Modeling HTS dynamo-type flux pumps: open-circuit mode and charge of an HTS coil

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Problem Configuration

Problem assumptions

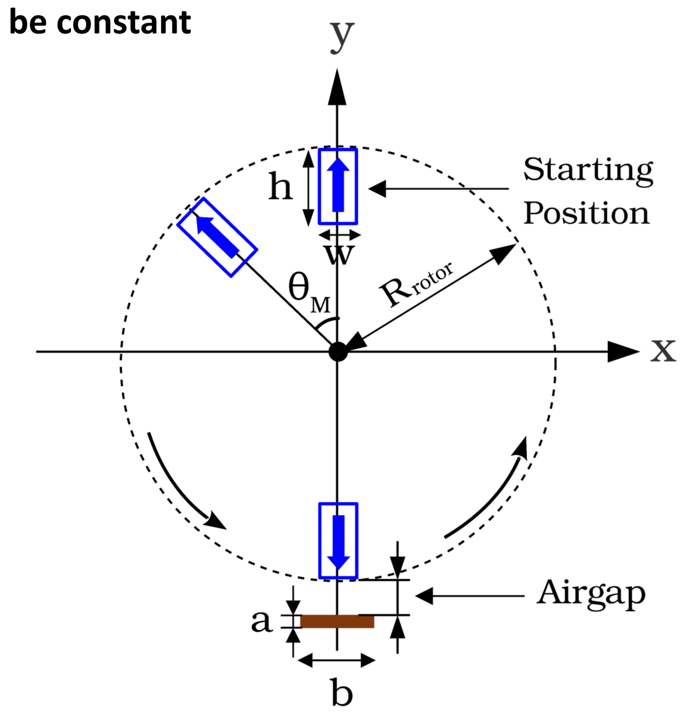
Tape and magnet are defined infinitely long in z direction
J_c and temperature are assumed to be constant
Lumped parameter elements
Ideal HTS coil

Magnet width (w) = 6 mm
Magnet height (h) = 12 mm
Effective depth (l) = 12.7 m
Remanent flux density (B_r) = 1.25 T

Tape width (b) = 12 mm
Tape thickness (a) = 1 µm
Critical current I_c = 283 A
n-value = 20

Coil inductance (L) = 0.24 mH
Joint Resistance (R_c) = 0.88 µΩ

R_{rotor} = 35 mm
Airgap = 1, 2, 3,7 mm
Rotation frequency (f) = 4.25, 25, 50 Hz



Calculation methods

General definitions

$$\mathbf{E}(\mathbf{J}) = E_c\left(\frac{|\mathbf{J}|}{J_c}\right)^n\frac{\mathbf{J}}{|\mathbf{J}|}$$ Isotropic E-J power law

$$\mathbf{E}(\mathbf{J}) = -\frac{\partial\mathbf{A}}{\partial t} - \nabla\varphi$$ Vector potential; Scalar potential

$$\nabla\cdot\mathbf{J} = 0$$ Current conservation equation

$$\nabla\cdot\mathbf{A} = 0$$ Coulomb's gauge

$$V(t) = l\cdot[E_{av}(J) + \partial_t A_{M,av} + \partial_t A_{J,av}]$$

$$V_{cumul}(t) = \int_0^t V(t')\,dt'$$ Cumulative total output voltage

$$V_{DC} = \frac{1}{T}\int_t^{t+T} V(t')\,dt'$$ DC output voltage

MEMEP (Minimum Electromagnetic Entropy Production) method

Calculated at IEE Slovak Academy of Sciences

For solving the problem, the functional F needs to be minimized

Solves current density J, which only exists inside the HTS tape

Fast method: mesh is only needed inside the HTS tape

Assumption of HTS tape, coil and series resistance far away from each other:

$$F = l\int_{S_S} d^2\mathbf{r}_2\left[\frac{1}{2}\Delta J\frac{\Delta A_J}{\Delta t} + \Delta J\frac{\Delta A_M}{\Delta t} + U(J)\right] + \frac{1}{2}L\frac{(\Delta I)^2}{\Delta t} + \frac{1}{2}RI^2$$

Due to current; Due to magnet; Dissipation factor; Coil inductance; Joint Resistance

