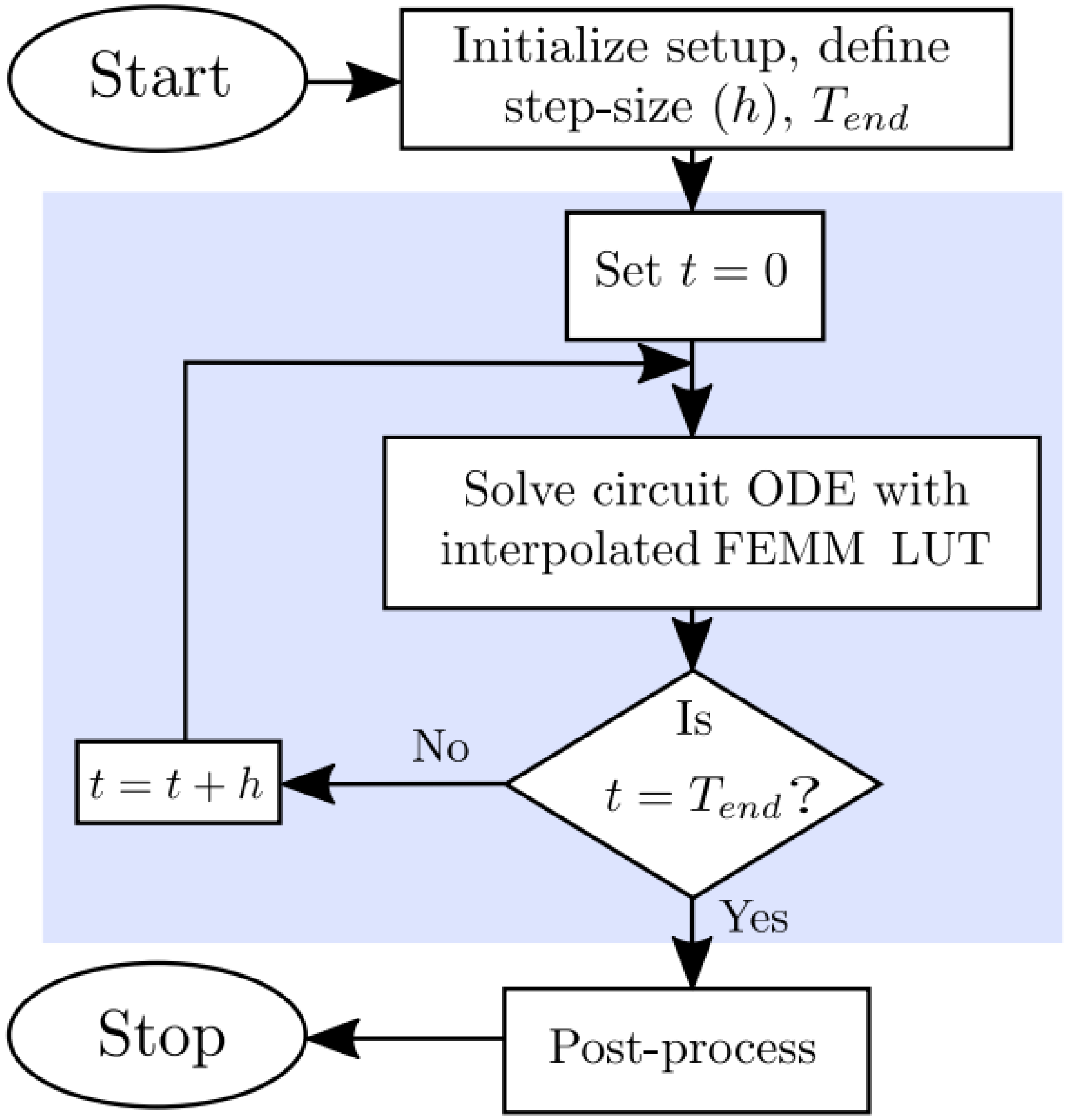

ODE: ordinary differential equation

(Note: static relations are modelled for simplicity).

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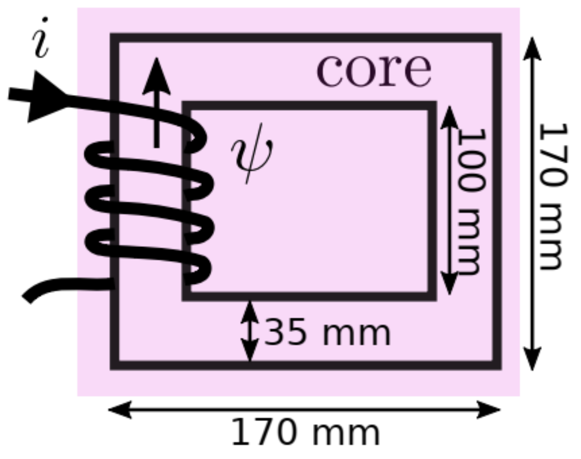
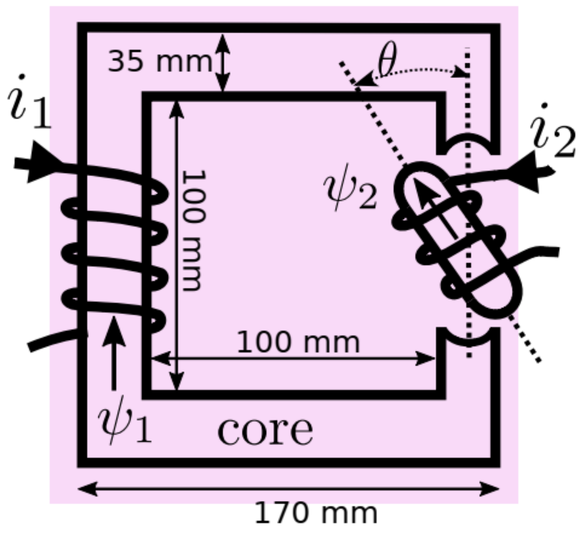
Coupled-field circuit problems

Ex1: Non-linear inductor



Ex2: Primitive AC generator



Coupled-field circuit problems

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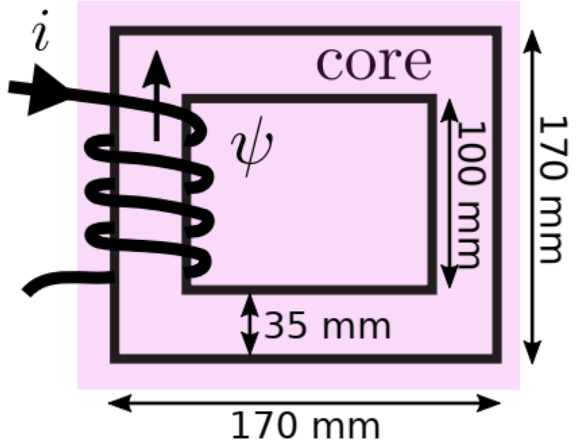
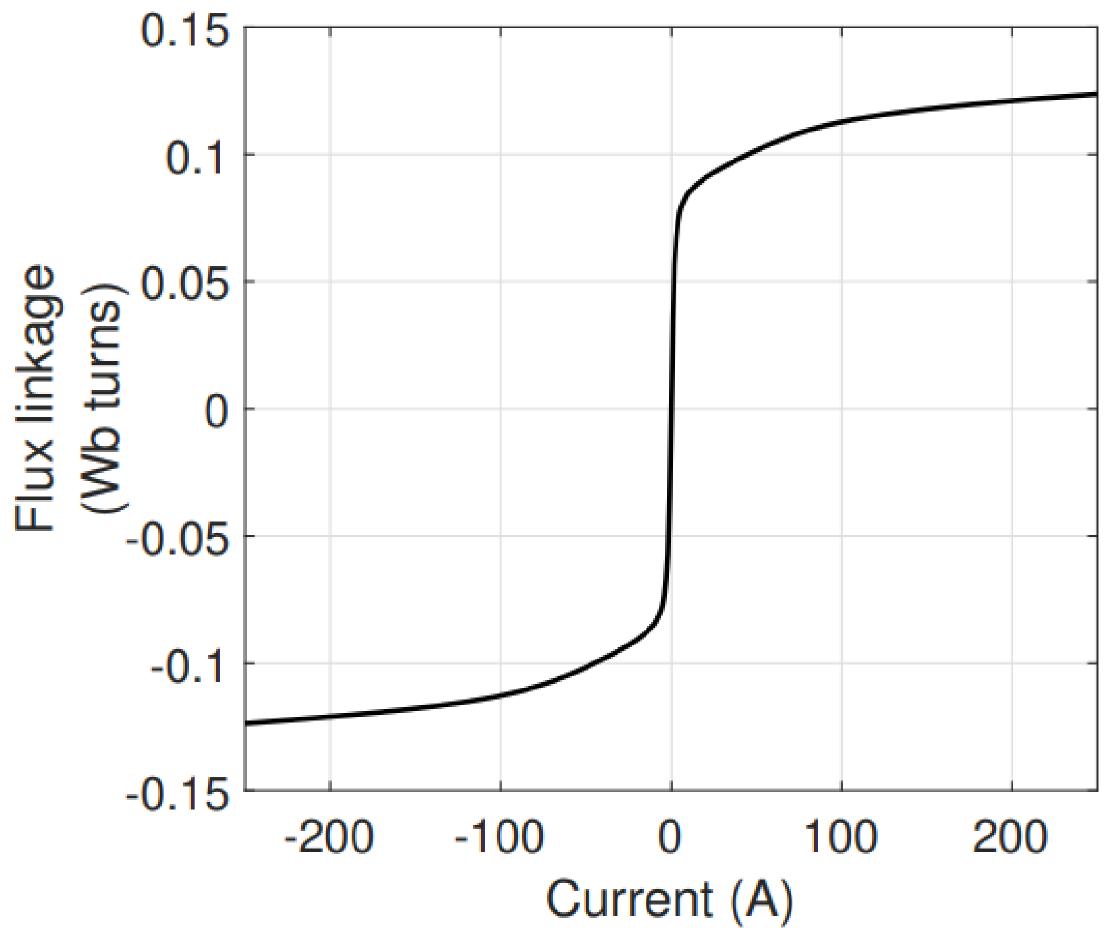


1-dimensional LUT



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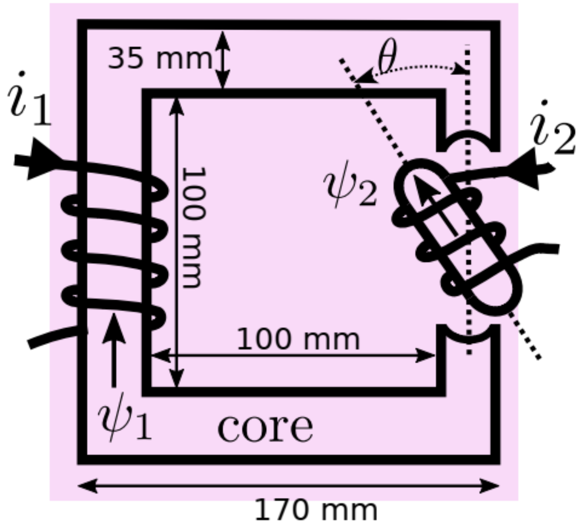

Coupled-field circuit problems

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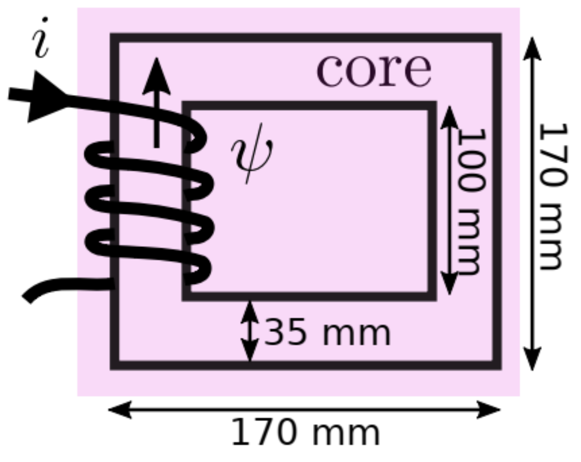

