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Modeling of high-temperature superconducting pancake coils using the axisymmetric partial element equivalent circuit method

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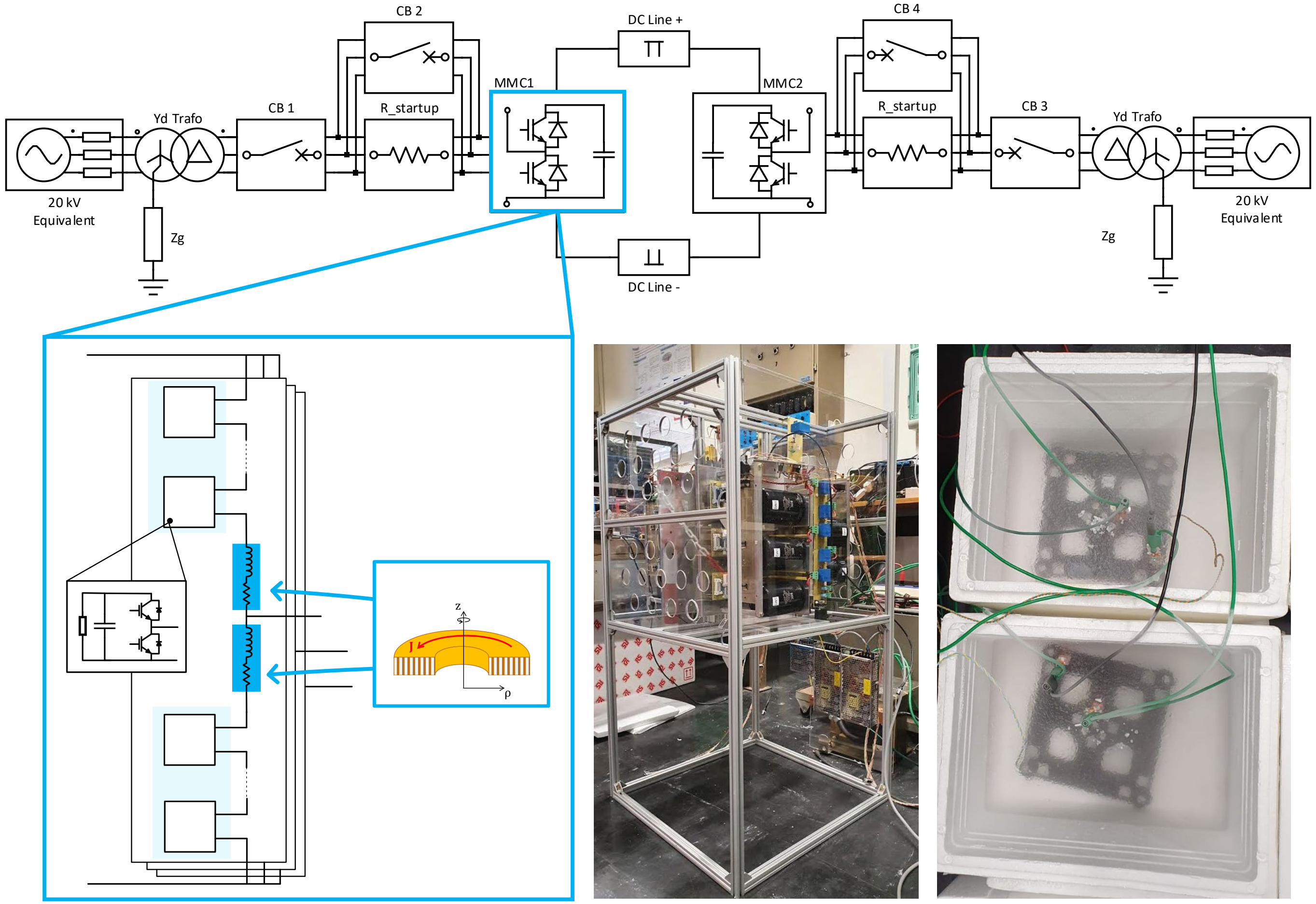
INTRODUCTION