Superconducting tape; Ideal coil; Series resistance

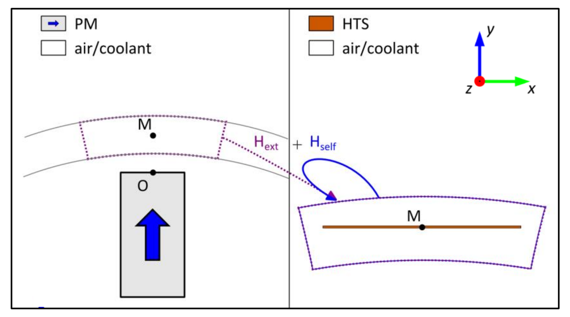
Segregated *H*-formulation method

Calculated at University of Cambridge

H-formulation: Independent variables are the components of the magnetic field strength *H*

Magnetostatic magnet model +
Time-dependent *H*-formulation HTS tape model

Unidirectional coupling between magnet and HTS models using electromagnetic boundary conditions and a rotation operator



Magnetostatic magnet model

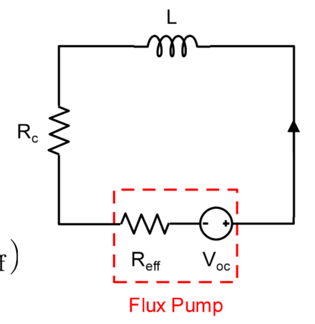
Time-dependent *H*-formulation HTS wire model

Analytical method

Flux pump can be modeled as a DC voltage source in series with an effective resistance

The coil can be treated as an independent LR circuit charged by the voltage source

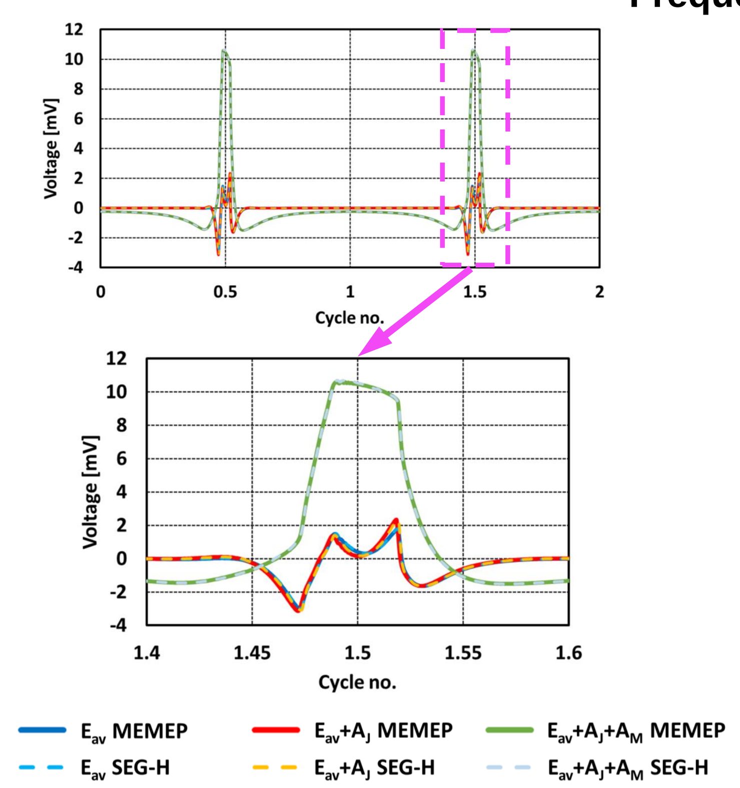
$$i(t) = I_{sat}\left[1 - e^{-t/\tau}\right] \qquad I_{sat} = V_{oc}/(R_c + R_{eff}) \qquad \tau = L/(R_c + R_{eff})$$