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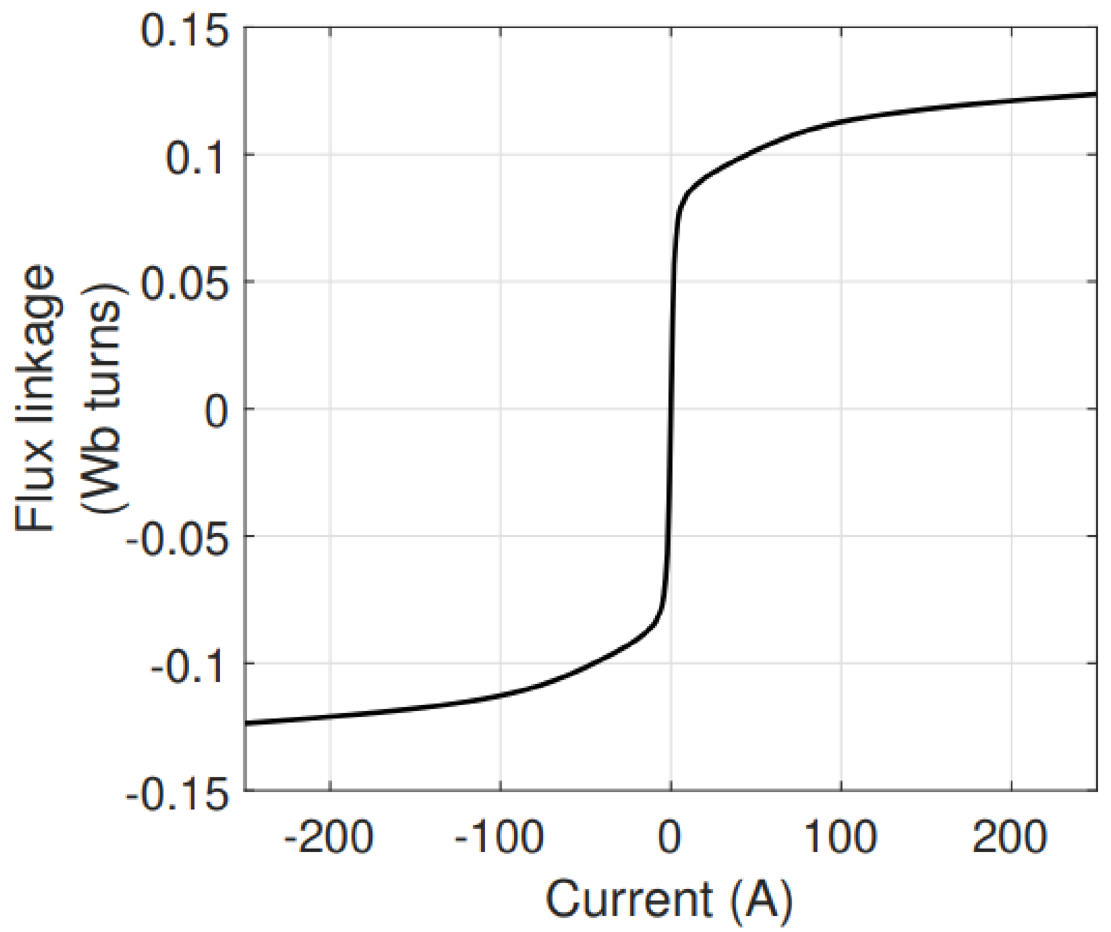

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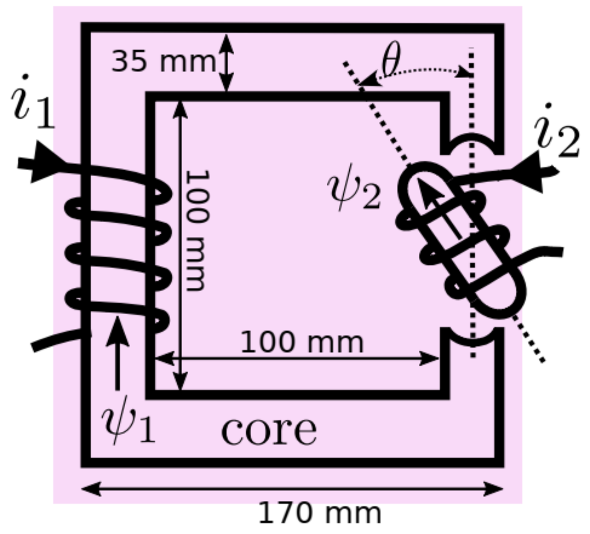
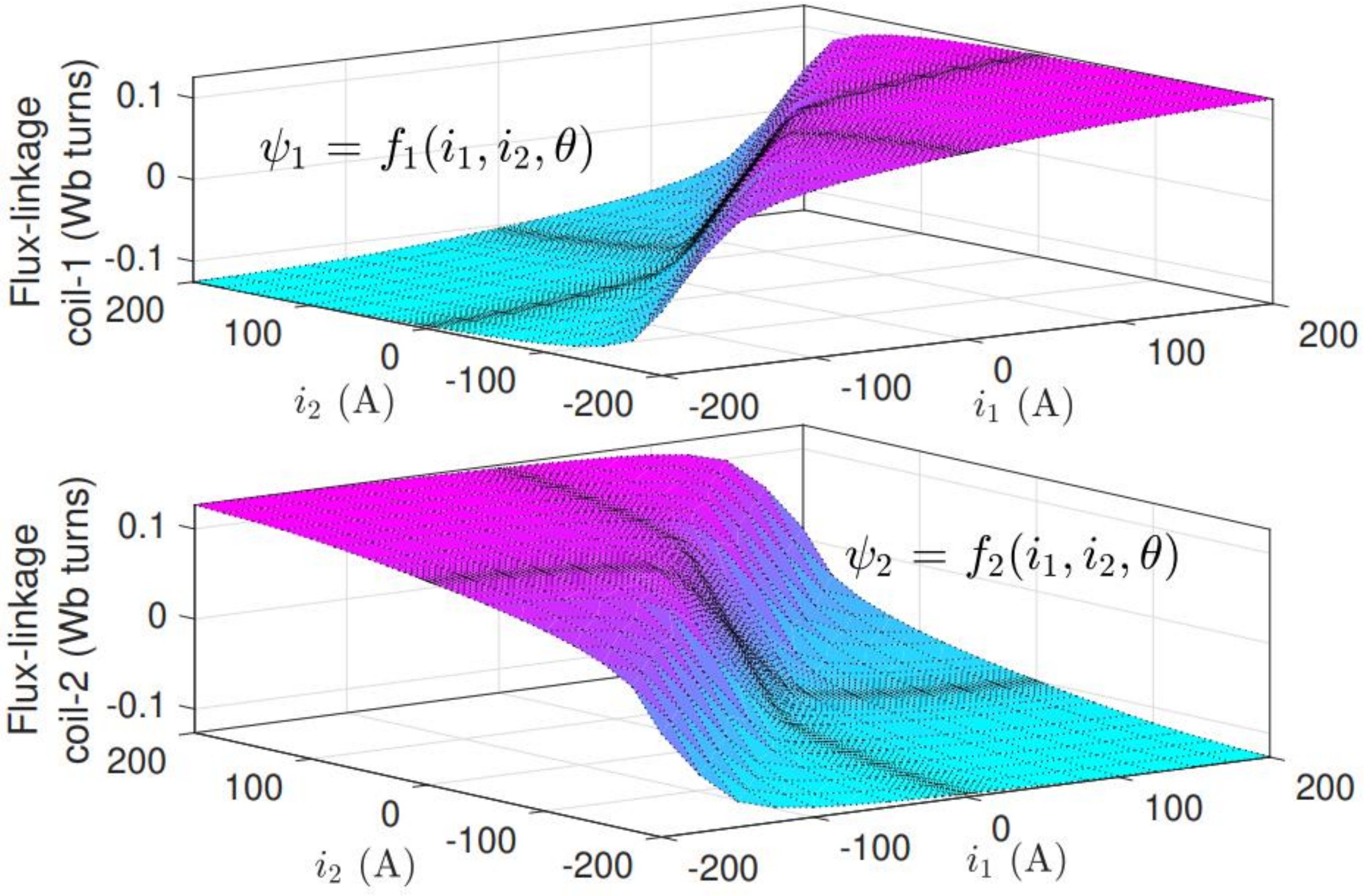
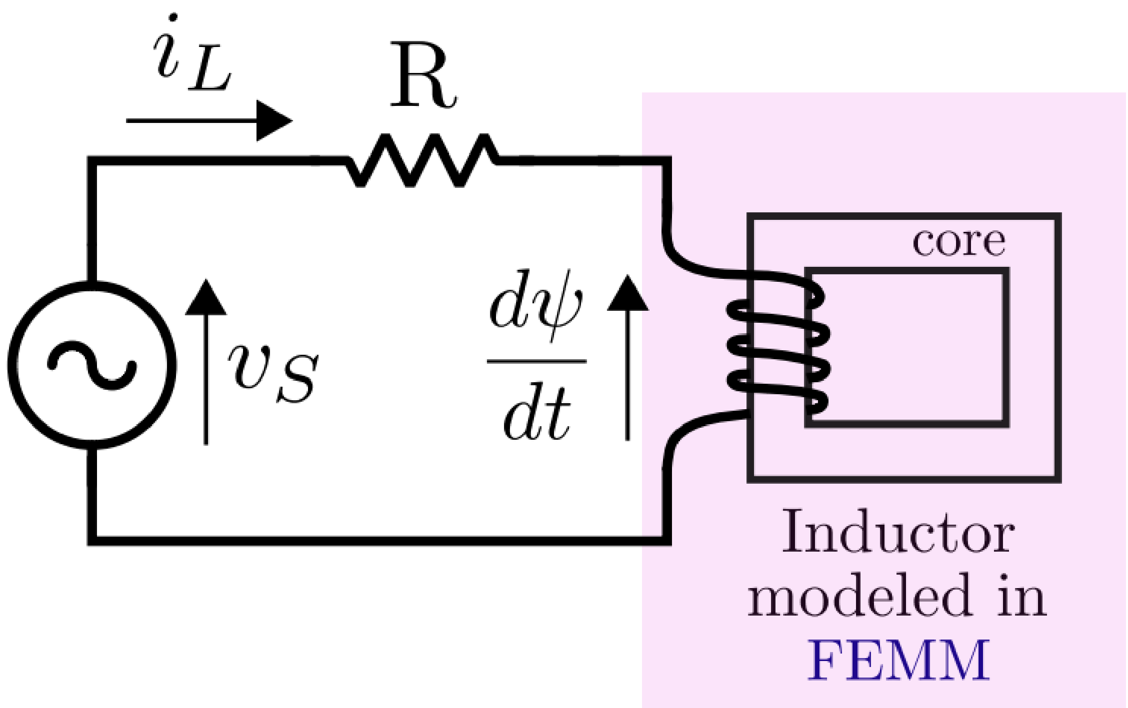