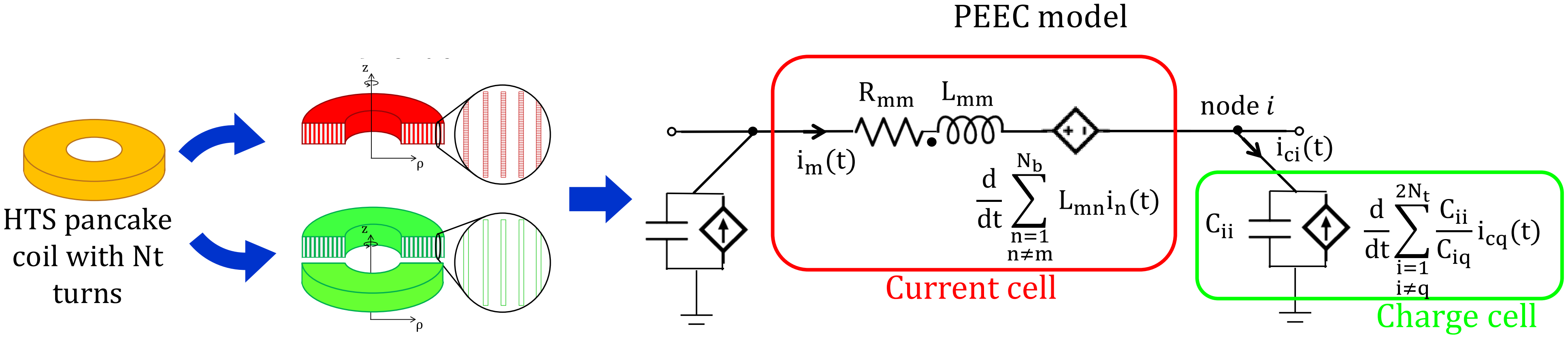
- High-temperature superconducting (HTS) devices are expected to operate in power grids where they may interact with power transformers, transmission lines, circuit breakers, power electronic converters, and electric machines.
- We are currently studying the integration of HTS coils into a modular multilevel converter (MCC) for medium and high-voltage direct-current (M/HVDC) applications.
- For such applications, there is a need to model HTS devices into circuit-based simulations.
- **The partial element equivalent circuit (PEEC) method has great potential to solve electromagnetic problems coupled with electric circuits.**



The Cryo-MMC, an integration between superconducting coils and a power electronic converter.

THE AXYSIMMETRIC PEEC

- The idea behind the PEEC method is to discretize the coil into current cells and charge cells for which the current and charge densities are space-independent, respectively.



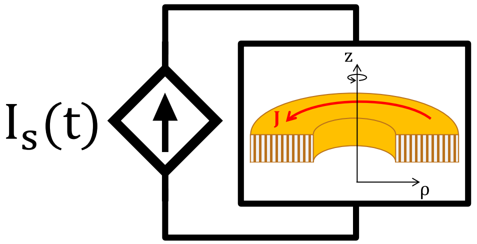
- We use an EJ power law for the superconducting regions. The PEEC model is a non-linear system of equations of the form,

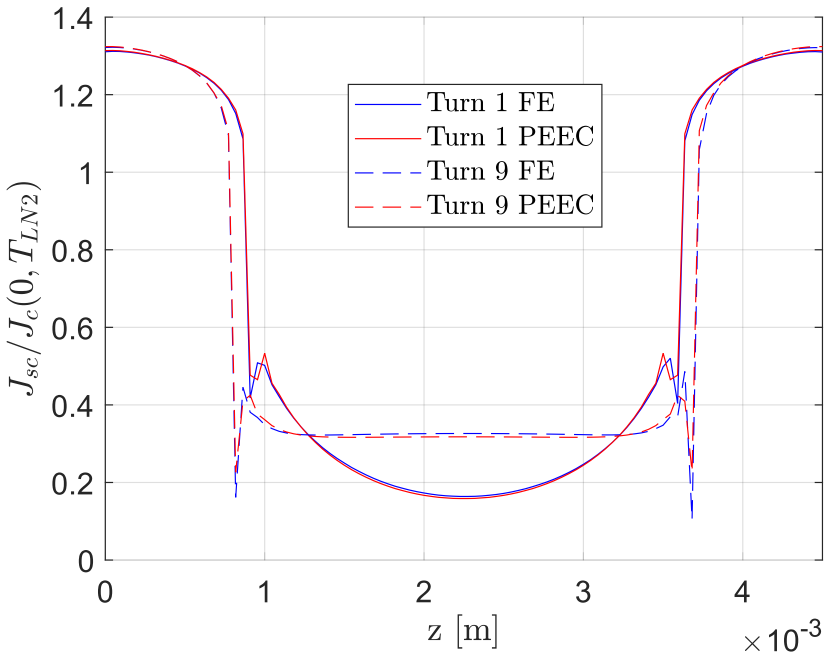
$$\mathbf{M}\frac{d}{dt}\mathbf{x}(t) = \begin{bmatrix} \mathbf{R}(\mathbf{I}(t))_{N_b\times N_b} & \mathbf{k_1}_{N_b\times 2N_t} \\ \mathbf{k_1^T} & \mathbf{k_2}_{2N_t\times 2N_t} \end{bmatrix}\mathbf{x}(t) + \begin{bmatrix} \mathbf{k_v}_{N_b\times 1} & \mathbf{k_i}_{2N_t\times 1} \end{bmatrix}\mathbf{u}(t)$$