Dynamic Charging of HTS Dynamo

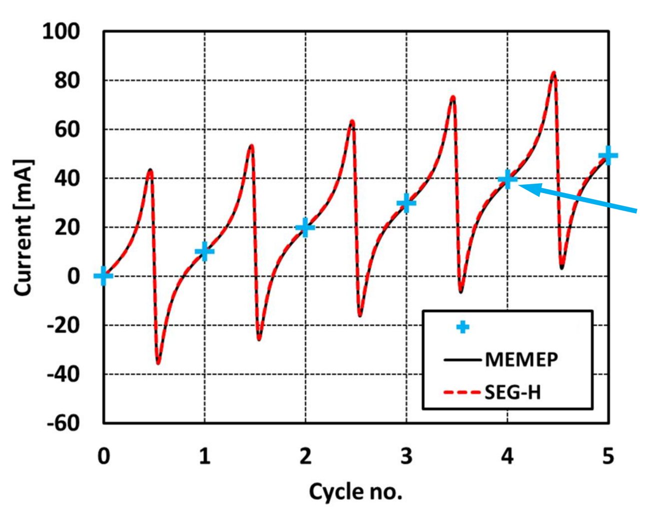
Instantaneous voltage

Airgap = 3.7 mm
Frequency = 25 Hz



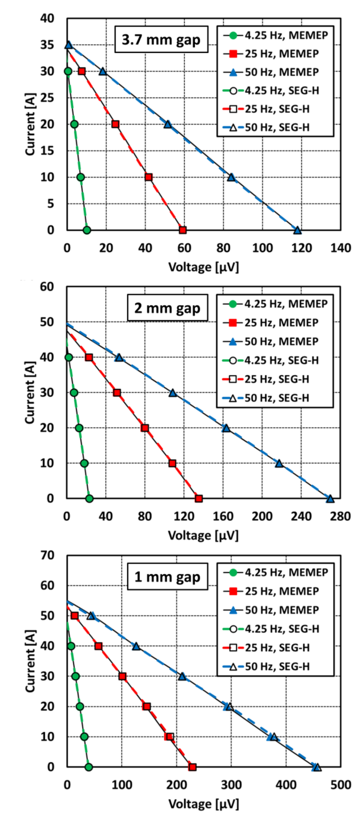
Instantaneous current

Ripples resemble the ripples of the cumulative total output voltage V_{cumul}



Extracted data points at the end of each cycle for plotting the coil charging current curves