Multi-dimensional LUT



Transient simulation

Non-linear inductor case



$$\frac{d\psi}{dt} = -i_L R + v_s; \quad \psi = f(i_L)$$

$$R = 0.1\ \Omega, \quad v_s = 25\ \sin(2\pi \times 50\, t)\ \mathrm{V}$$

Transient simulation

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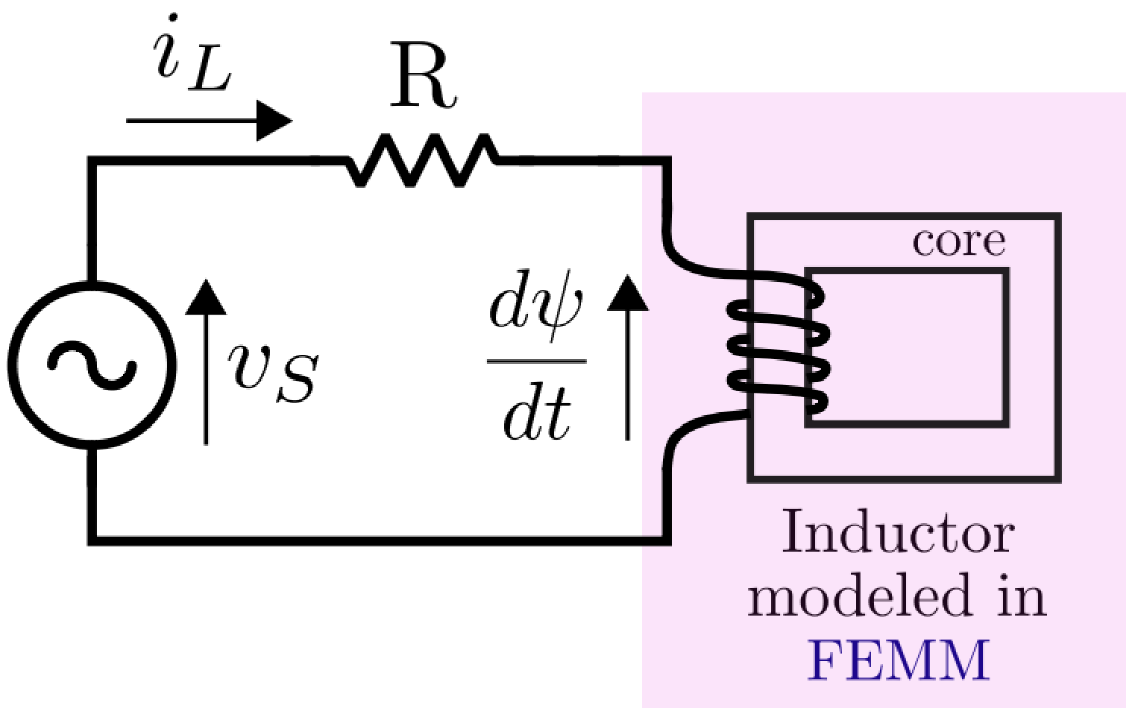

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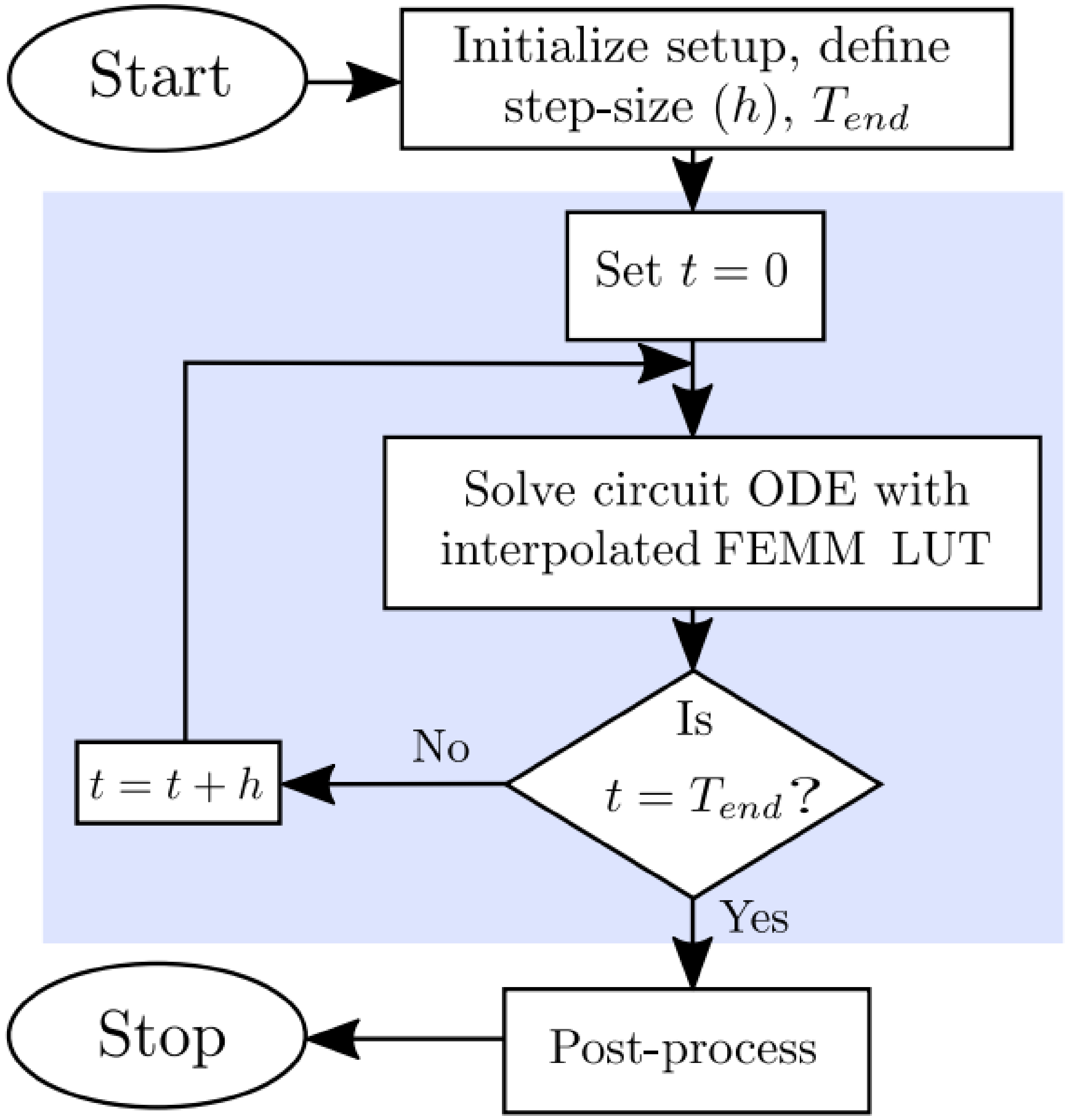

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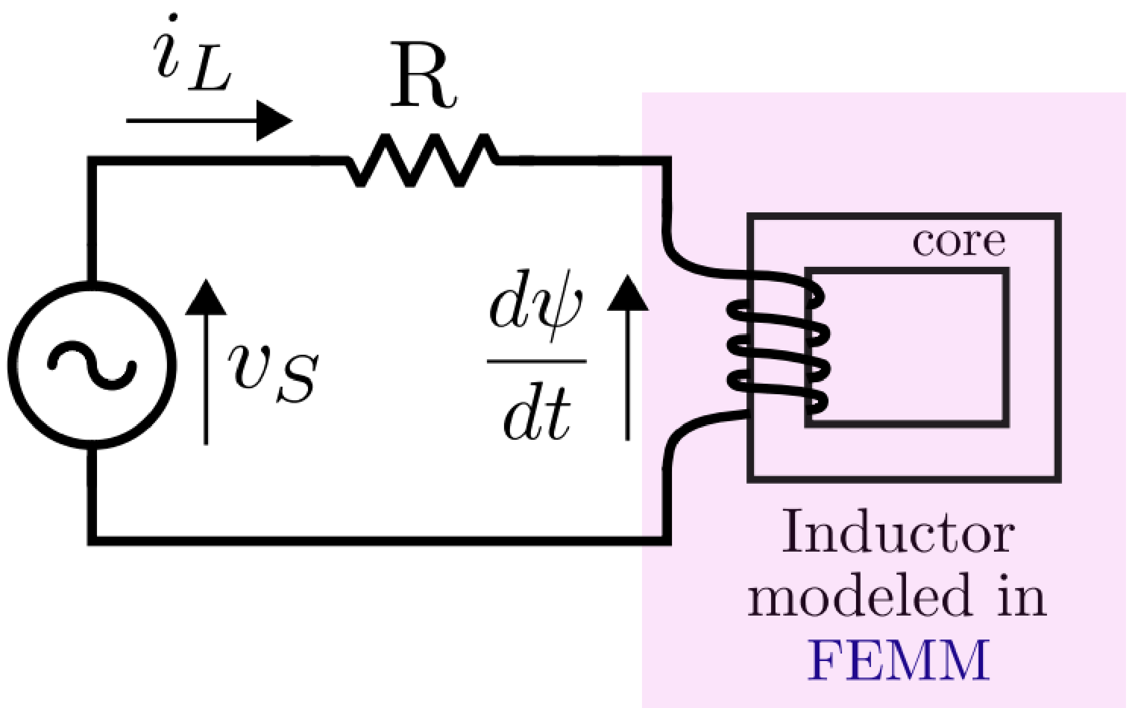