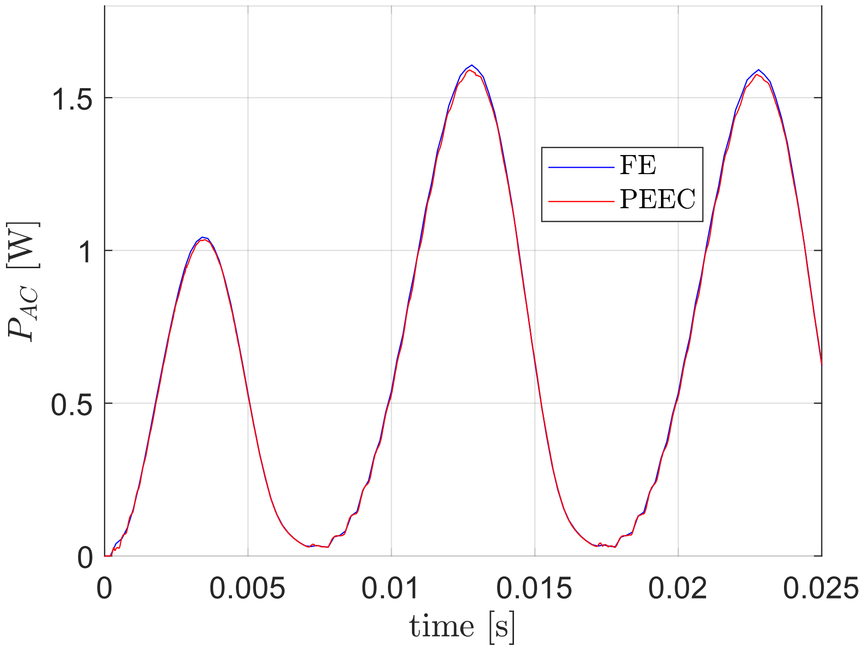
$$\mathbf{M} = \begin{bmatrix} \mathbf{L}_{N_b\times N_b} & \mathbf{0}_{N_b\times 2N_t} \\ \mathbf{0}_{2N_t\times N_b} & \mathbf{C}_{2N_t\times 2N_t} \end{bmatrix} \qquad \mathbf{x}(t) = \begin{bmatrix} \mathbf{I}(t)_{N_b\times 1} \\ \mathbf{V}(t)_{2N_t\times 1} \end{bmatrix} \qquad \mathbf{u}(t) = \begin{bmatrix} V_s(t) \\ I_s(t) \end{bmatrix}$$

SIMULATION OF A 10-TURNS HTS PANCAKES COIL

- **<u>Hyp.</u>:** current excitation
  - **Case 1:** $I_s(t) = 120\sin(2\pi 50t)$
  - The current density is plotted at t = 0.025 s (2-nd AC peak).





