Modelling AC ripples in HTS coated conductors by integral equations

Francesco Grilli, Zhihan Xu

Institute for Technical Physics - ITEP

This presentation consists of two parts

1. Calculation of AC current ripples by means of 2-D *H*-formulation

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Modelling ac ripple currents in HTS coated conductors

Zhihan Xu and Francesco Grilli

2. Calculation of AC current ripples by means of 1-D integral equations
   - Superconductor modeled as 1-D line
   - 100-200 DOFs → Very fast computation
   - Comparison with *H*-formulation
   - Influence of *n*-value
   - Influence of $J_c(B)$ dependence

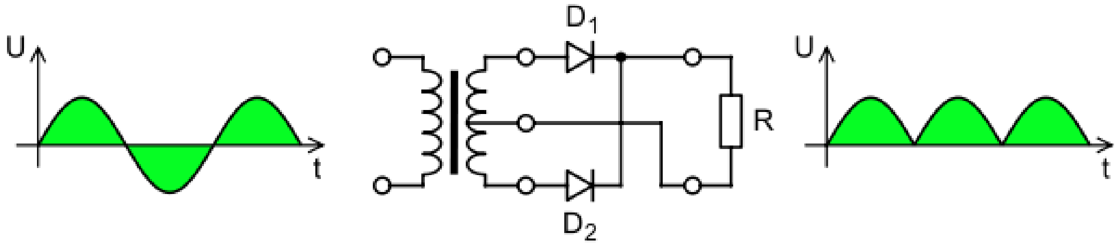
HTS coated conductors for DC transmission

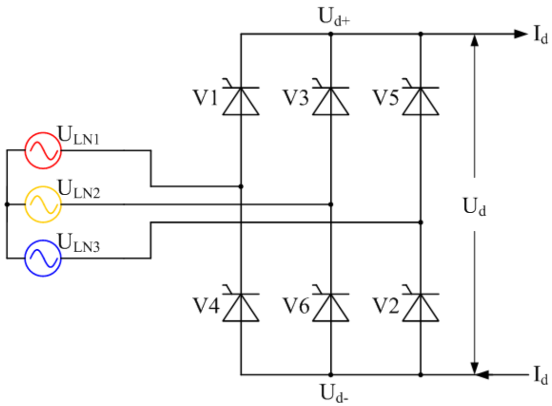
- Large green energy sources typically located far away from major consumption centres, up to several thousand km →
- Effective long-distance power transmission of GW level required →
- One potential solution: “lossless” HTS DC cables

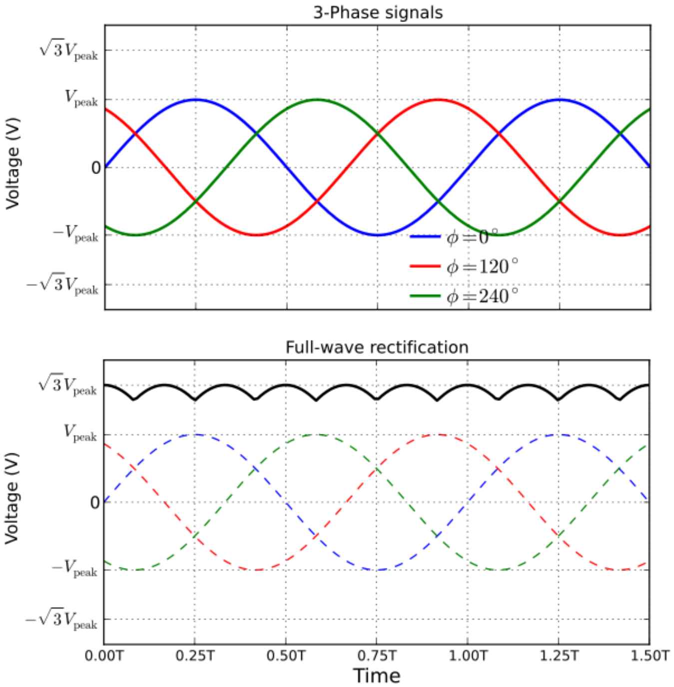
* This is not a new idea, but rather one that has achieved a practical possibility only lately, owing to recent advances in superconducting materials, cryogenics and AC-DC conversion techniques.

AC ripples in DC transmission cables

- Rectifiers: AC → DC + pulses/ripples
  - Single-phase, full-wave rectification
  - Three-phase, full-wave rectification







- **AC ripples → AC losses!**
- HTS DC cables are not completely lossless!

Modelling AC ripples

The problem

- Consider a 4-mm-wide YBCO tape subject to DC + AC ripples
- A typical applied current: $I_{DC} = 0.8*I_c$ plus $I_{AC} = 10\%*I_{DC}*\sin(\omega t)$
- To estimate the losses caused by the ripples
- To understand the mechanisms behind

Modelling AC ripples

The method

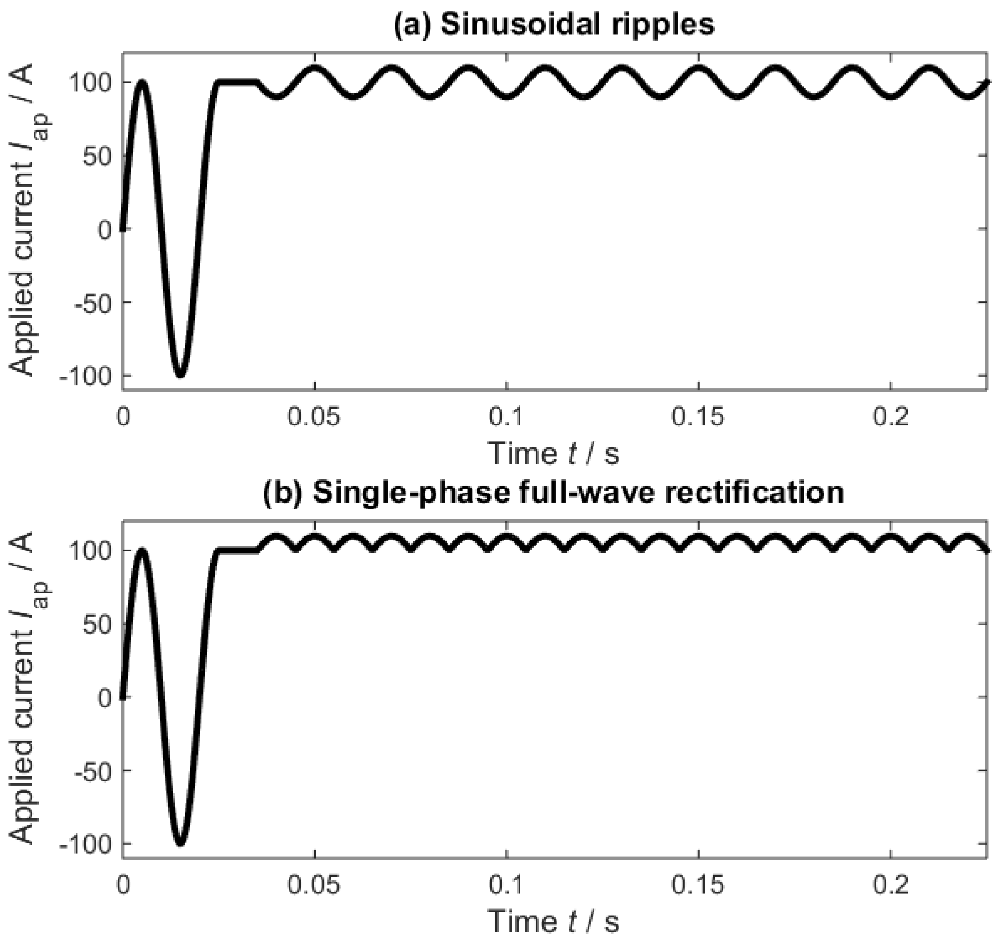
- 2-D finite-element analysis in COMSOL Multiphysics
- Maxwell's equations → H formulation
- E-J relation
  - The power law: n = 25