I-V curve of the flux pump



3.7 mm

2 mm

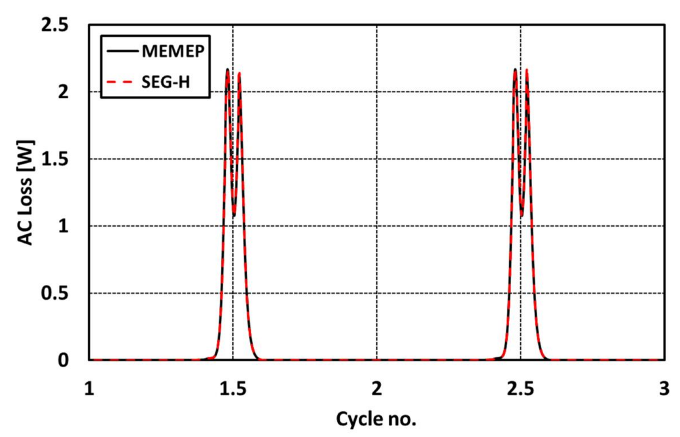
1 mm

Slope of I-V curve shows the effective resistance R_{eff}

R_{eff} is constant for each frequency in superconducting regime

R_{eff} increases directly proportional to frequency

Ripple AC loss

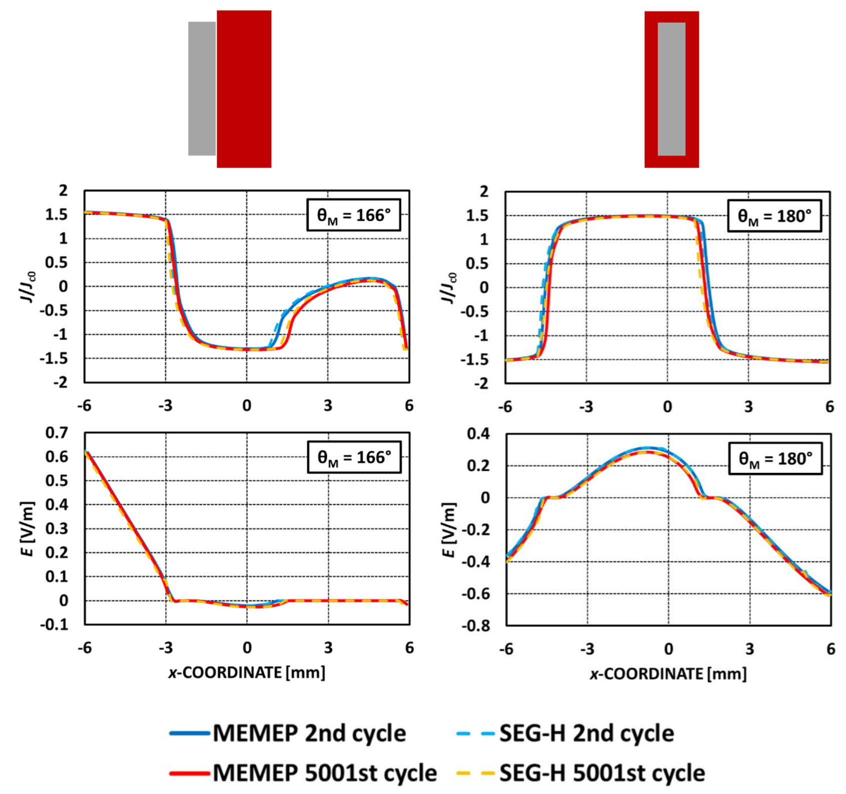


Average AC loss cycle no. 1-5 ≈ 135.6 mW
Average AC loss cycle no. 5001 ≈ 135.8 mW

Calculated ripple AC loss is almost constant for a given frequency

Agrees with measurements presented in *Hamilton et al. IEEE Trans. Appl. Supercond. 2020*

Current density and electric field distributions across the tape width



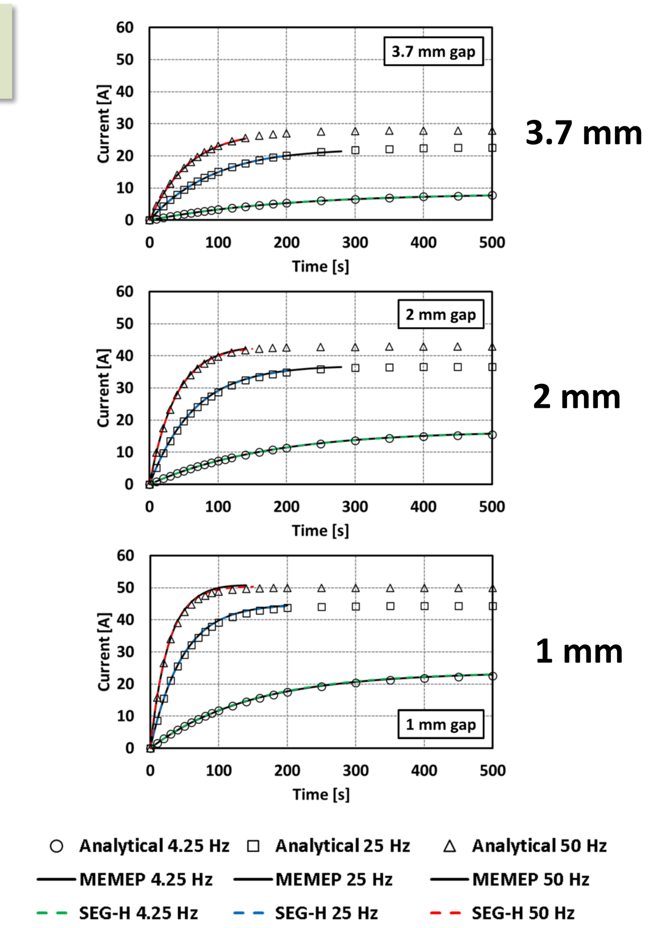
Current density and electric field distributions are mostly similar

AC loss remains mostly the same!

Coil charging behavior

For a given frequency, coil current saturates faster and at a higher value as the airgap decreases

For a given airgap, the coil current saturates faster with a higher value of I_{sat} as the frequency increases



Summary

- Two novel numerical methods for modeling the charging process of a coil by an HTS dynamo were presented
- Nine different cases including various airgaps and frequencies over thousands of cycles were compared
- Current charging curve contains ripples within each cycle, which cannot be captured via the analytical method
- Current ripples cause ripple AC loss in the HTS dynamo
- The ripple AC loss is almost constant during the whole charging process
- The two numerical methods and the analytical method showed excellent quantitative and qualitative agreement
- The numerical modeling frameworks presented here have the potential to be coupled with other multiphysics analyses as well as with a model of an HTS coil

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