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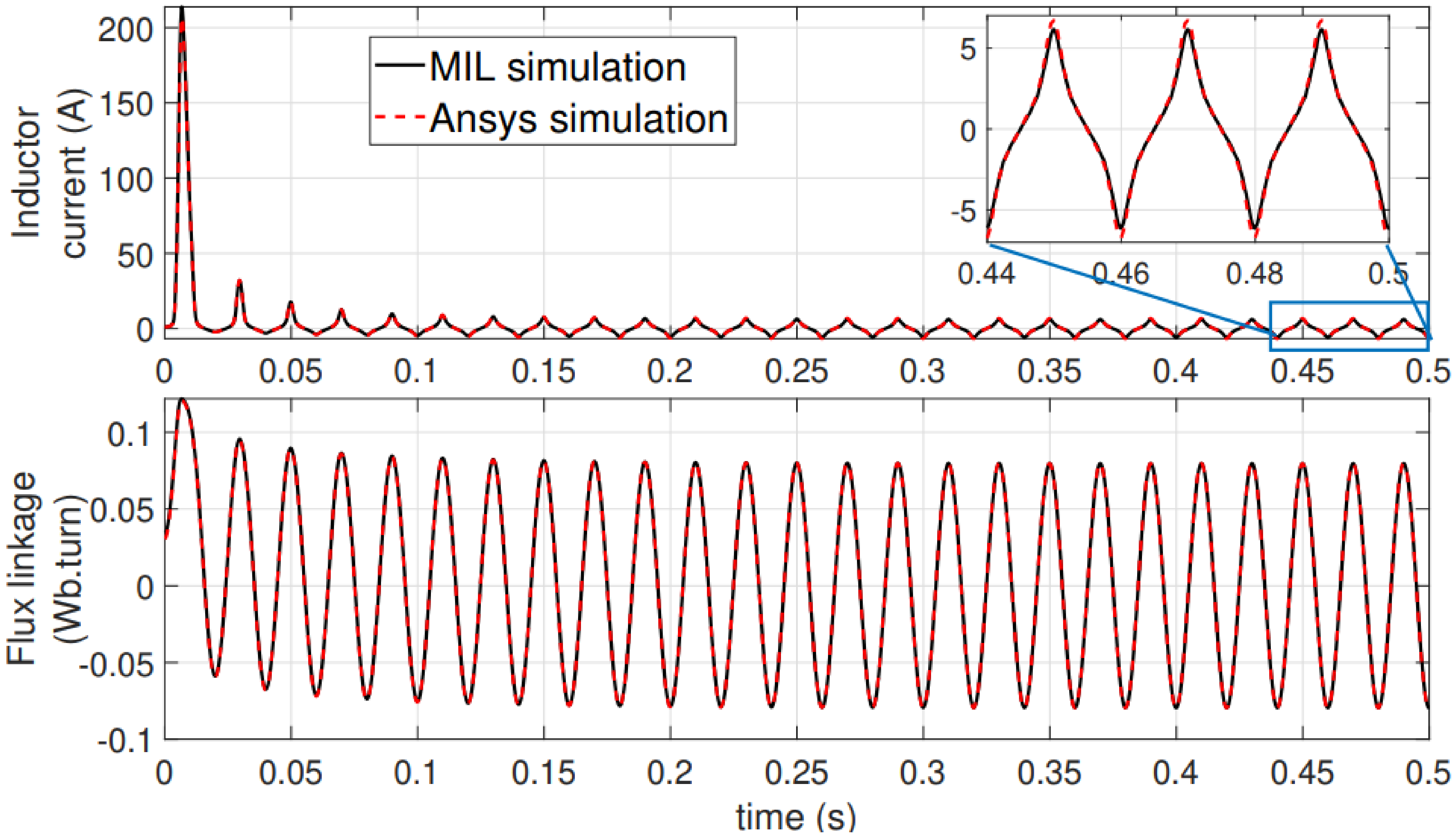
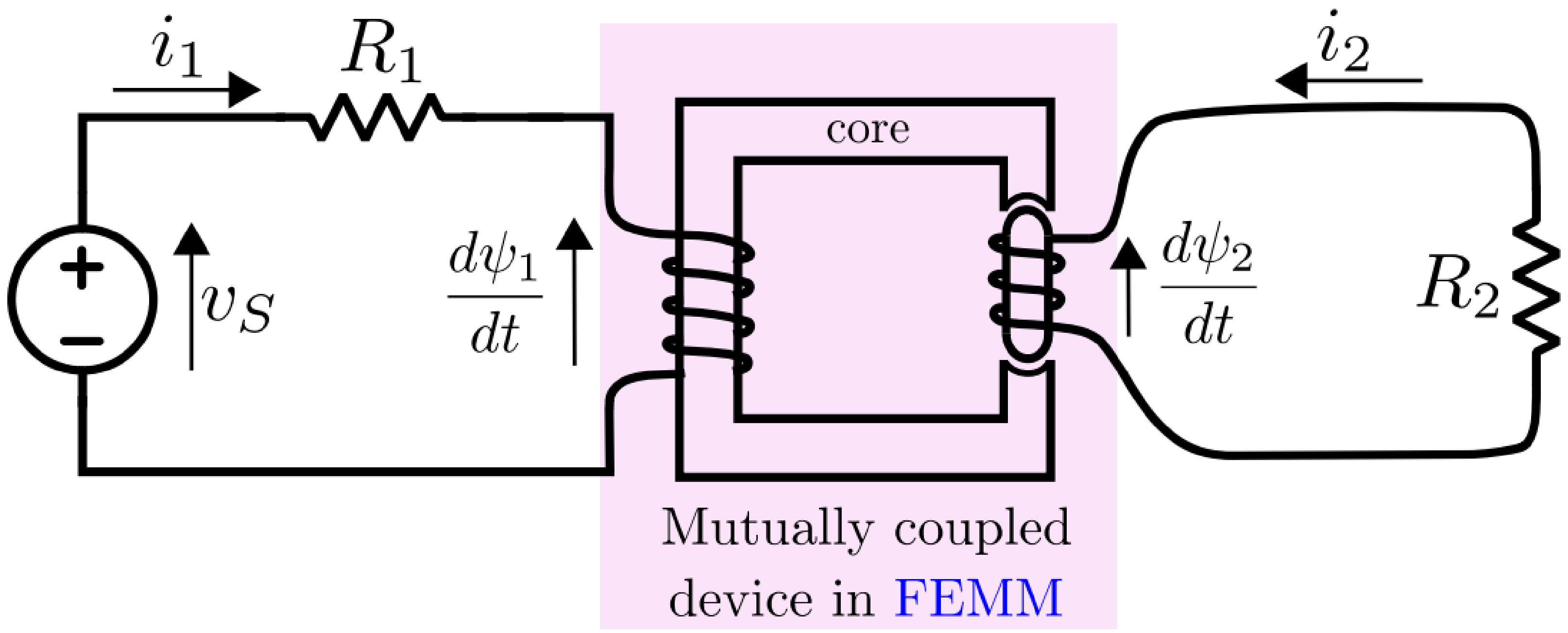


Transient simulation

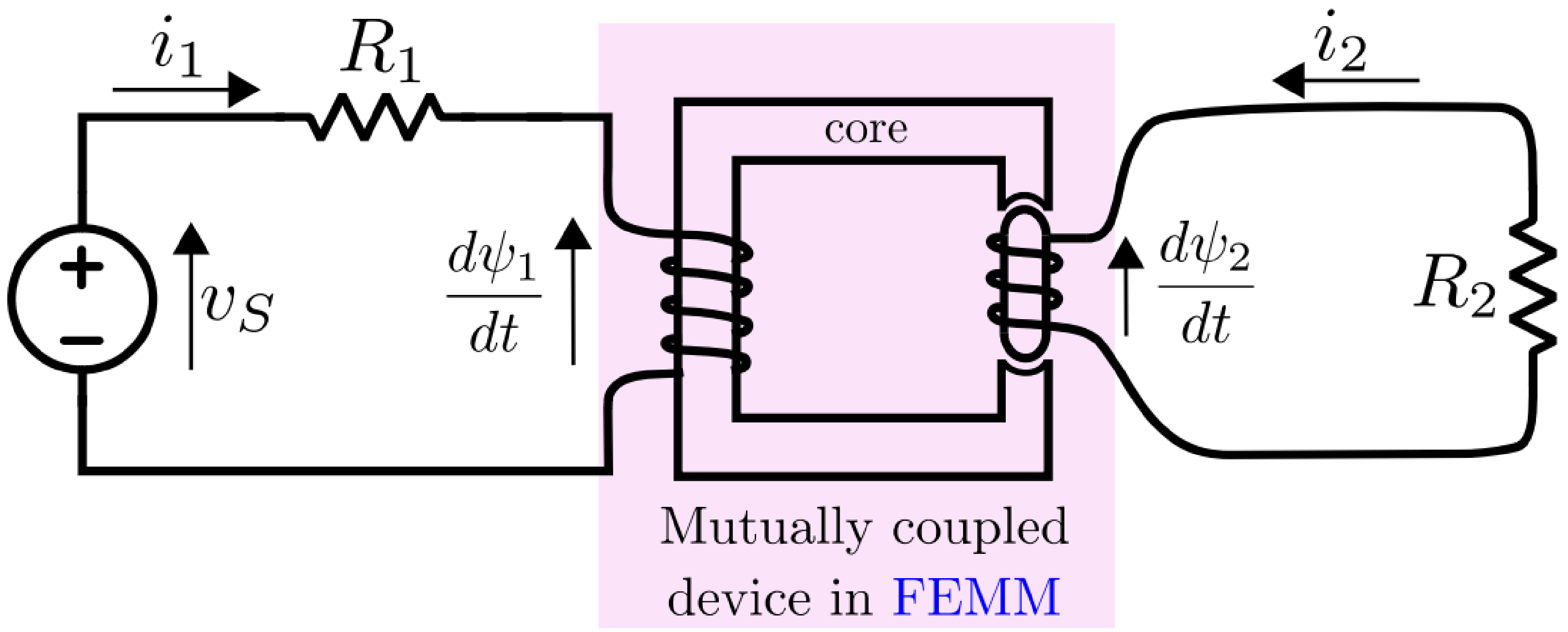
Primitive AC generator case



$$R_1 = 1\ \Omega, \quad R_2 = 5\ \Omega, \quad v_s = 5\ \text{V}$$

Transient simulation

Primitive AC generator case



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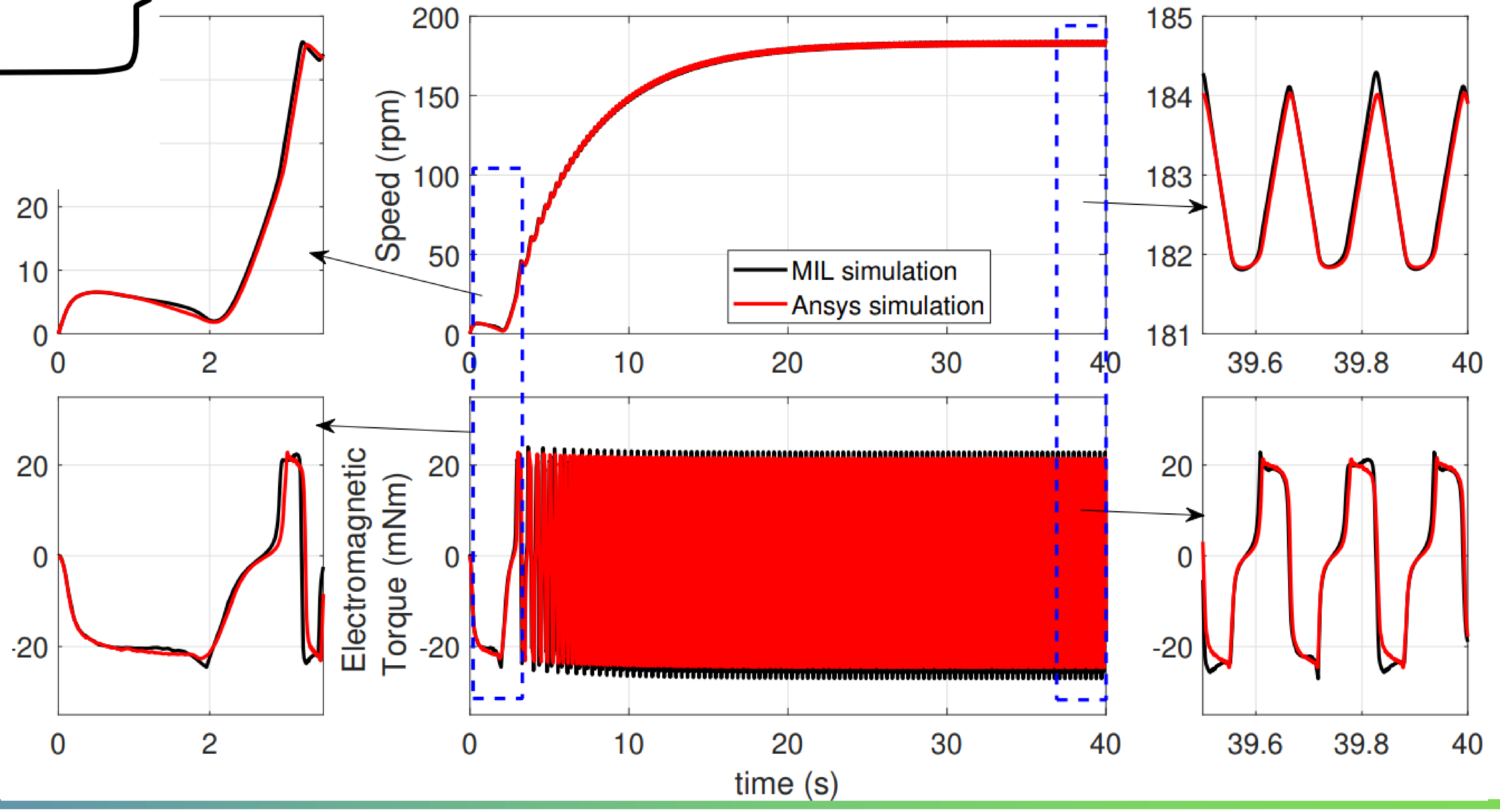
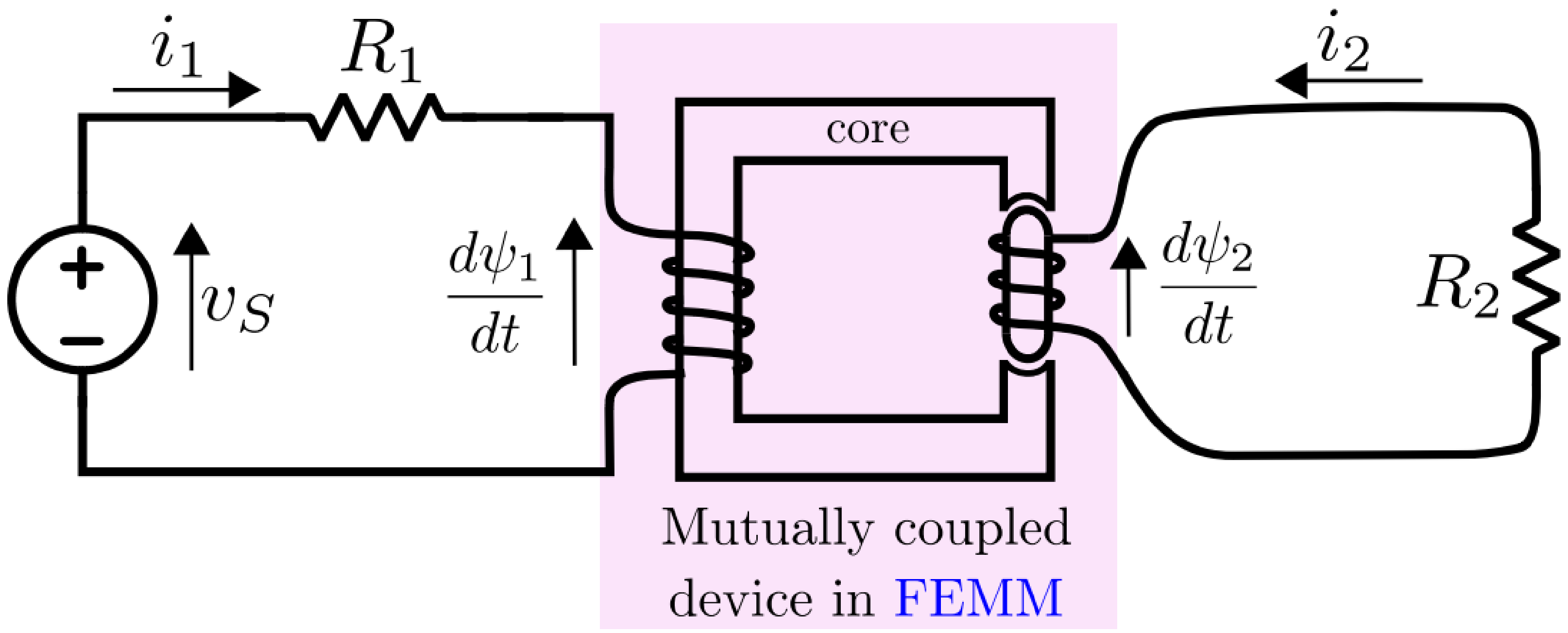