$$E = E_c \left| \frac{J}{J_c} \right|^n$$

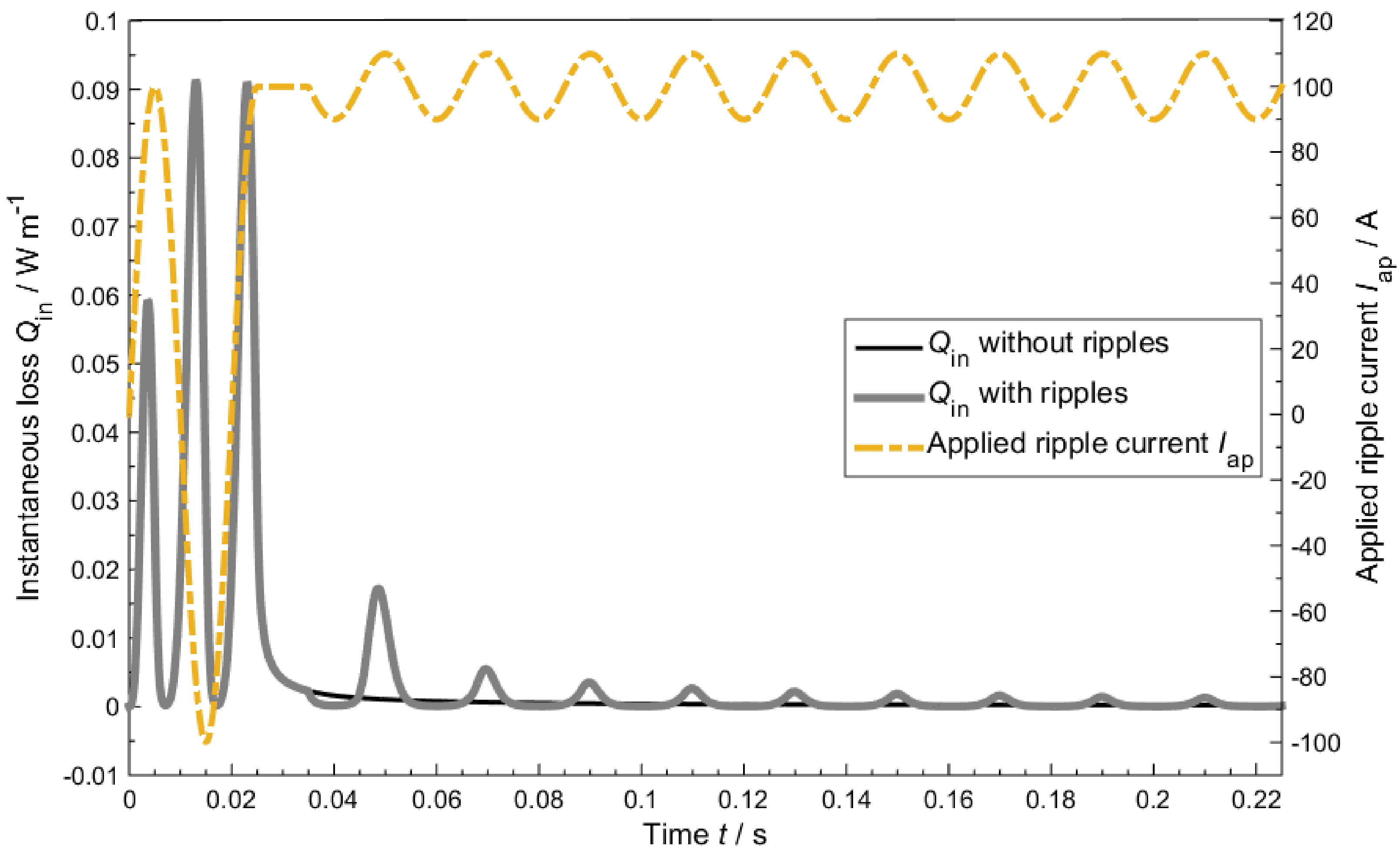
- J_c-B relation
  - The constant-J_c model: $J_c = 3.125^{10}$ A m^{-2} → I_c = **125 A**
  - The elliptical model: $J_{c0} = 4*10^{10}$ A m^{-2}, B_0 = 0.02 T, k=0.3, b=0.6 → I_c = **125 A**

$$J_c = \frac{J_{c0}}{\left(1 + \frac{\sqrt{k^2 B_{par}^2 + B_{perp}^2}}{B_0}\right)^b}$$

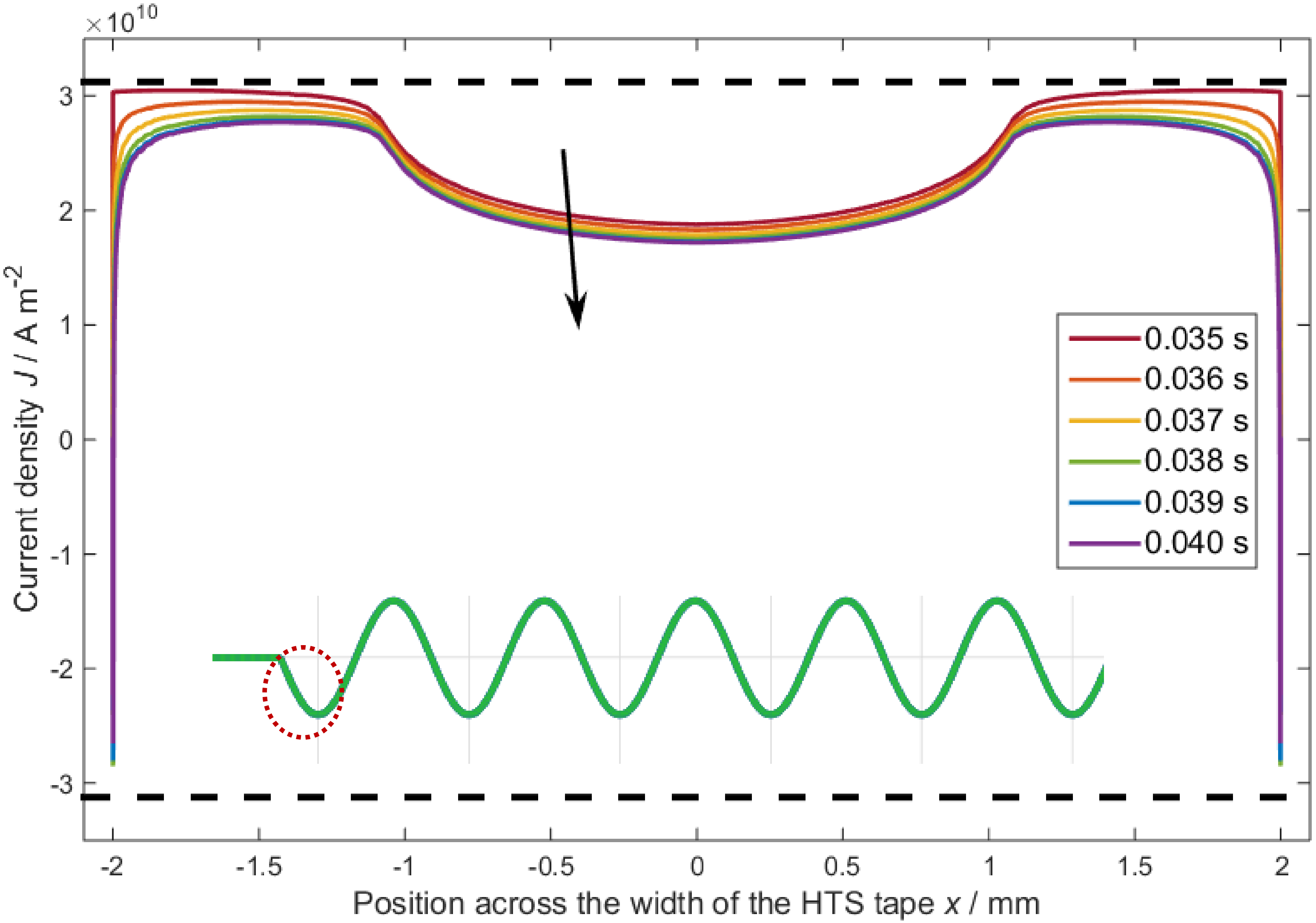
Application of AC ripples (10%, 50 Hz)



