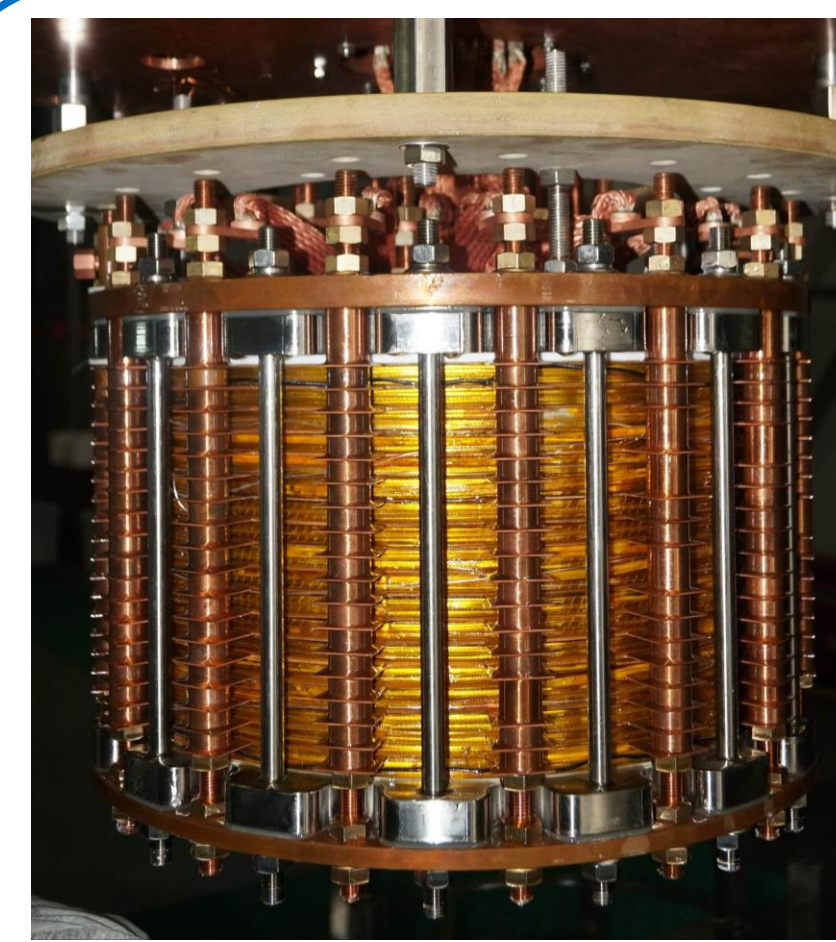


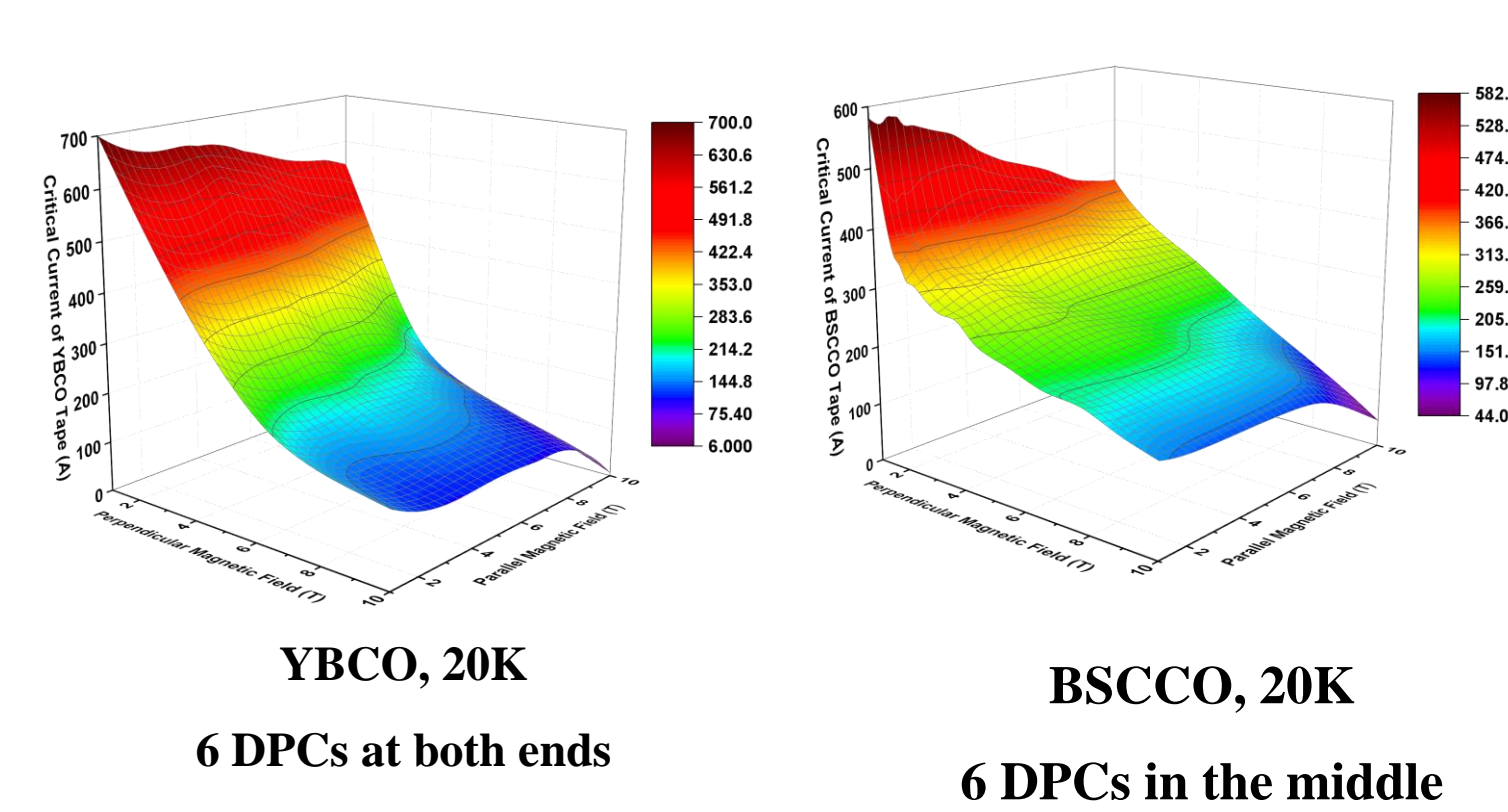
Abstract—High temperature superconducting magnetic energy storage (HTS SMES) is expected to be utilized in power grid for dynamic power compensation with low losses and high energy storage density during steady-state operation. Under transient operating conditions, especially in the case of fast power switching process, AC losses of the SMES will occur and lead to changes in equivalent resistance, total inductance, and critical current distribution throughout the magnet. In this paper, the dynamic performance of a 150kJ SMES has been analyzed based on a co-simulation model of MATLAB and COMSOL. The SMES element is a customized module by self-code S-Function in MATLAB. A magneto-thermal finite element model based on the PDE and Heat Transfer Modules of COMSOL is built in the module. Thus, the operating states of the SMES such as the distribution of the AC losses, magnetic flux density, critical current, maximum temperature increment, and the fluctuation of inductance and equivalent resistance have been comprehensively monitored in the power switching process.