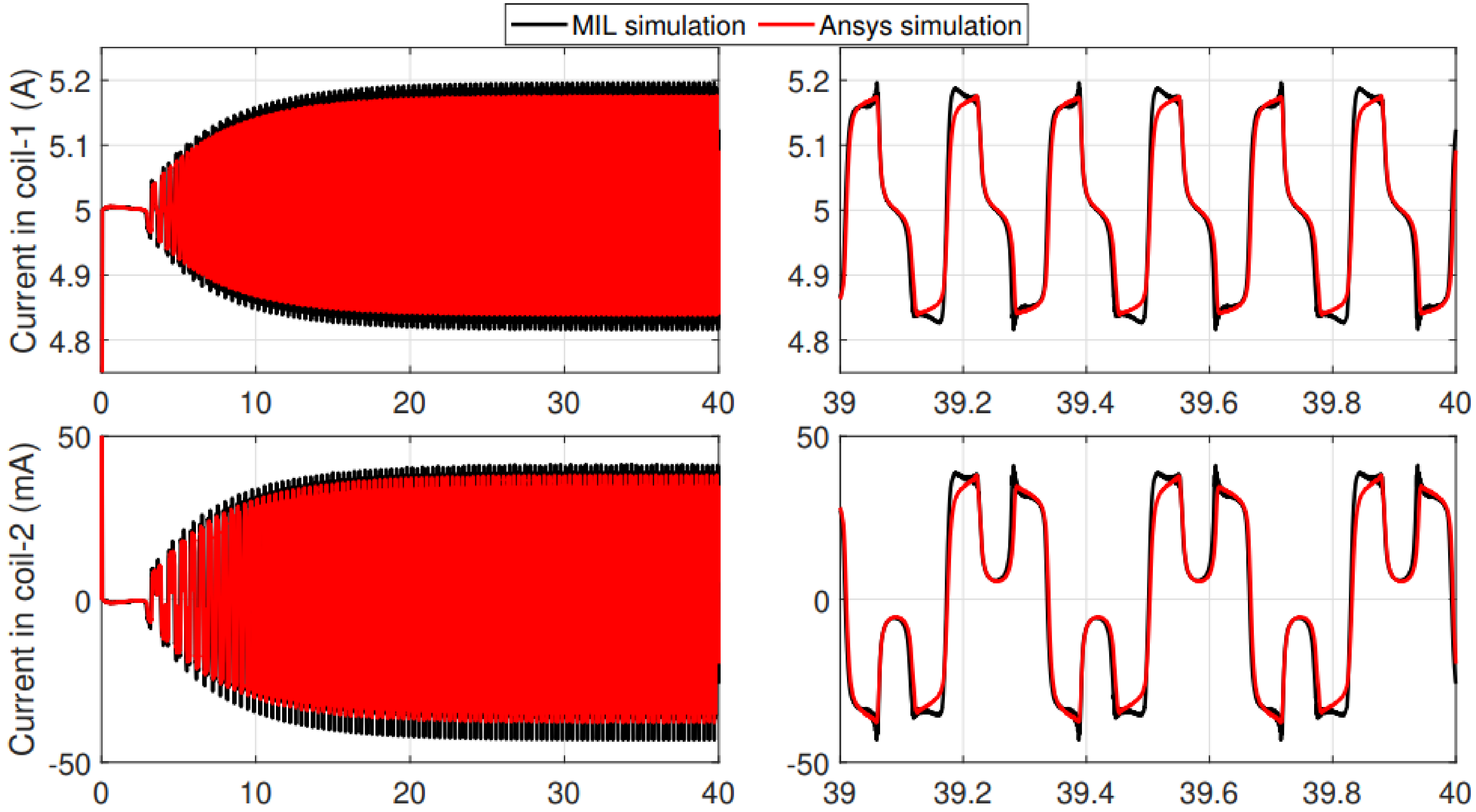
Transient simulation

Primitive AC generator case



$$R_1 = 1\ \Omega, \quad R_2 = 5\ \Omega, \quad v_s = 5\ \text{V}$$

A fundamental frequency of **3.0474 Hz** (i.e., a time period of **0.3282 s**)



Periodic steady-state computation

Method:

1. Time-domain method
2. Newton-Raphson based solution
3. State’s initial values are updated

T. J. Aprille and T. N. Trick, “**Steady-state analysis of nonlinear circuits with periodic inputs**,” *Proceedings of the IEEE*, 1972.

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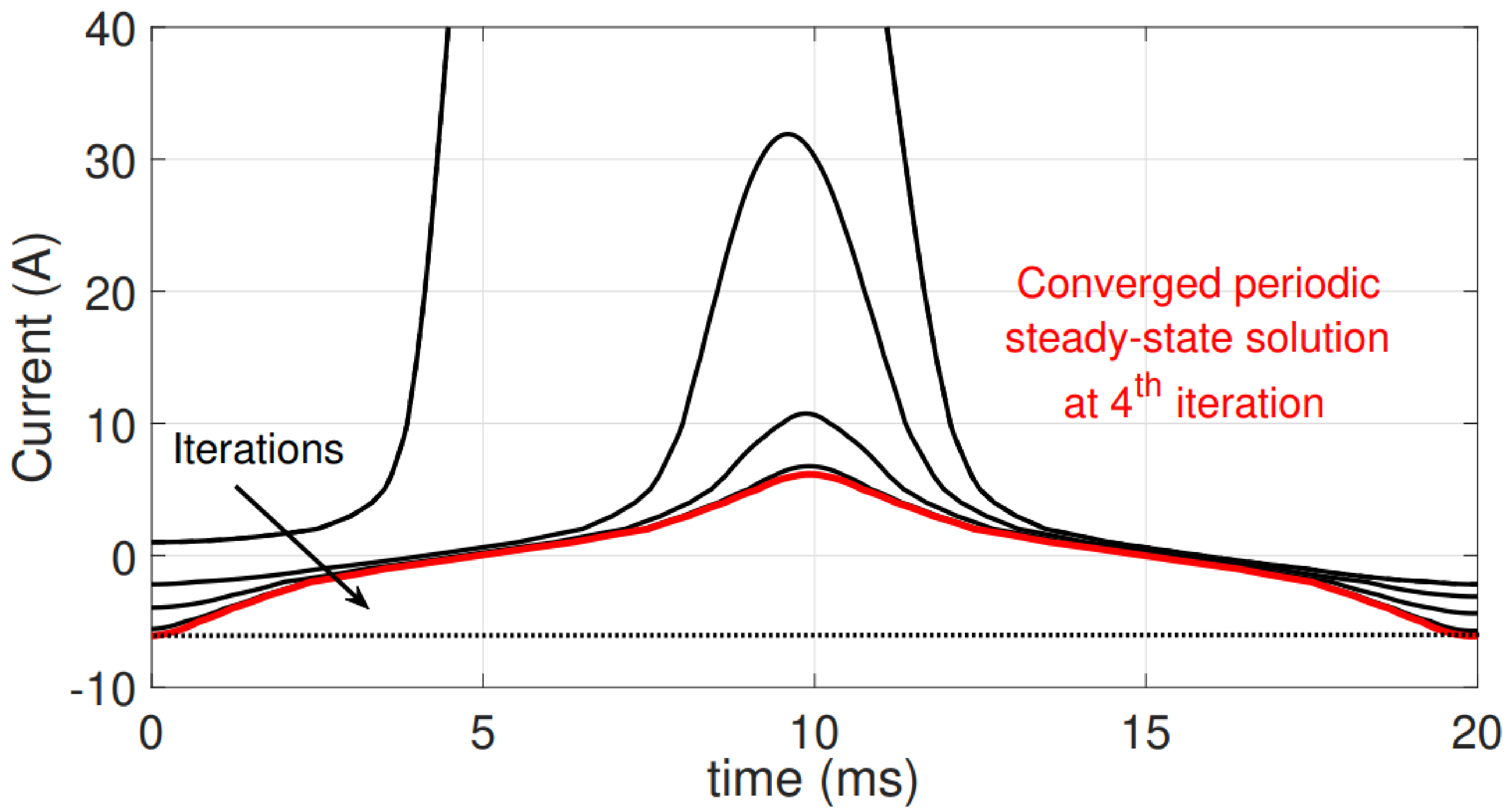