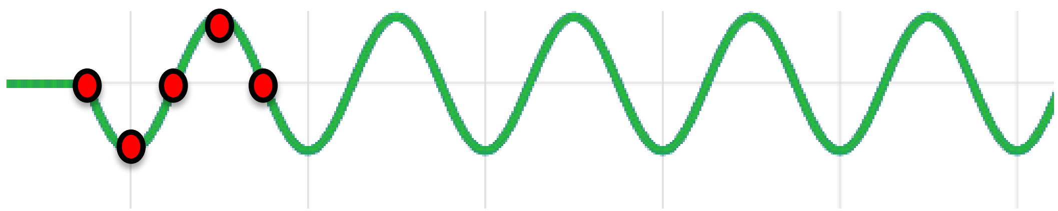
Instantaneous dissipation

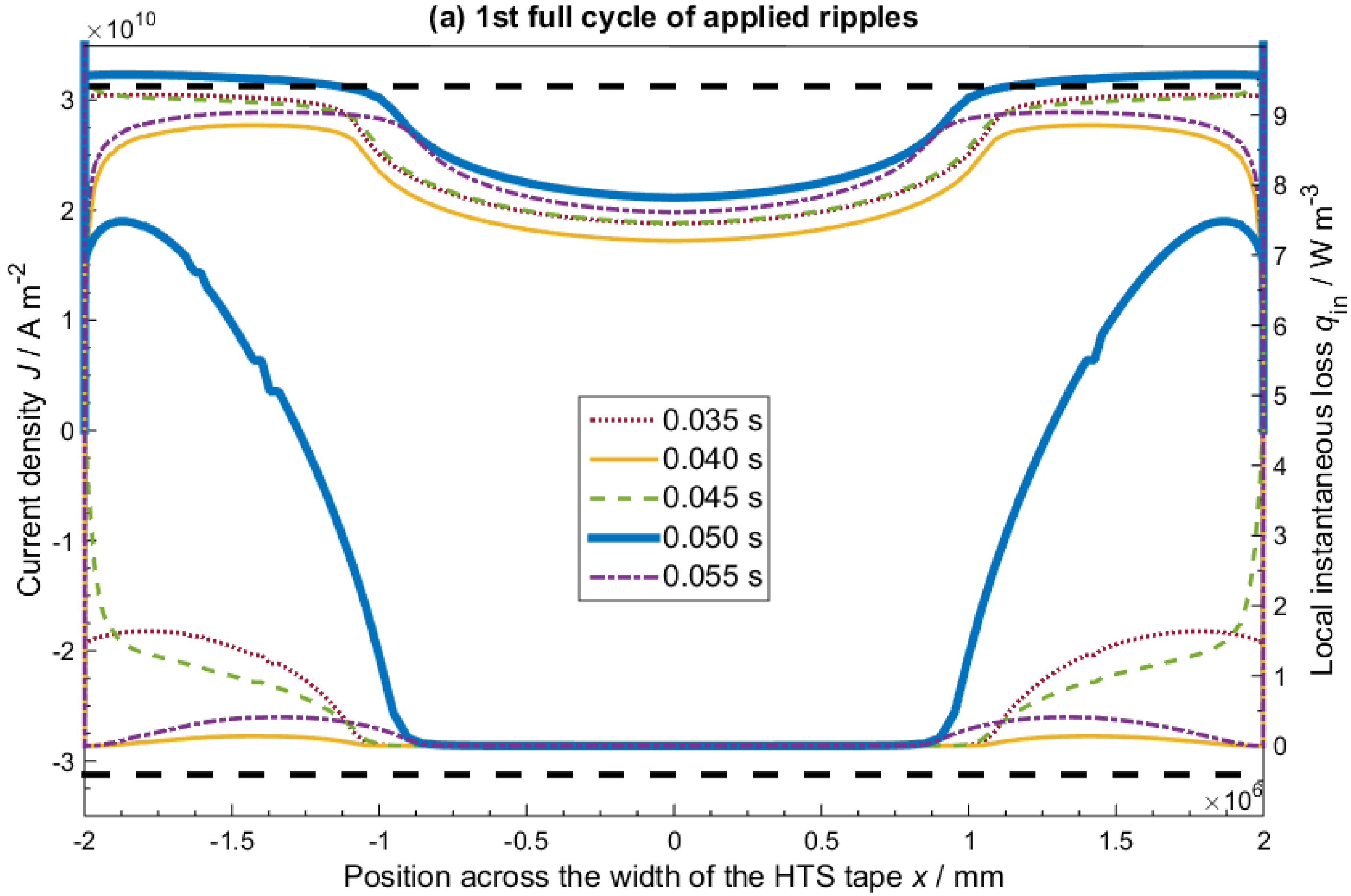


Critical state ($-J_c$) not reached at the valleys



Local power dissipation





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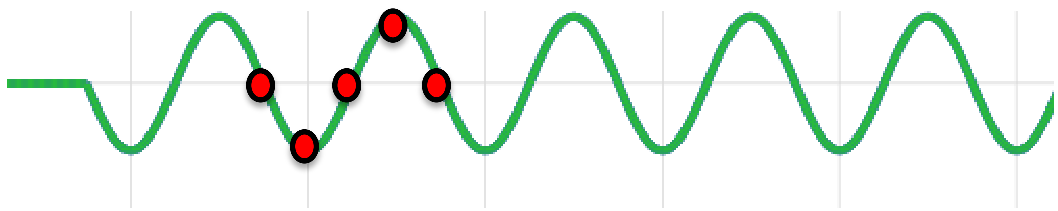