1. Features of the 150kJ SMES



150kJ HTS SMES

Critical current performance of the two tapes

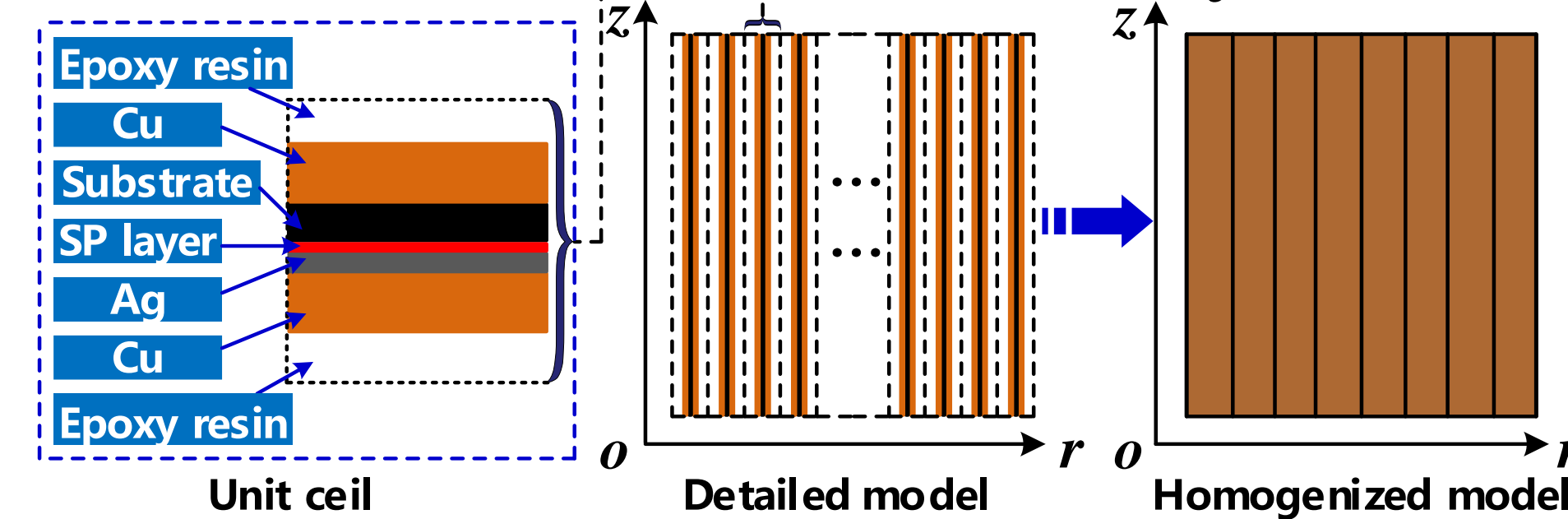


Structure parameter

Item	Value
Magnet Type	Solenoid
Number of DPCs (YBCO/BSCCO)	18 (6/12)
Inner radius (YBCO/BSCCO)	132 mm/120 mm
Outer radius (YBCO/BSCCO)	198 mm/198 mm
Height of DPC (YBCO/BSCCO)	11.5 mm/12 mm
Total length of tapes(YBCO/BSCCO)	4.8 km/2.4 km