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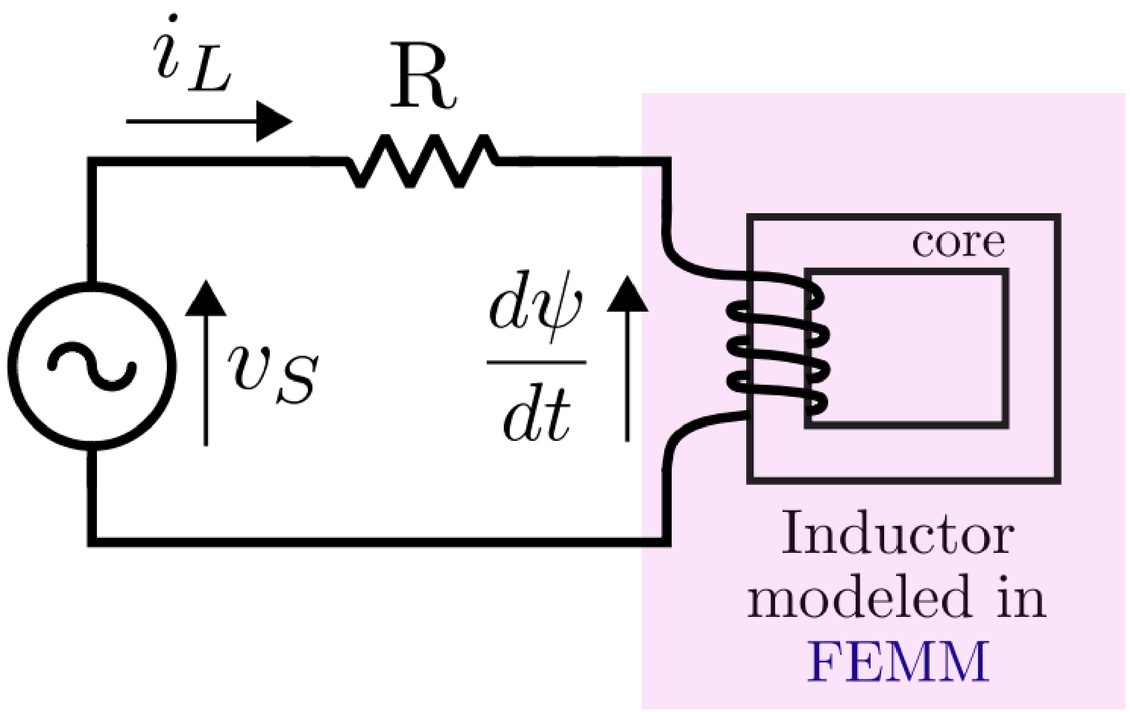
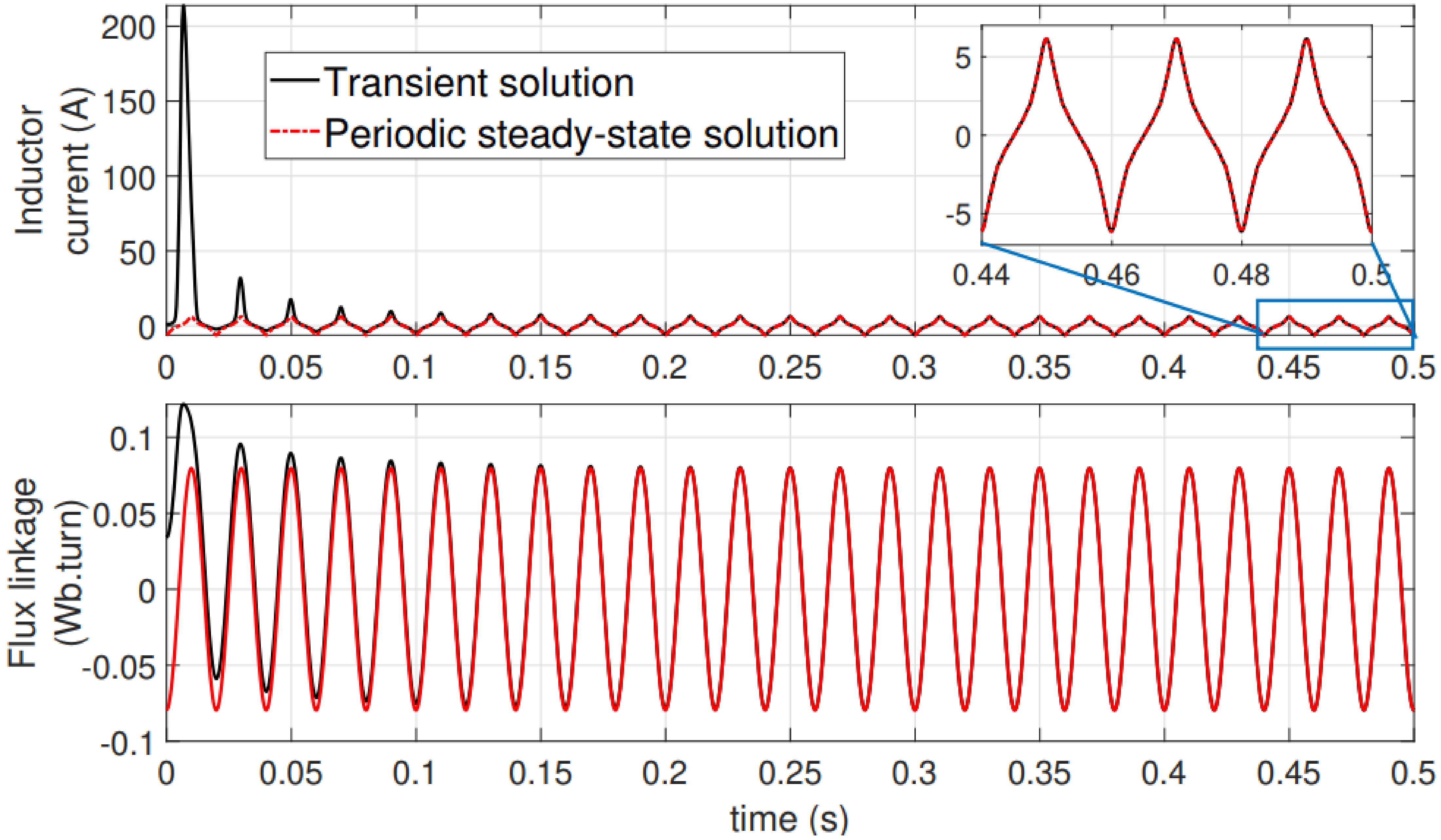
Periodic steady-state computation