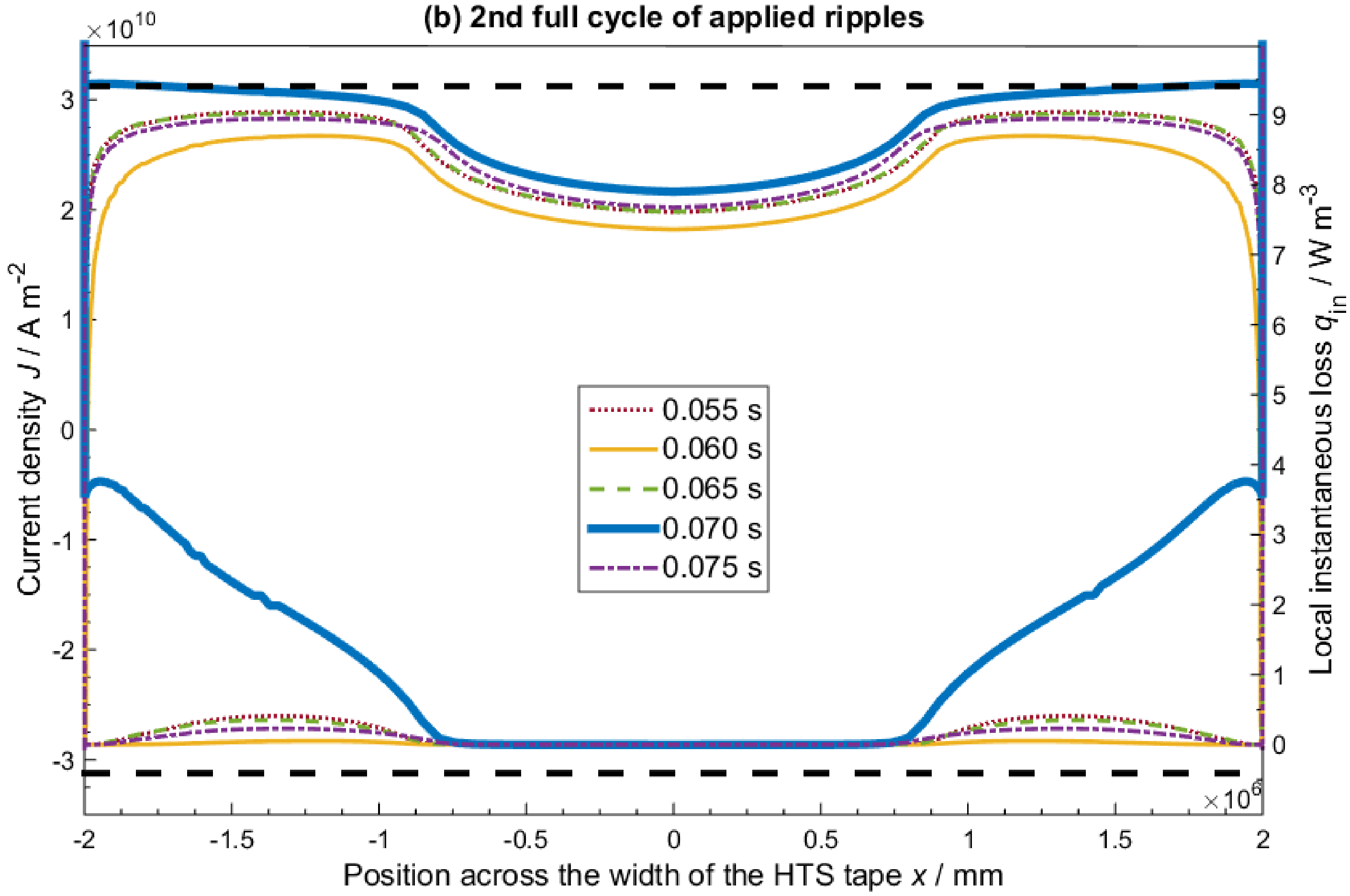

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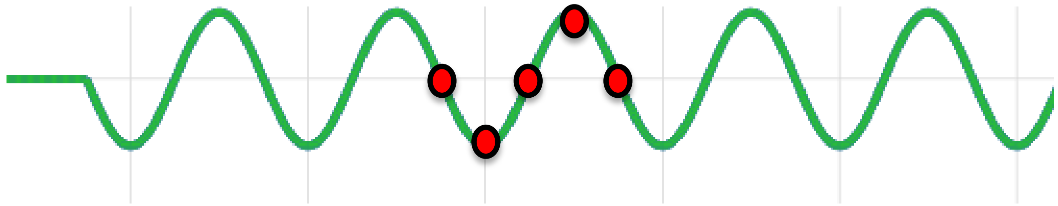
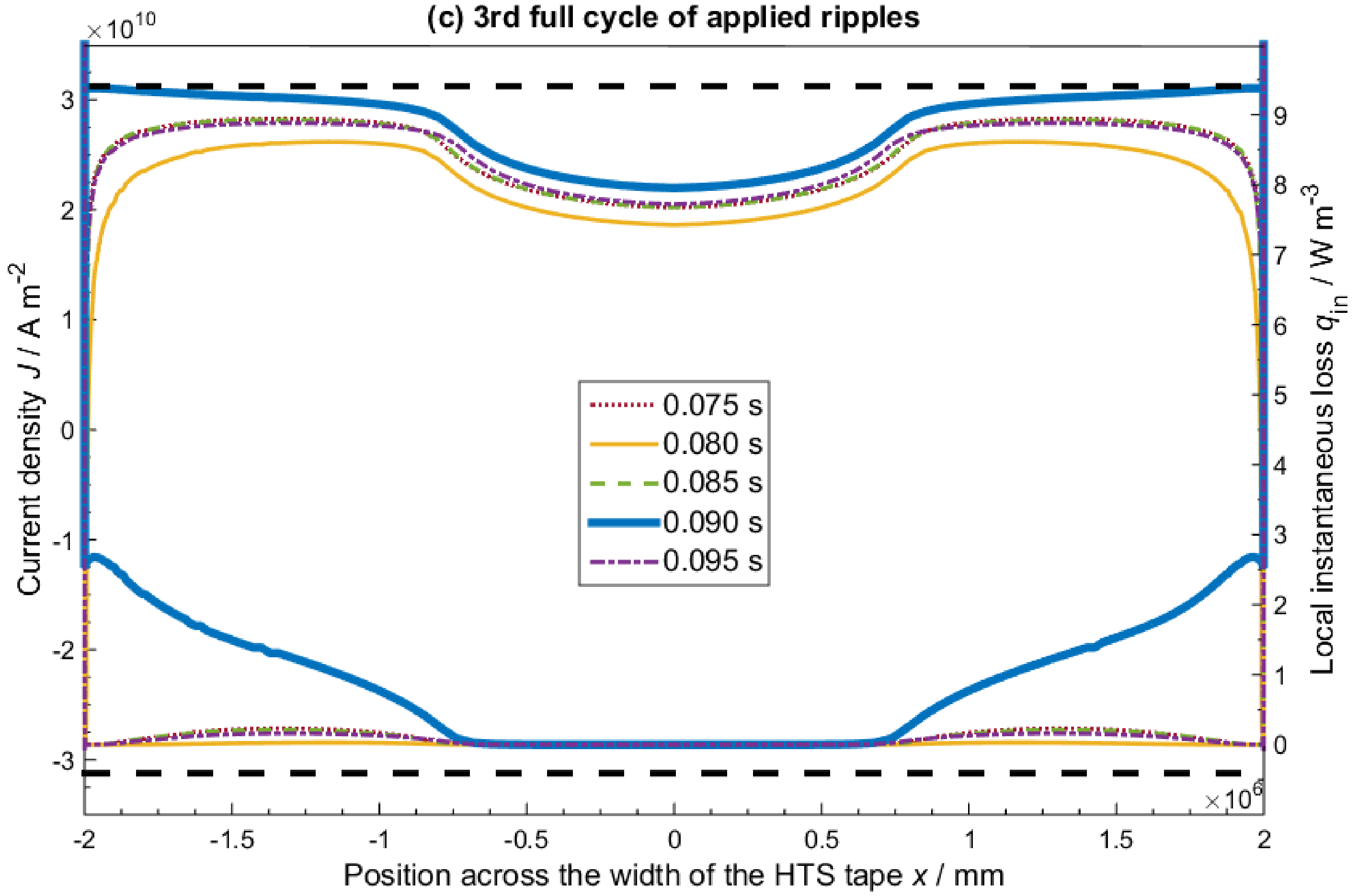
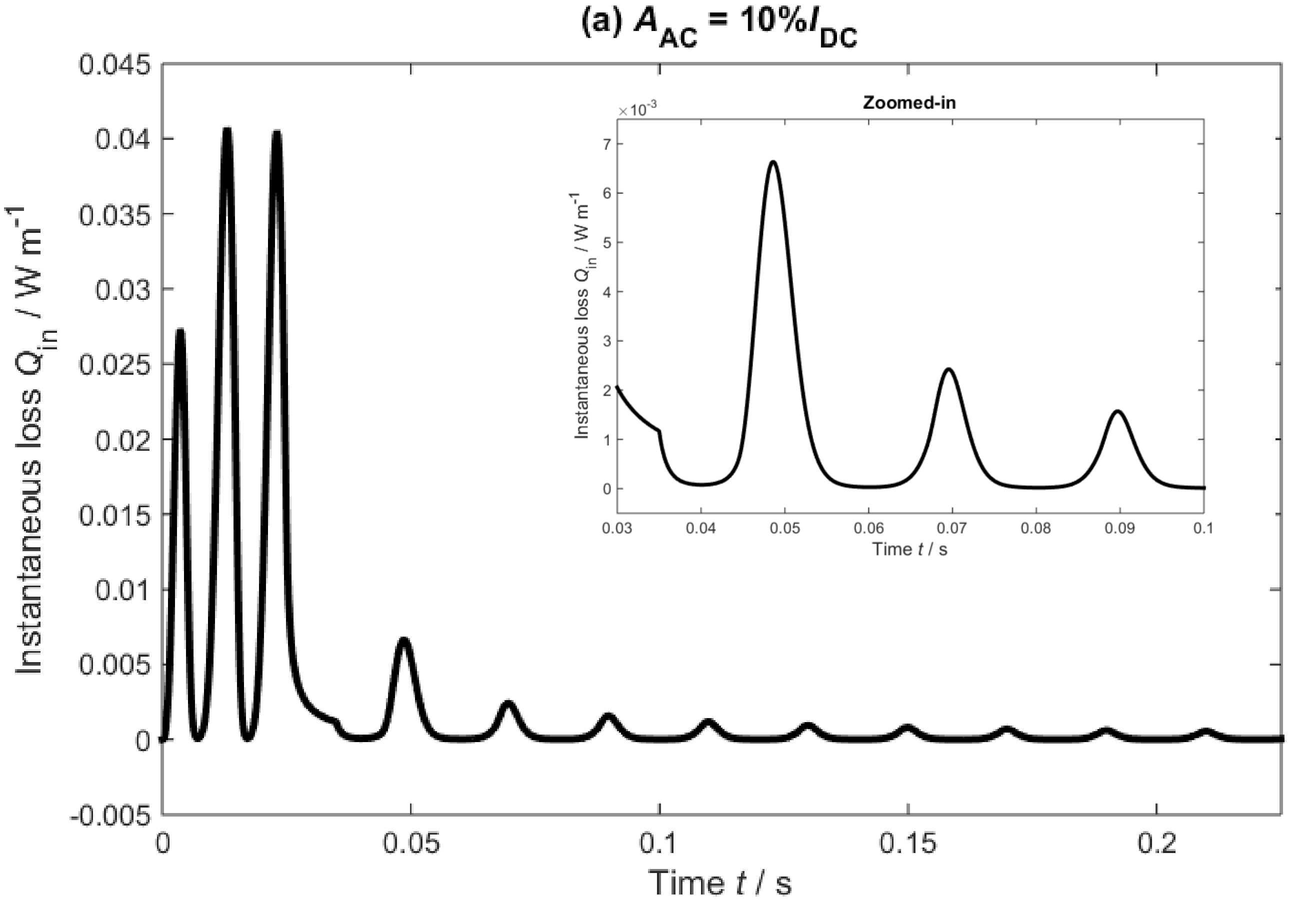




How about larger ripples? Will $-J_c$ be reached?

- $0.7*I_c$ + **10%**, to be compared with ripples of 20% and 30%



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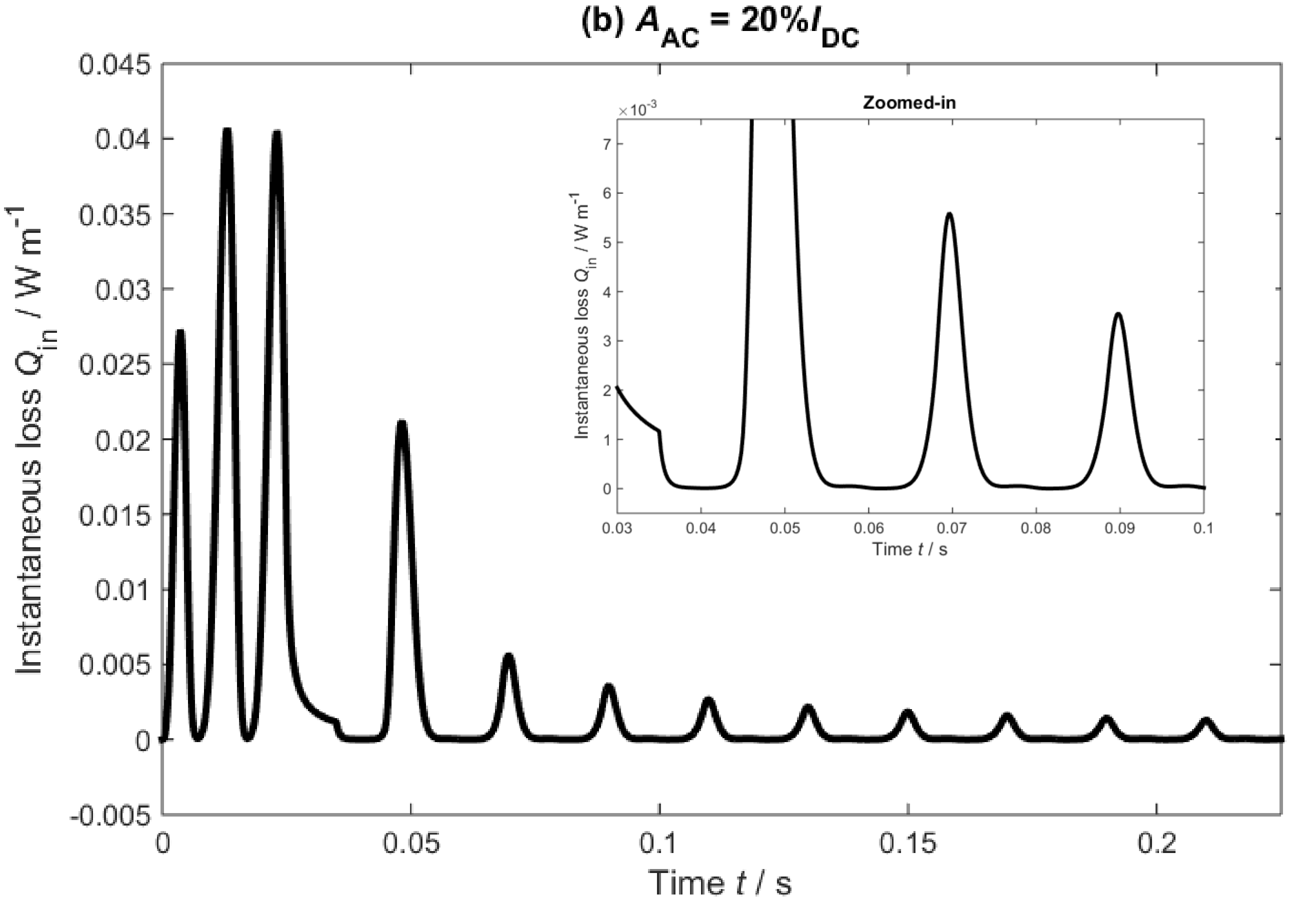