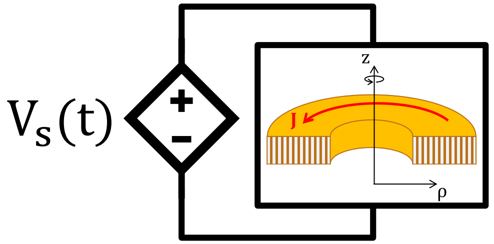


☺ **< 7.3 % relative error**

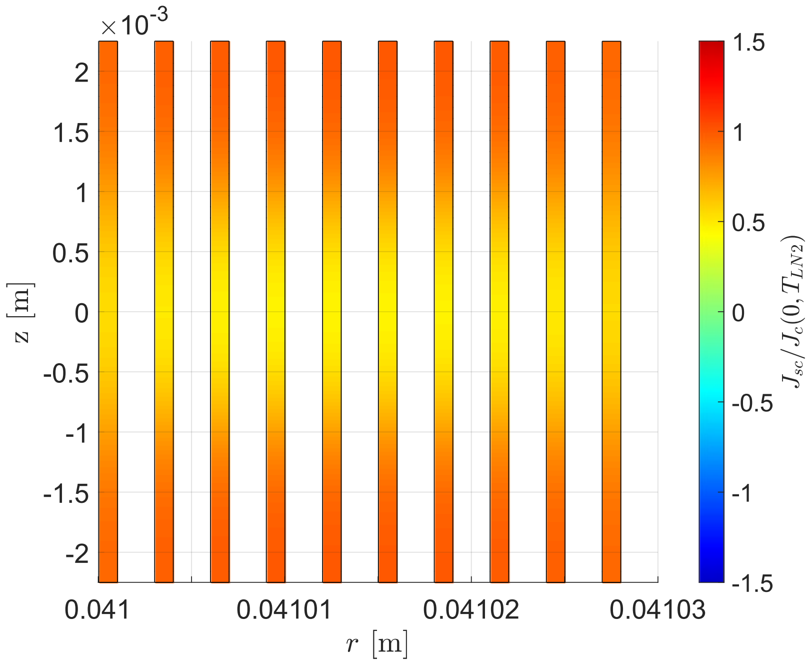
☺ **< 4.7 % relative error**

SIMULATION OF A 10-TURNS HTS PANCAKES COIL

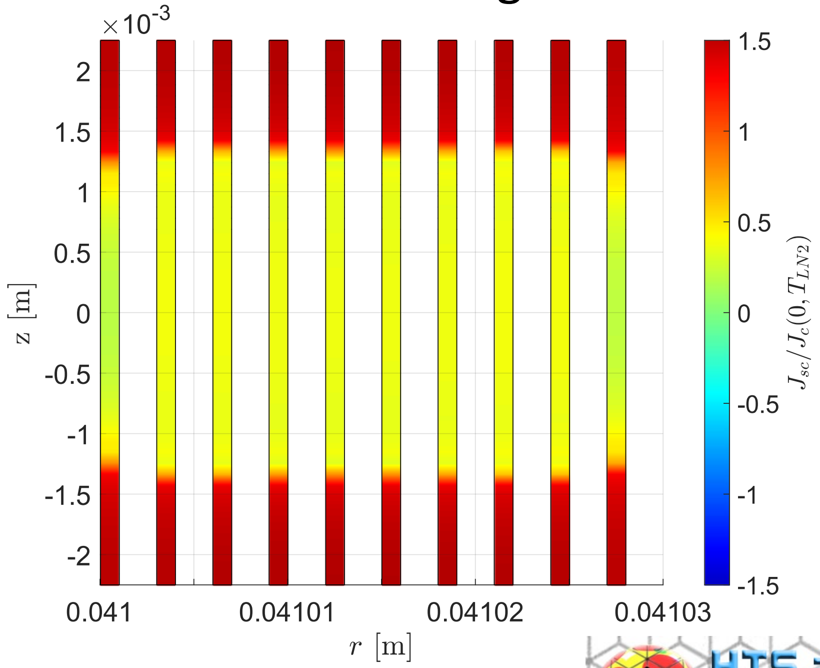
- **Hyp.:** voltage excitation
  - **Case 2:** DC $V_s(t) = 0.142$
  - **Case 3:** AC $V_s(t) = 0.71\cos(2\pi 50t)$
  - The two voltages will generate a current with a peak at 120 A.
  - The current density is plotted at t =0.1843 s (9-th AC peak).



Case 2: DC voltage



Case 3: AC voltage



CONCLUSION

- The PEEC model is an alternative to FE model to simulate HTS coils' behavior in circuit-based simulations.
- The PEEC can treat both voltage and current source excitation problems.
- The average relative error in the current density distribution is smaller than 7.3 % while the relative error in AC losses is smaller than 4.7 %.
- The computation time per AC period ($T_0 = 20$ ms)of the presented simulations are:

Case	Computation time per AC period
1 - H-form. AC current source	154 s
1 - PEEC AC current source	8 s
2 - PEEC DC voltage source	2 s
3 - PEEC AC voltage source	10 s

Intel Core i5-9400H CPU @ 2.50 GHz 32.00 Go RAM, Windows 10 Professional operating system.

- Coming soon: PEEC model of HTS coil integrated into a modular multilevel converter.

Thank you

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