Non-linear inductor case

Iterations: 4

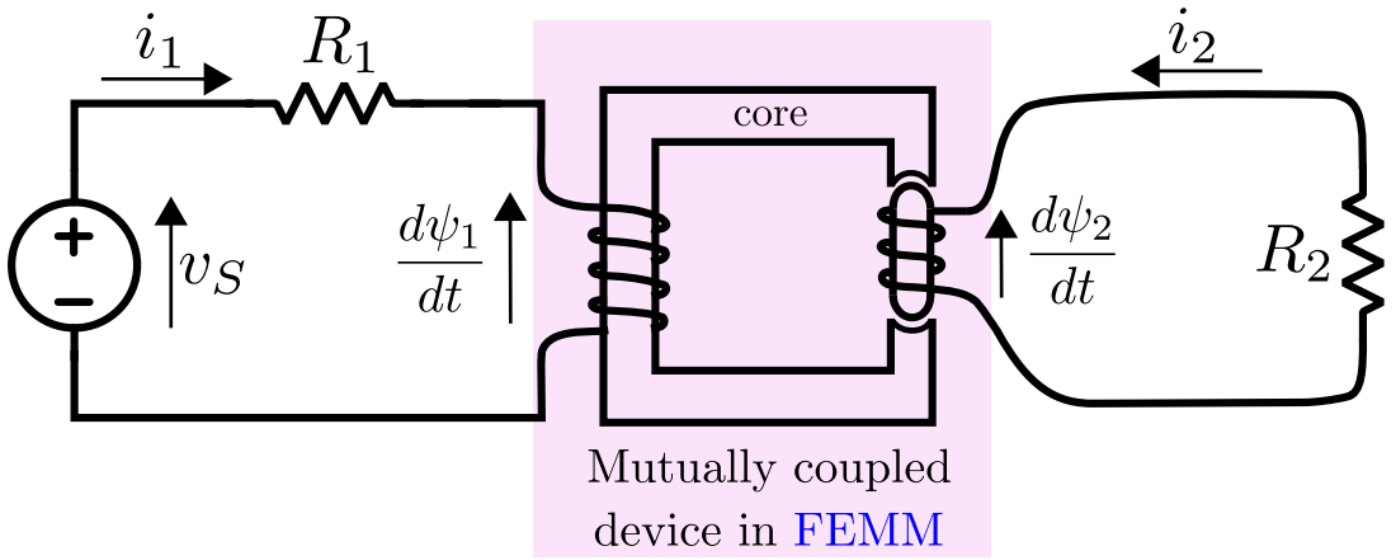


$$R = 0.1\ \Omega, \quad v_s = 25\,\sin(2\pi \times 50\,t)\ \text{V}$$



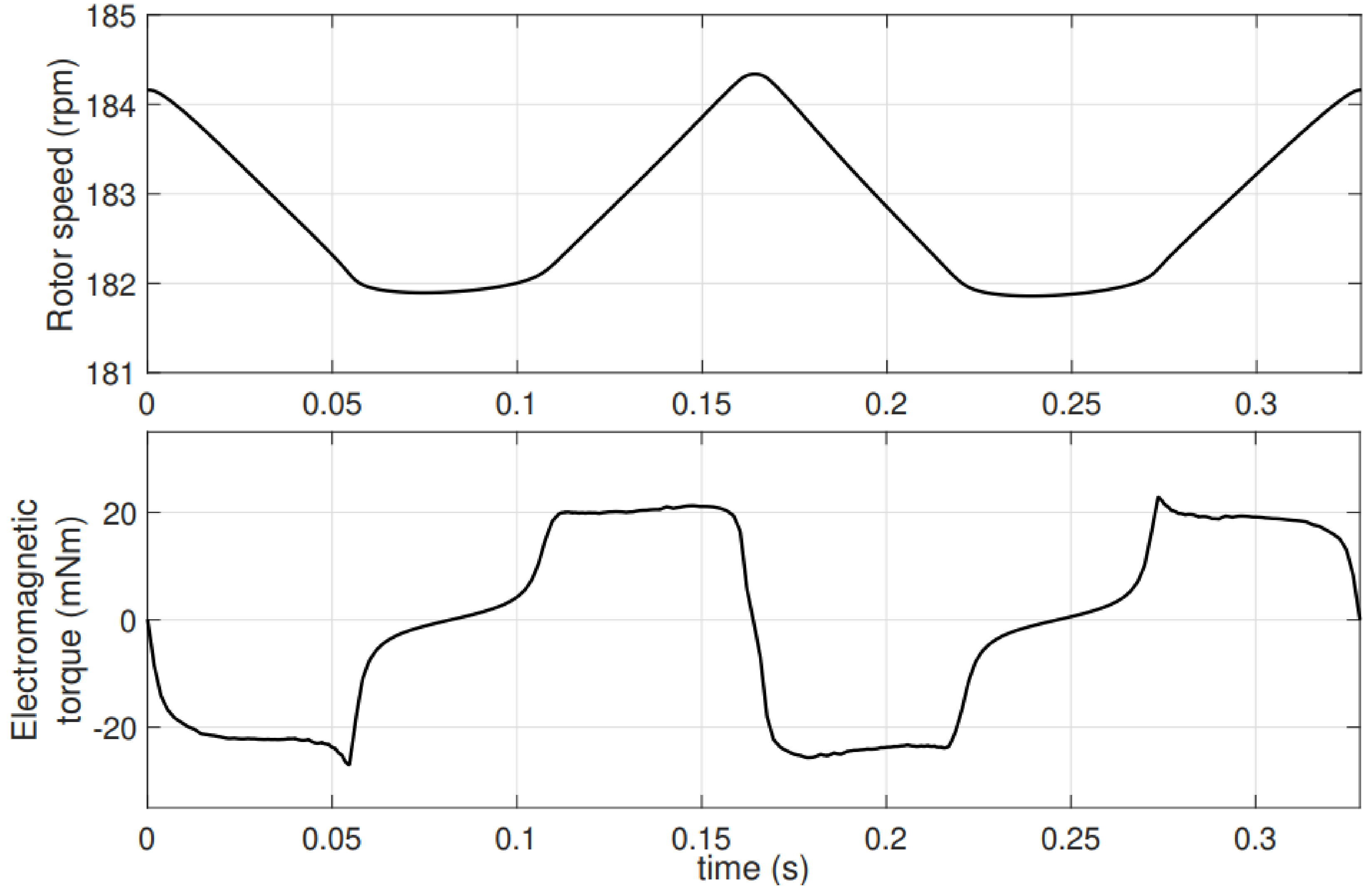
Periodic steady-state computation

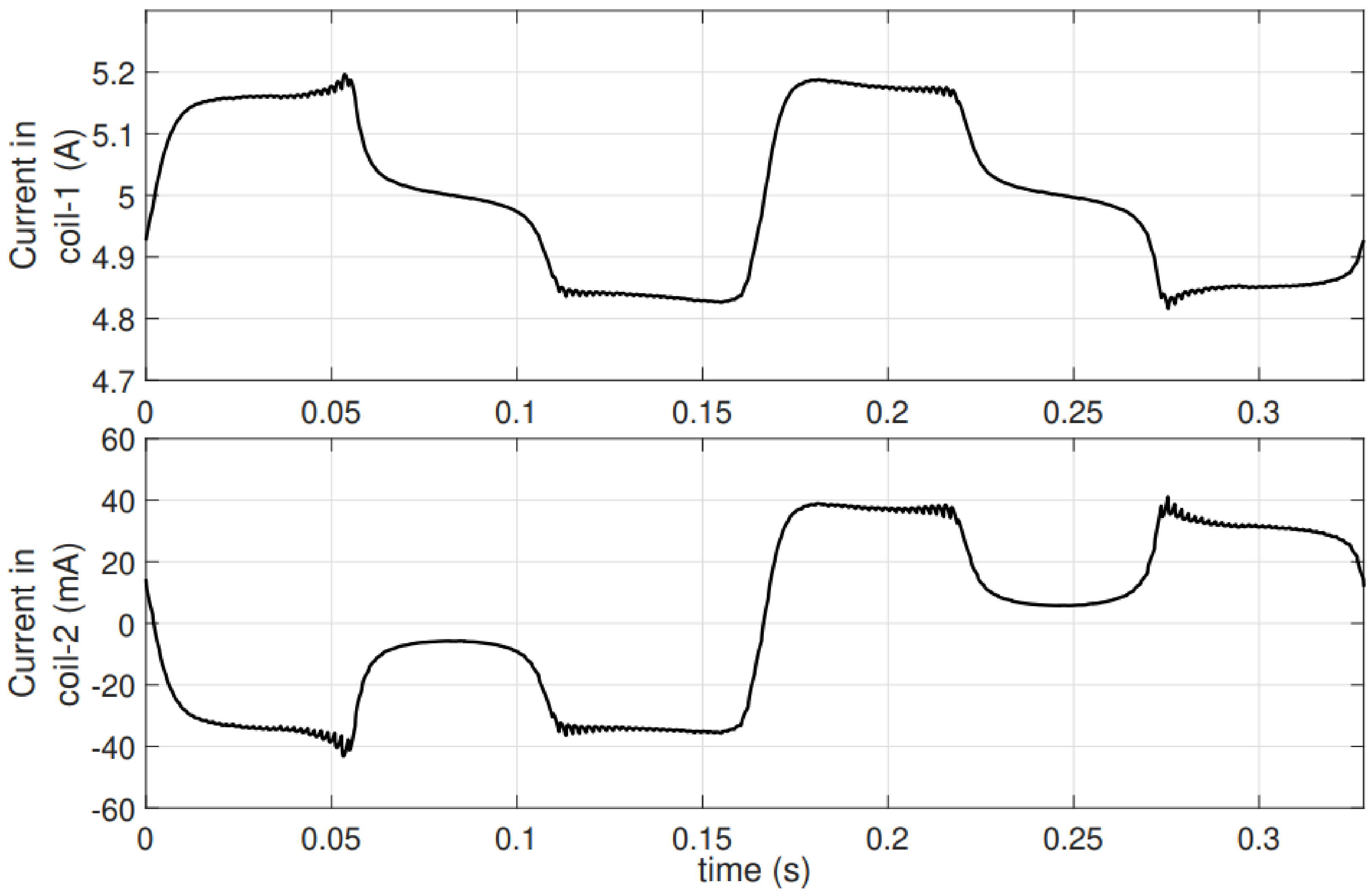
Primitive AC generator case



Iterations: 10

$$R_1 = 1\ \Omega, \quad R_2 = 5\ \Omega, \quad v_s = 5\ \mathrm{V}$$





Summary

1. MIL approach → coupled-field circuit problems
2. Transient simulations → verified with Ansys simulation
3. Periodic steady-state computation is performed
4. Using FOSS.

Slides and paper materials are available in github.

THANK YOU

Suggestions and feedback:
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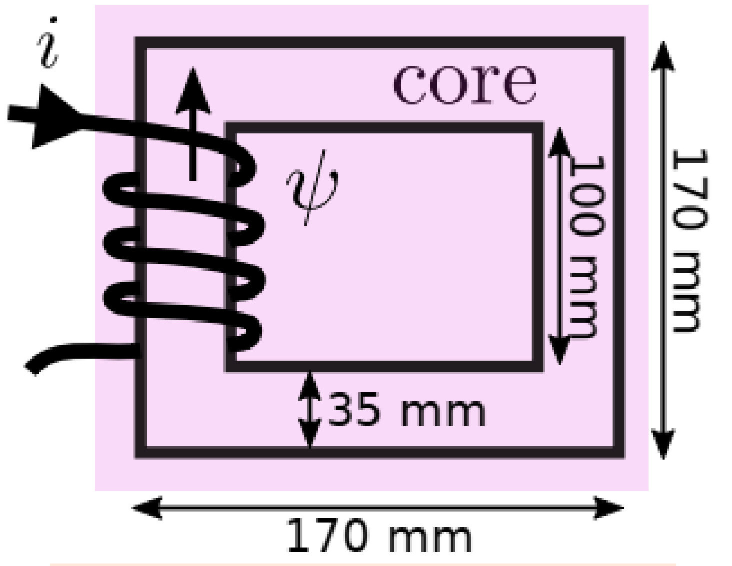
svsingh@ee.iitb.ac.in
santoshvsingh68@gmail.com

MIL simulation

Back-up slides

Dimensions and materials

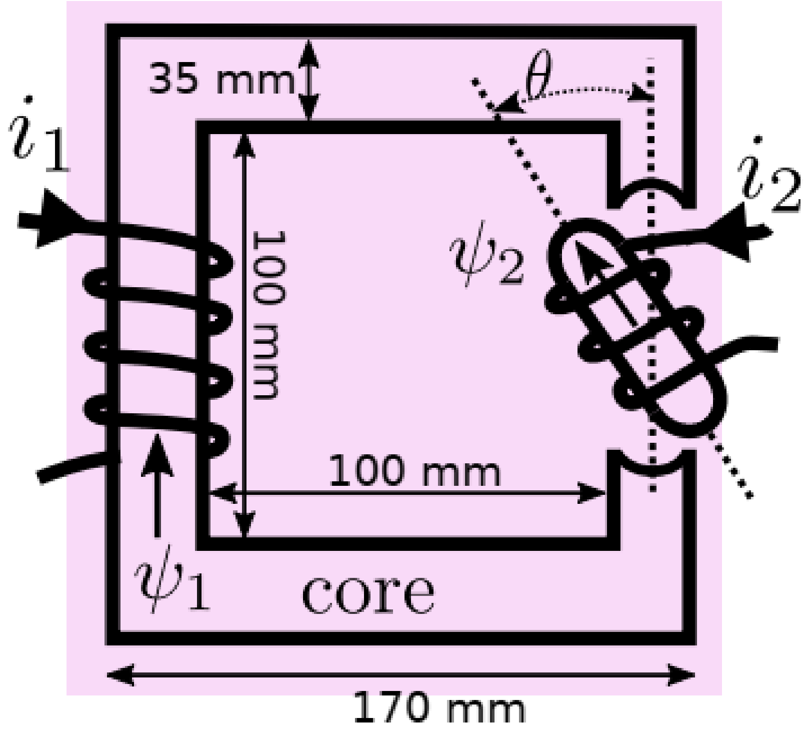
Non-linear inductor



Coil: 50 turns of 18 AWG Copper

Core: 35 mm depth, M22_24G material

Primitive AC generator



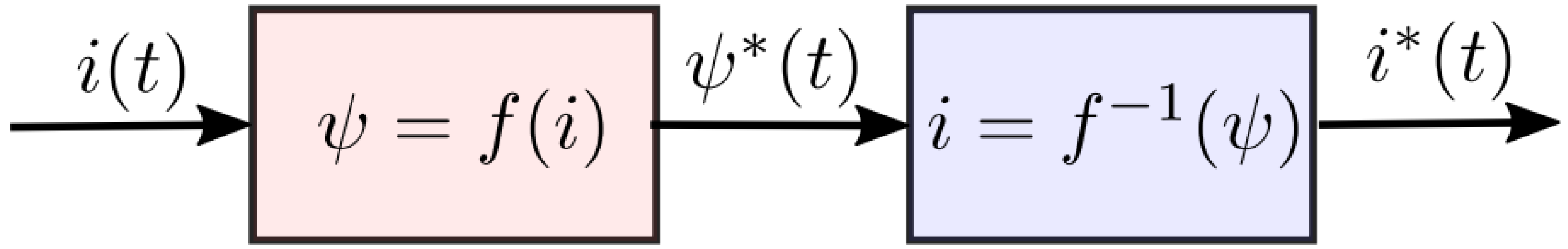
Coils: Each with 50 turns of 18 AWG Copper

Core: 35 mm depth, M22_24G material
Rotor core diameter: 68 mm
Total air-gap spacing: 2 mm