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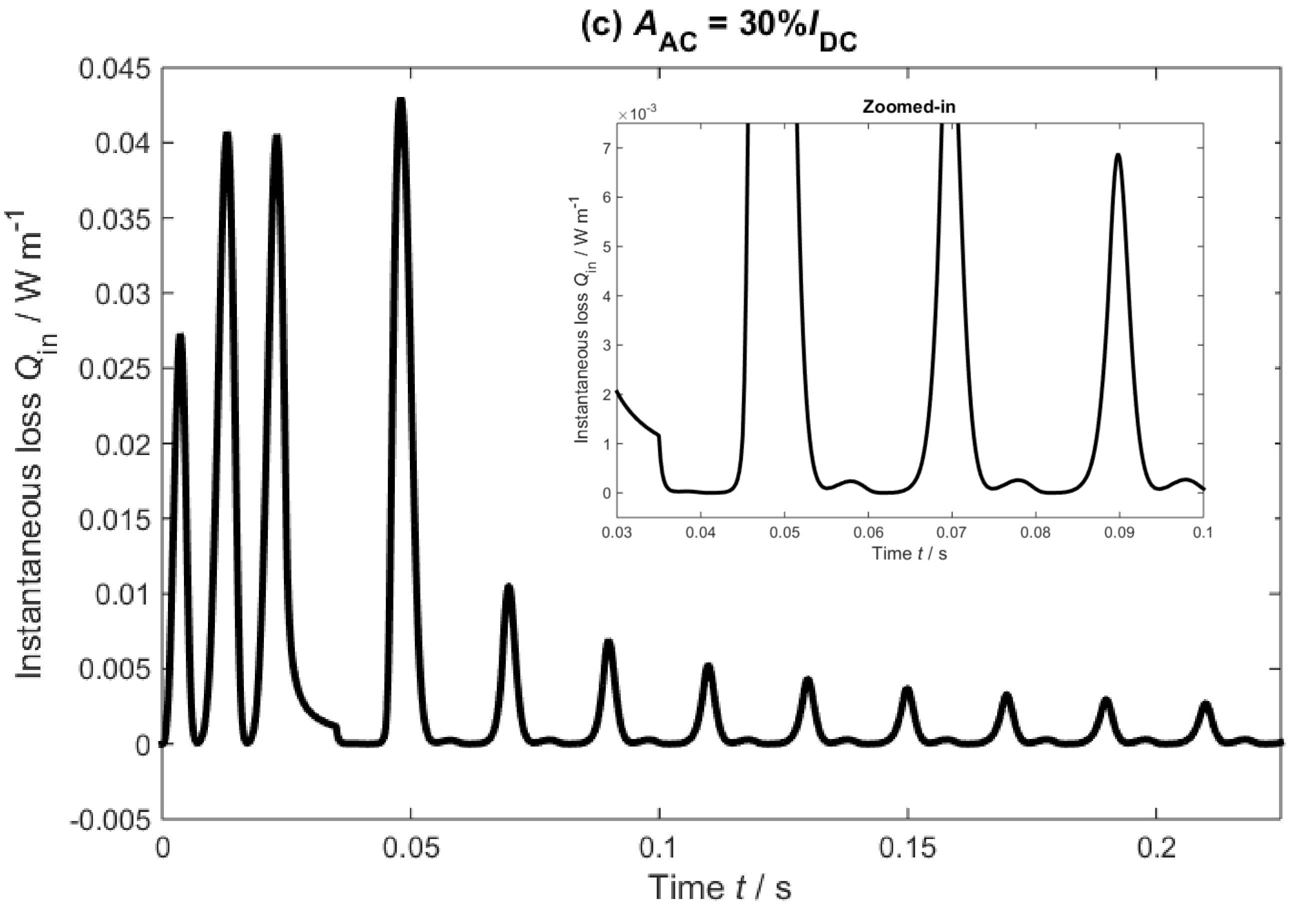
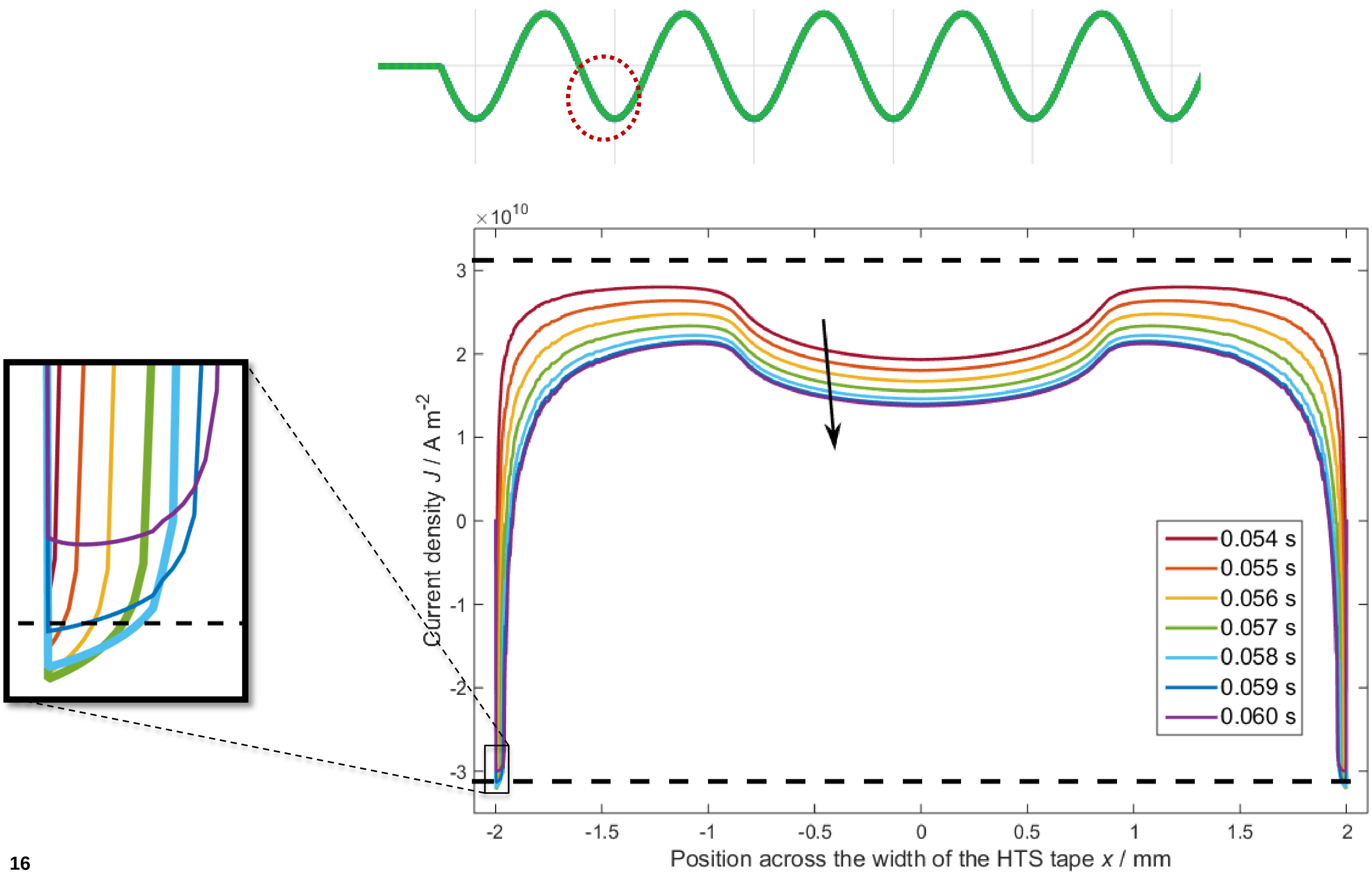
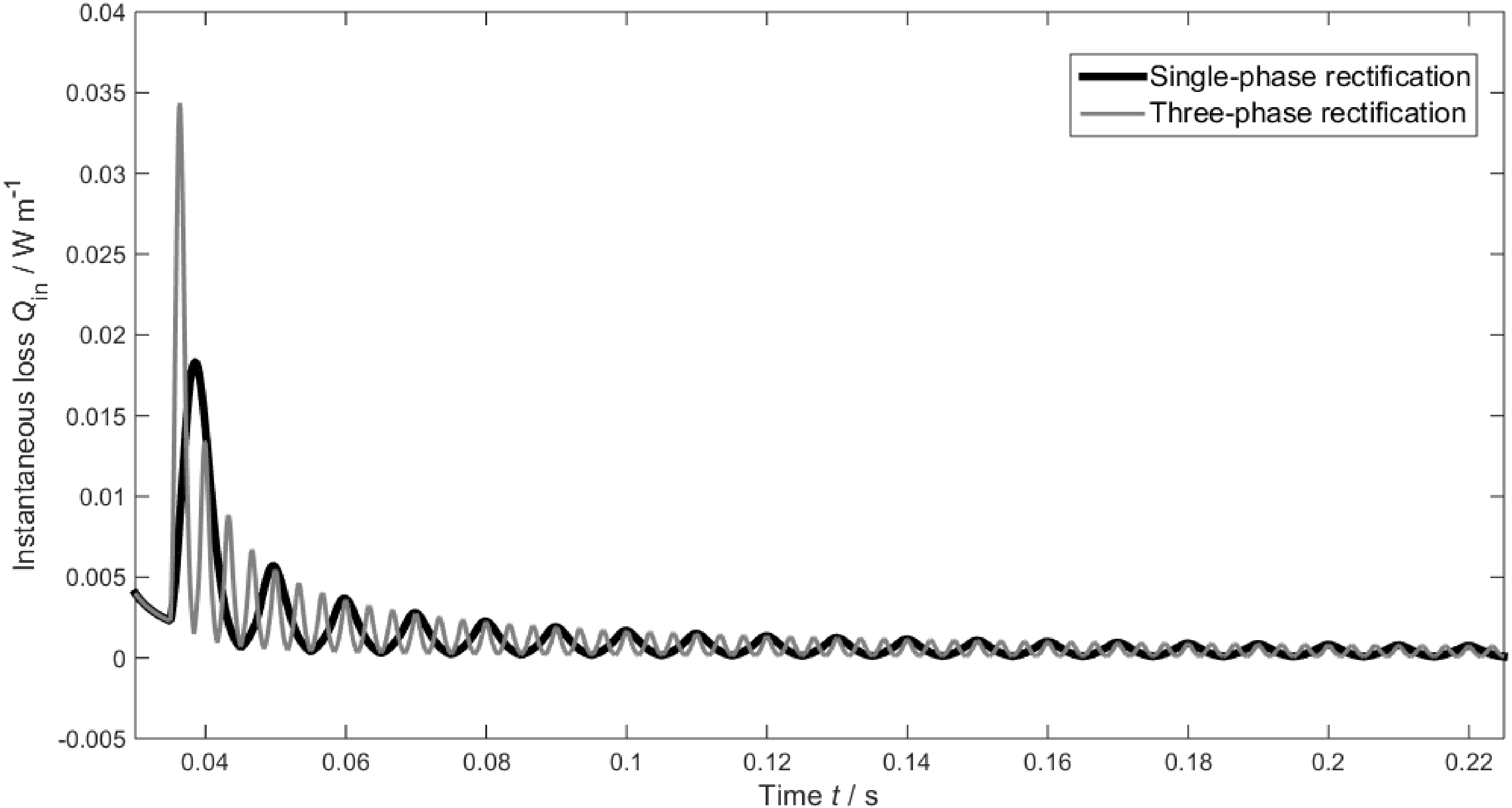