Static inductance	10 H

2. Homogenized Model in Magneto-Thermal Analysis

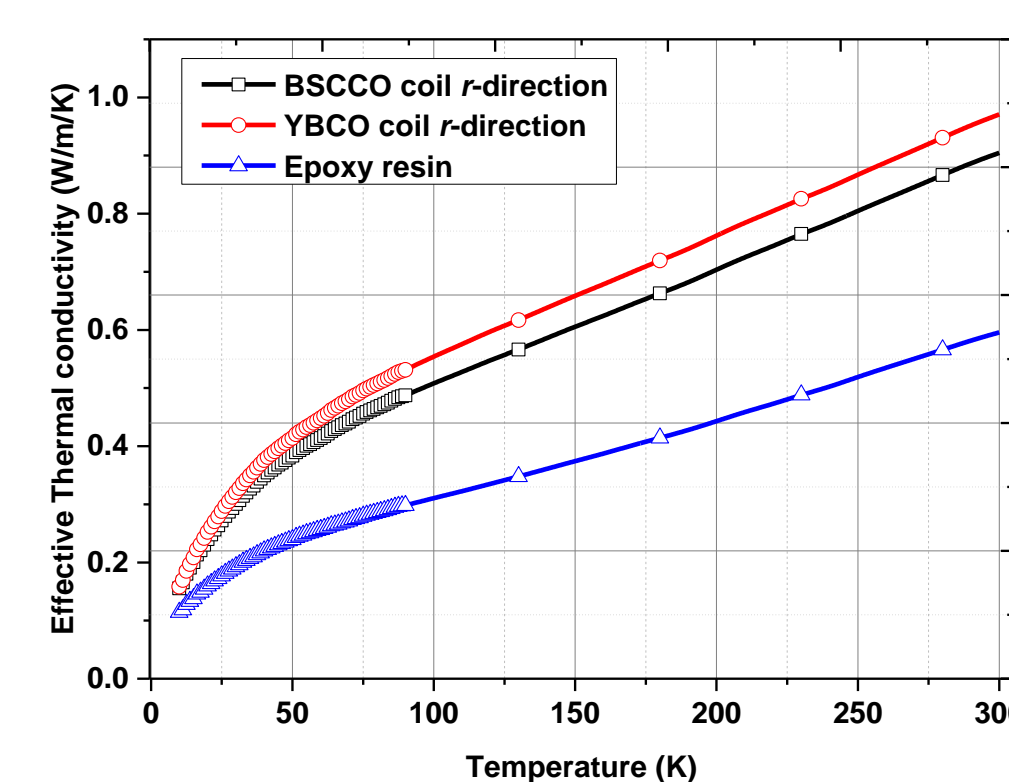
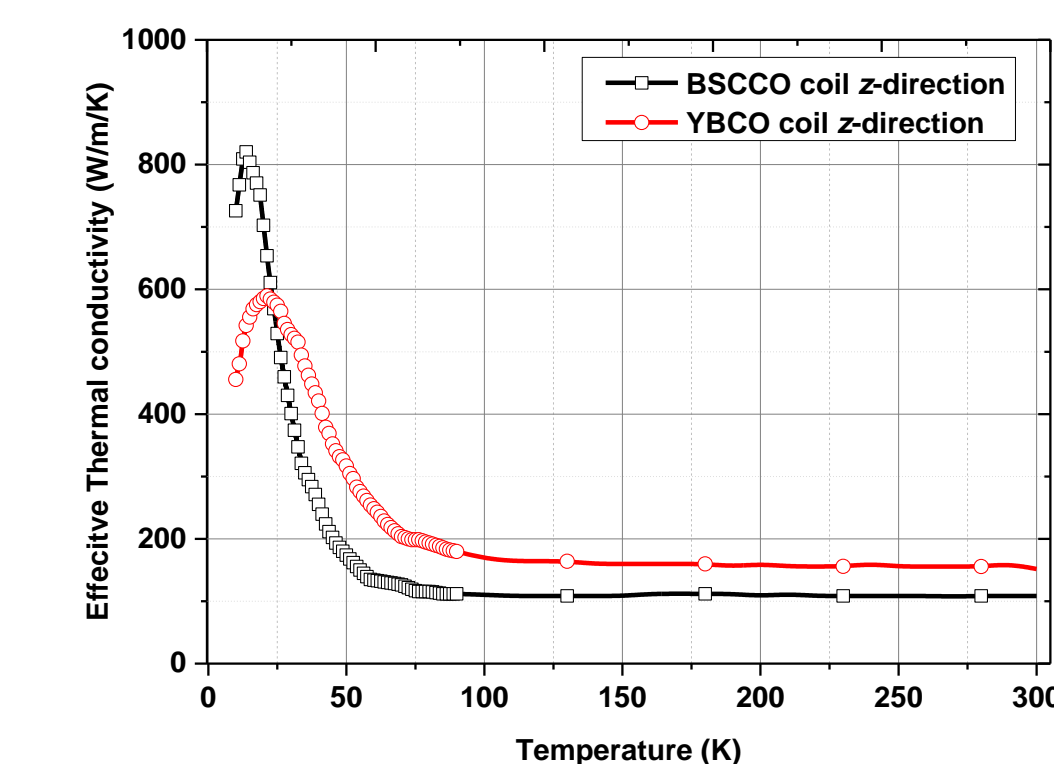
Homogenized model is applied to reduce the calculation DOFs. A *PDE Module* and a *Heat Transfer Module* are adopted to achieve magneto-thermal analysis. The AC losses calculated in *PDE Module* were introduced as heat source in *Heat Transfer Module*.