MIL simulation

Back-up slides

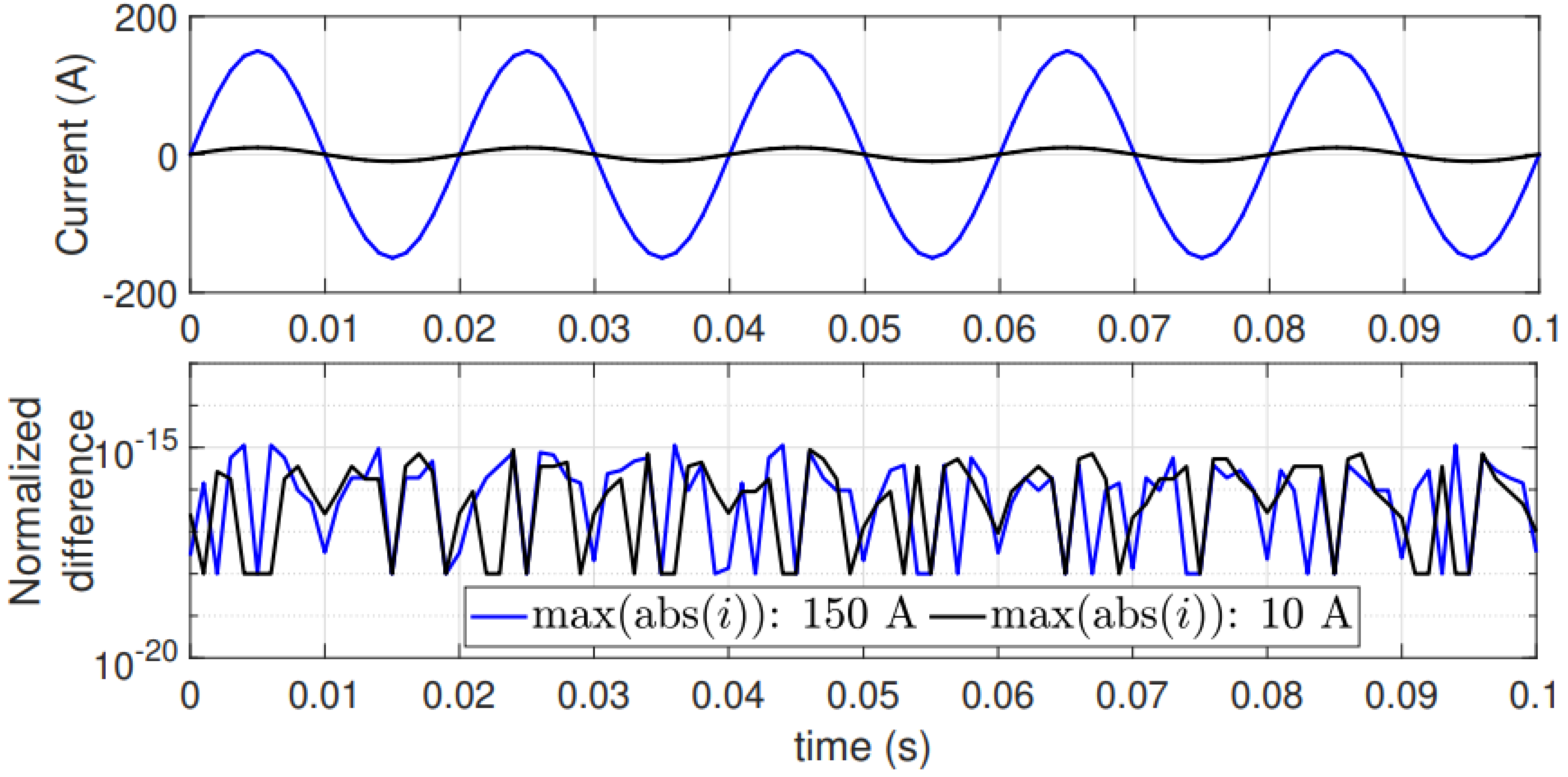
Loop-back test

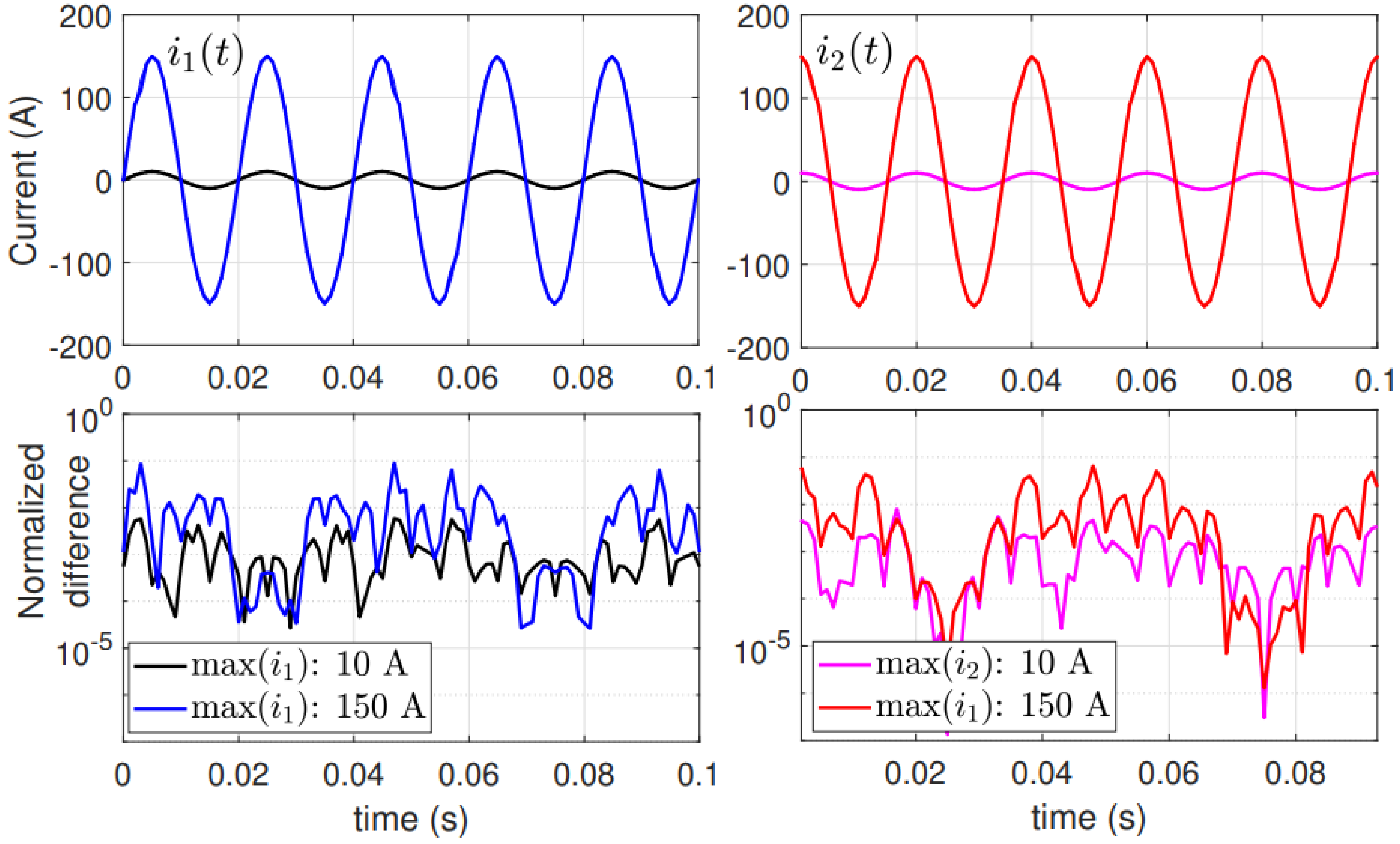


$$\epsilon_i = |i(t) - i^*(t)|$$

Primitive AC generator

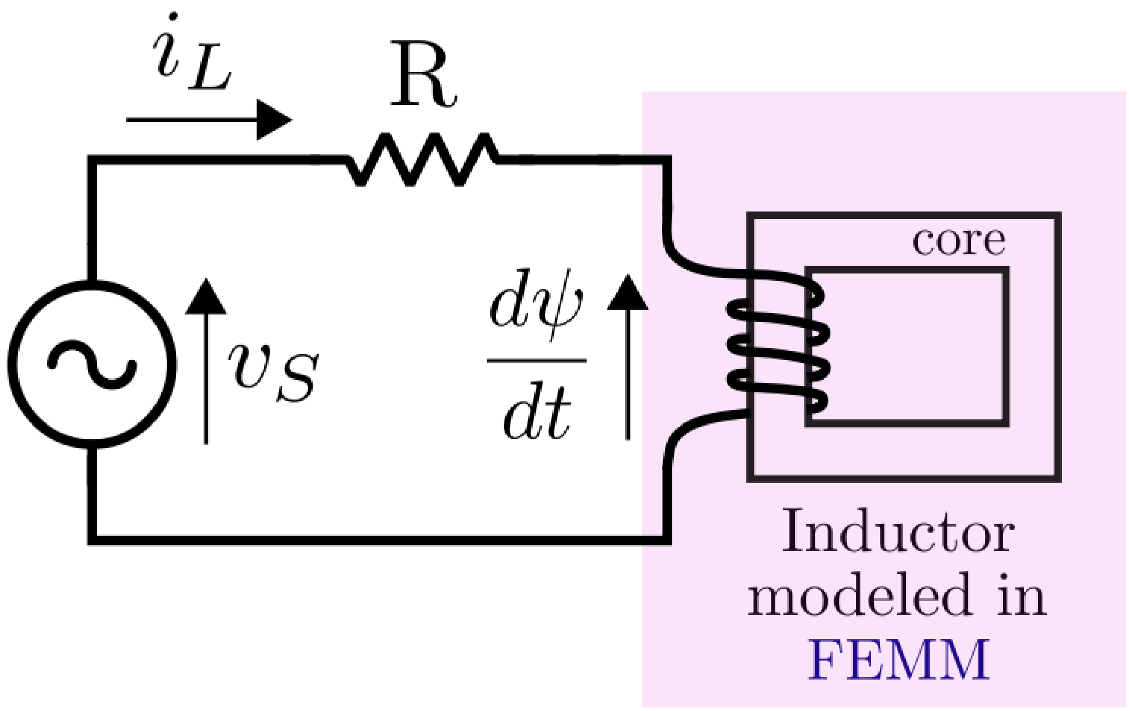
Non-linear inductor





Transient simulation

Back-up slides



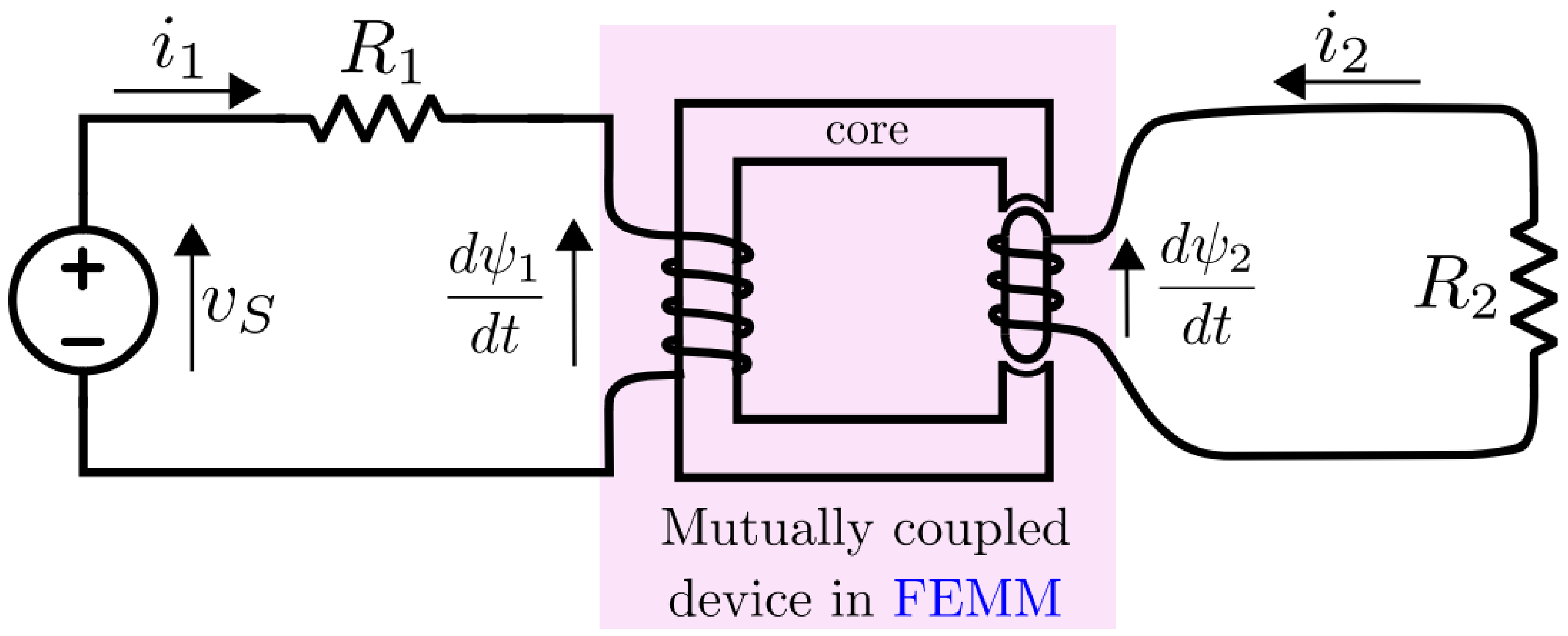
Time-step: 1 ms
Tolerance set: 1e-4

$$\frac{d\psi}{dt} = -i_L R + v_s; \quad \psi = f(i_L)$$

$$R = 0.1\ \Omega, \quad v_s = 25\ \sin(2\pi \times 50\,t)\ \mathrm{V}$$

Transient simulation

Back-up slides



$$\frac{d\psi_1}{dt} = -i_1 R_1 + v_S; \quad \frac{d\psi_2}{dt} = -i_2 R_2$$

$$\psi_1 = f_1(i_1, i_2, \theta); \quad \psi_2 = f_2(i_1, i_2, \theta)$$

$$i_1 = f_1^{-1}(\psi_1, \psi_2, \theta); \quad i_2 = f_2^{-1}(\psi_1, \psi_2, \theta)$$

$$\frac{d\omega}{dt} = \frac{1}{J}\left(T_m - T_{em} - B_m\,\omega\right)$$

$$\frac{d\theta}{dt} = \omega; \quad T_{em} = f_3(i_1, i_2, \theta)$$

$R_1 = 1\ \Omega, \quad R_2 = 5\ \Omega, \quad v_s = 5$ V

$T_m = 0.0198$ Nm, (mechanical torque)

$B_m = 0.977 \times 10^{-3}$ Nm-s/rad

$J = 5 \times 10^{-3}$ kg-m^2 (moment of inertia of the rotor)