J(x) distribution for 0.7*I_c + 30%

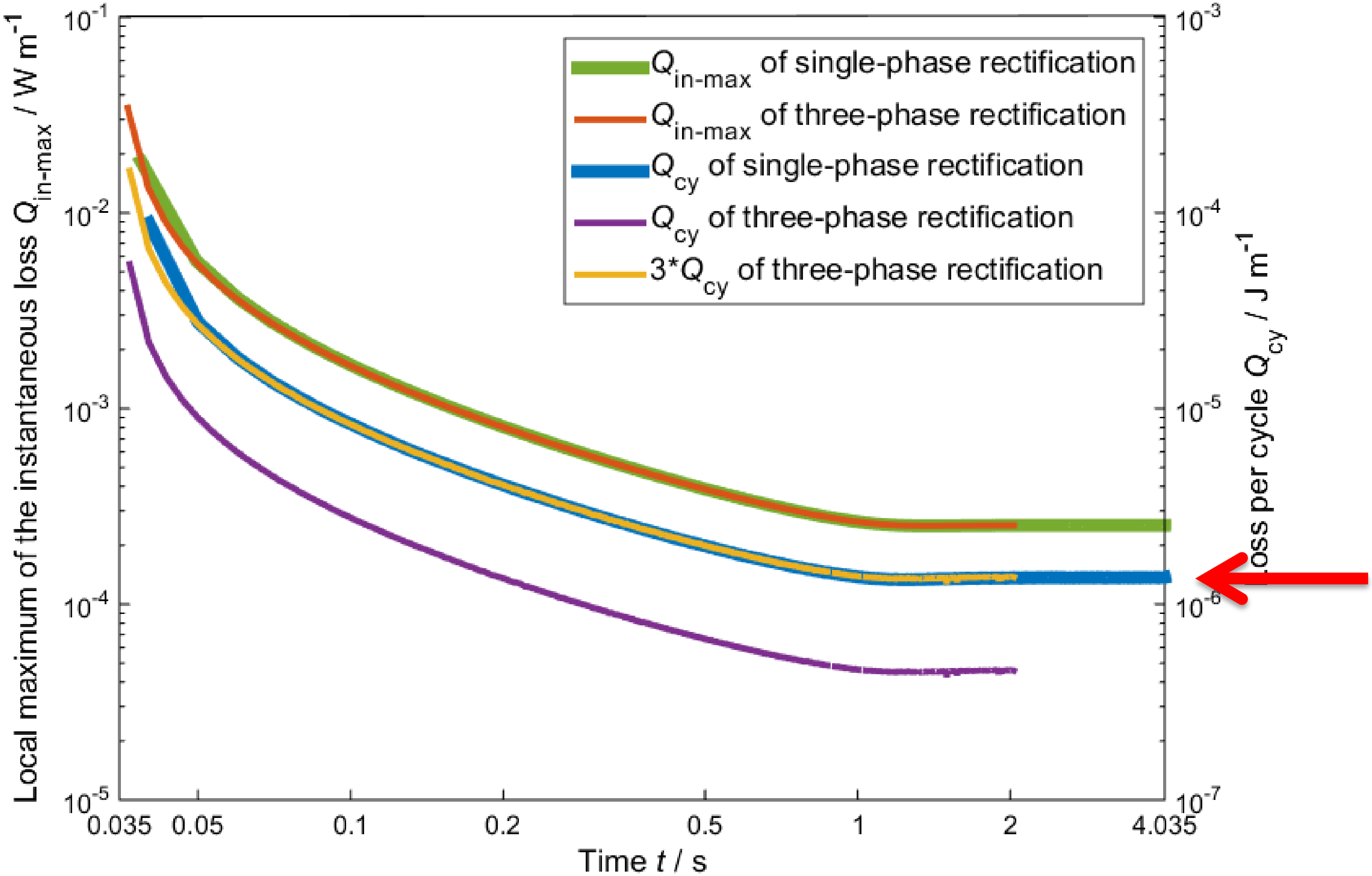


Single-phase, full-wave rectification (10%, 100 Hz)

Amplitude of instantaneous dissipation not influenced by frequency of ripples



Three-phase, full-wave rectification (10%, 300 Hz)



What does this mean for a kA-range DC cable (20 tapes)?

$$P = 1.5 \times 10^{-4}\ \mathrm{W\ m^{-1}} \times 20 = 3 \times 10^{-3}\ \mathrm{W\ m^{-1}}$$

Radiation heat loss is typically 1 W m^{-1}

Loss caused by AC ripples not a concern

Integral equations

Integral equations

- Superconductor modeled as 1-D line
- Finite elements, 100-200 DOFs → Very fast computation
- In the following:
  - Comparison with H-formulation
  - Influence of *n*-value
  - Influence of $J_c(B)$ dependence

$$J(x,t) = \frac{\mu d}{\rho}\left[\int_{-a}^{x} \dot{H}_a(u,t)\,du + \int_{-a}^{a} \dot{J}(u,t)\,\frac{1}{2\pi}\log|x-u|\,du\right] + C(t)$$

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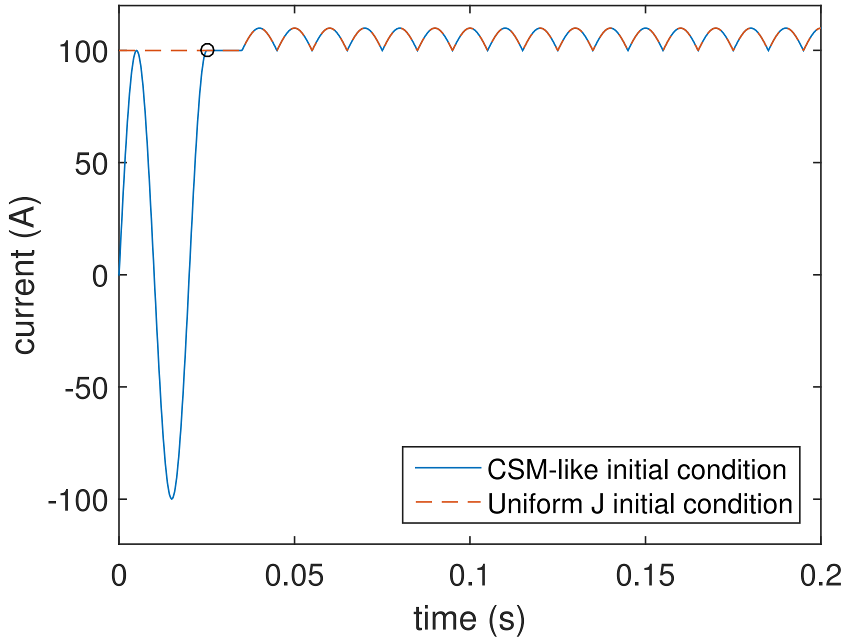
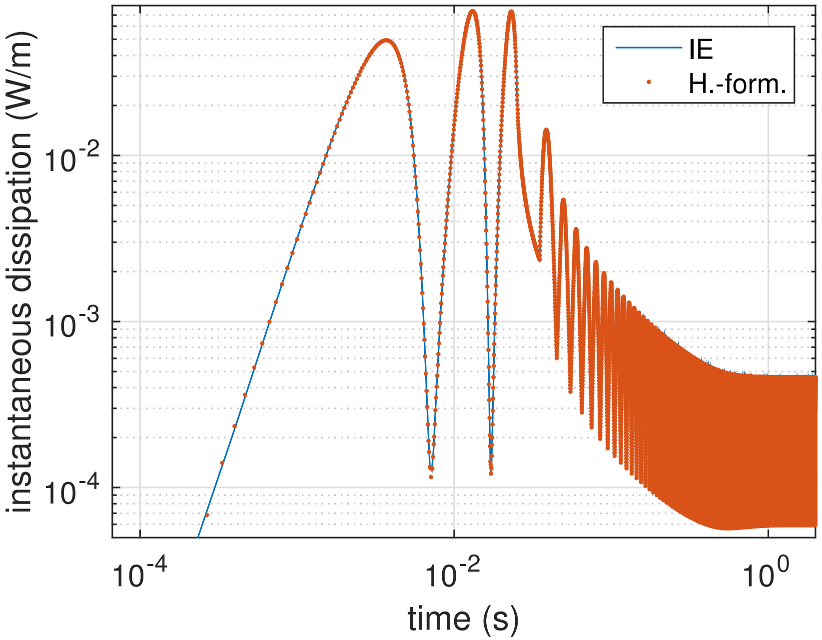
Integral equations for the current density in thin conductors and their solution by the finite-element method

Roberto Brambilla[1], Francesco Grilli[2], Luciano Martini[1] and Frédéric Sirois[2]

IE and H-formulation model agree well.





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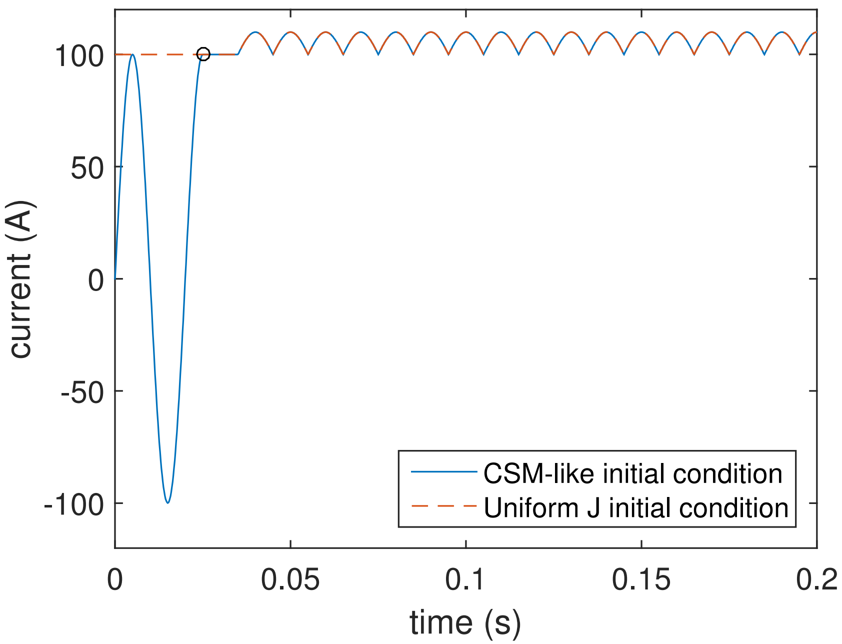
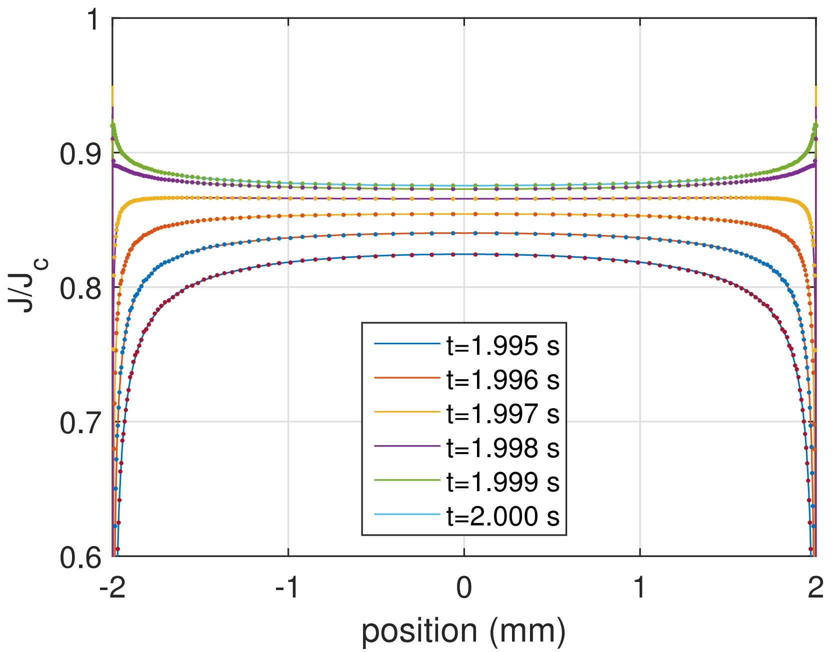
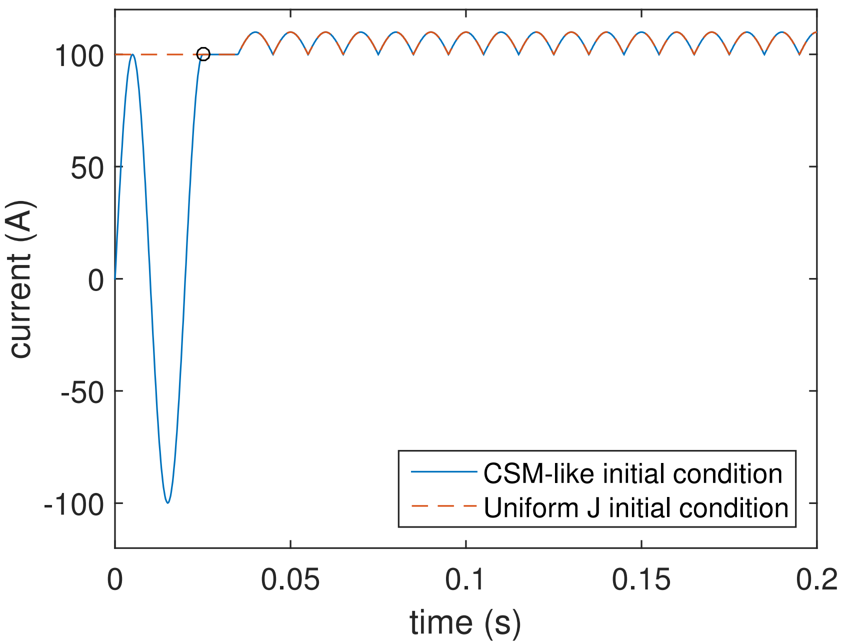
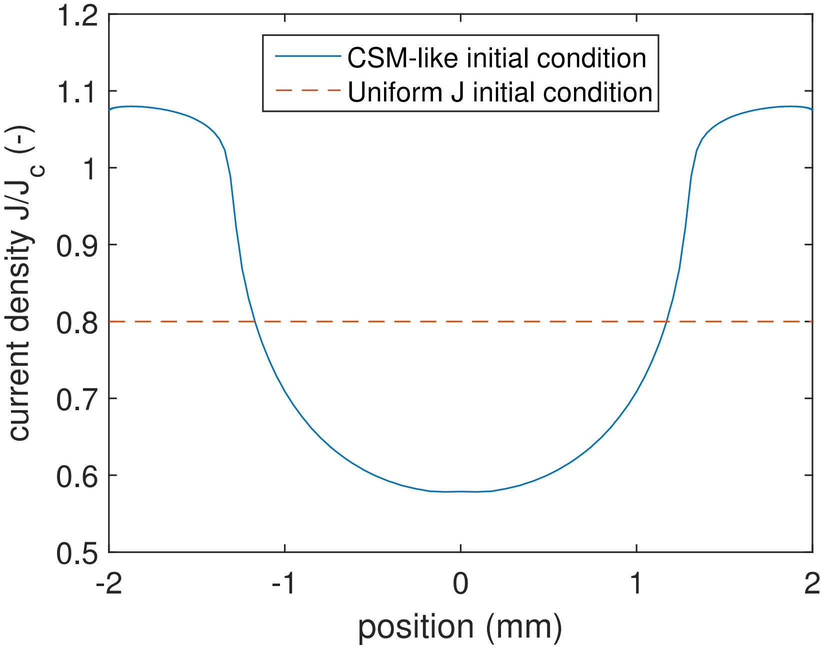


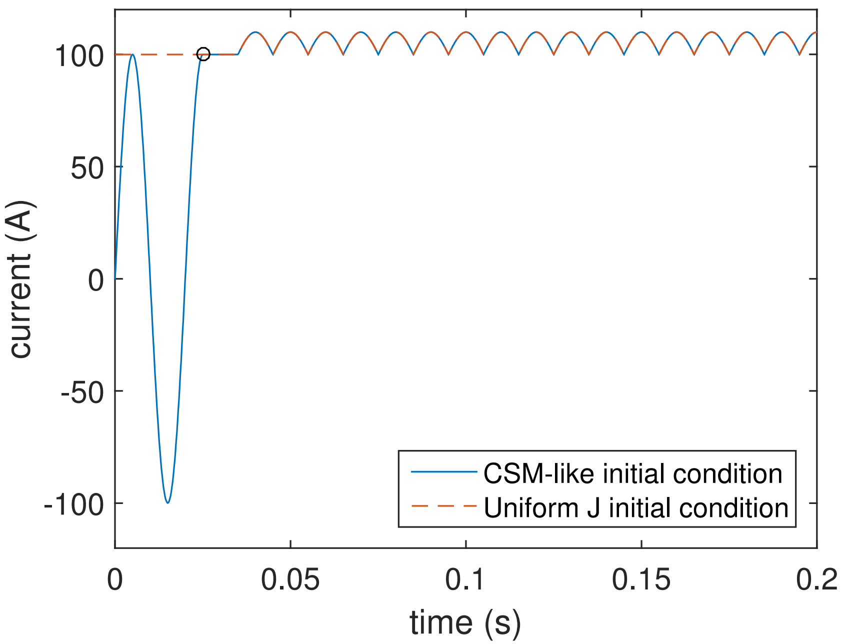


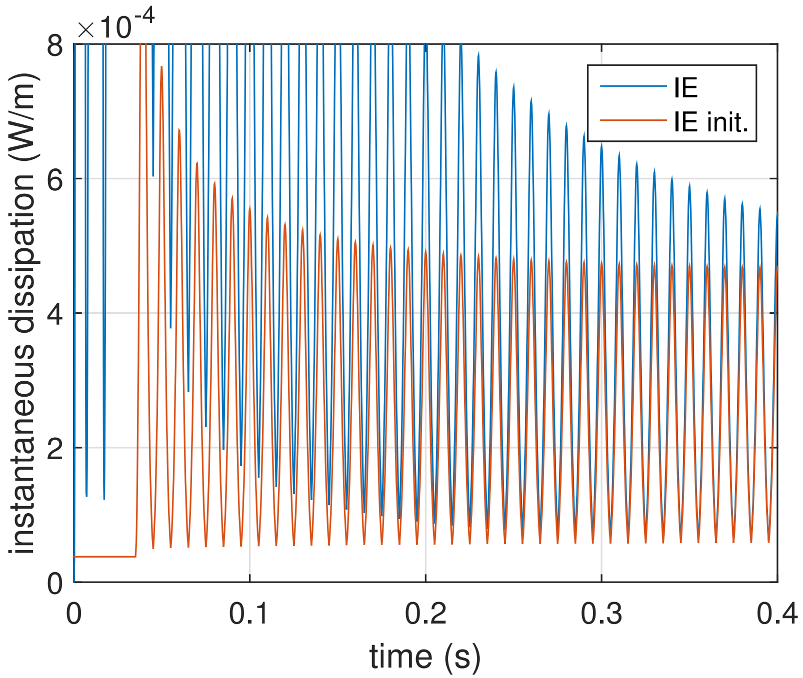
IE allows imposing a *J* distribution as initial condition.



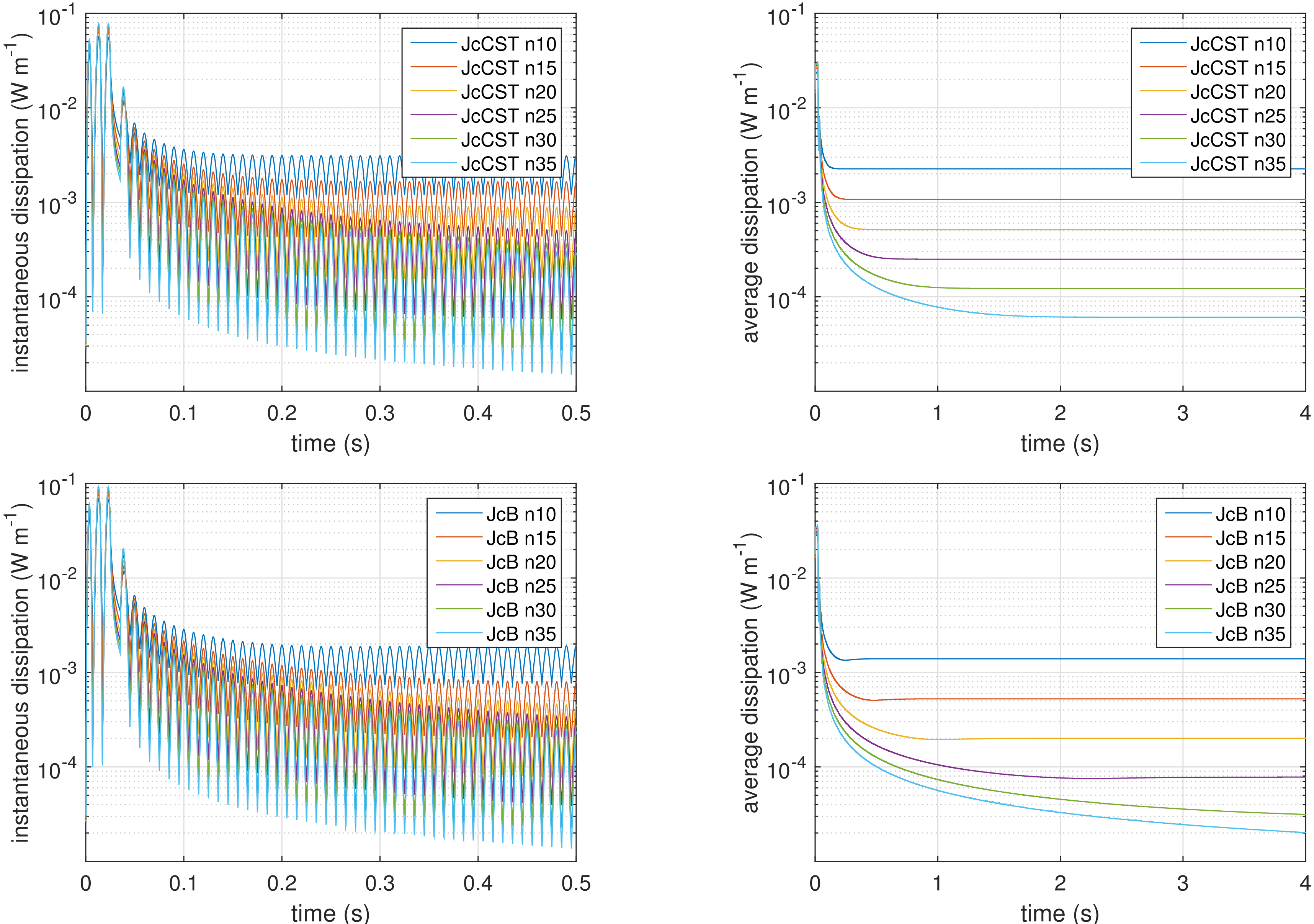


This allows reaching the steady state more quickly.





n-value and $J_c(B)$ greatly influence the results.



This is in contrast with ‘conventional’ AC simulations.

AC power loss (Wm^{-1}) for different current amplitudes (I_a/I_c) and n-values.

I_a/I_c	Norris	n=10	n=25	n=35
0.2	8.47E-05	1.28E-04	1.05E-04	1.00E-04
0.3	4.38E-04	5.69E-04	5.11E-04	4.95E-04
0.4	1.43E-03	1.66E-03	1.59E-03	1.56E-03
0.5	3.63E-03	3.83E-03	3.89E-03	3.75E-03
0.6	7.97E-03	7.66E-03	8.20E-03	8.24E-03
0.7	1.59E-02	1.39E-02	1.57E-02	1.59E-02
0.8	3.00E-02	2.36E-02	2.82E-02	2.90E-02
0.9	5.60E-02	3.81E-02	4.87E-02	5.10E-02
0.99	1.07E-01	5.67E-02	7.84E-02	8.45E-02

Summary

- Current density dynamics investigated in detail
- Due to DC bias, $-J_c$ not reached during cycle → one peak per cycle
- Integral equation method → Very fast, allows more comprehensive studies
- AC ripple loss not a concern in practical cables

But…

A few questions remain:

1. What is the *J* distribution associated to a purely DC current?
2. Is the power-law the correct constitutive equation to model AC ripples?
3. Can these small losses be measured experimentally?

Thank you for listening!