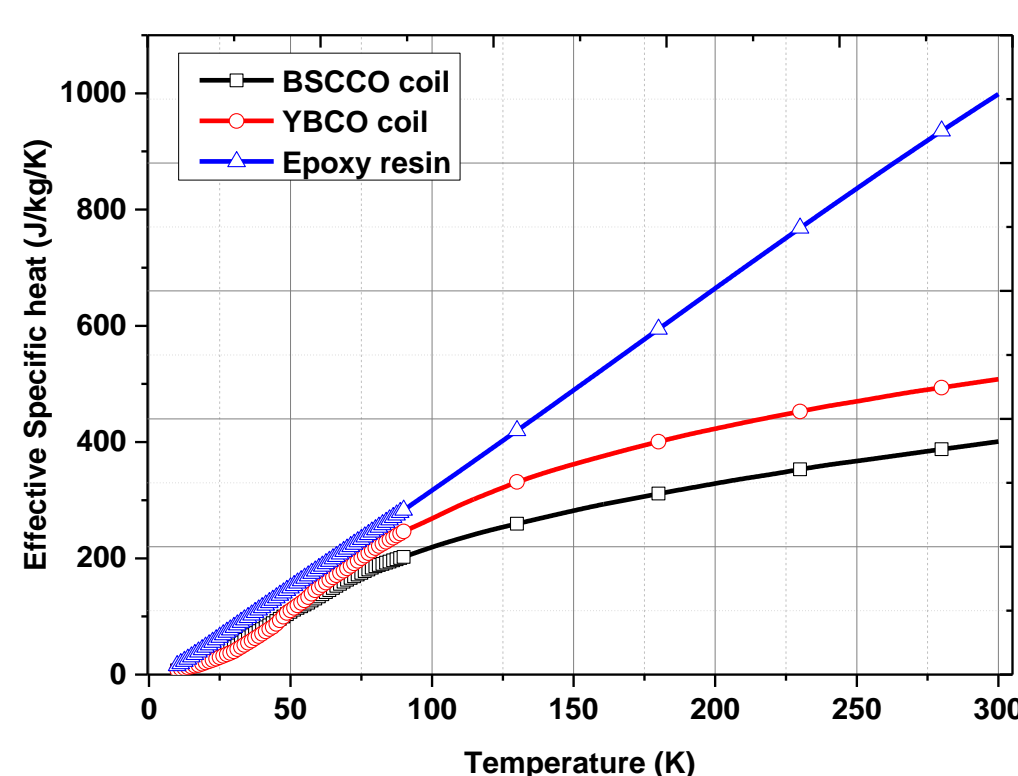
According to Faraday's law, where $\vec{J} = \nabla \times \vec{H}$,

$$\frac{\partial(\mu_r \mu_0 \vec{H})}{\partial t} + \rho_{sc} \nabla \times \vec{J} = 0, \quad \rho_{sc} = \frac{E_0}{J_c(B, T)} \left| \frac{J}{J_c(B, T)} \right|^{n-1}$$

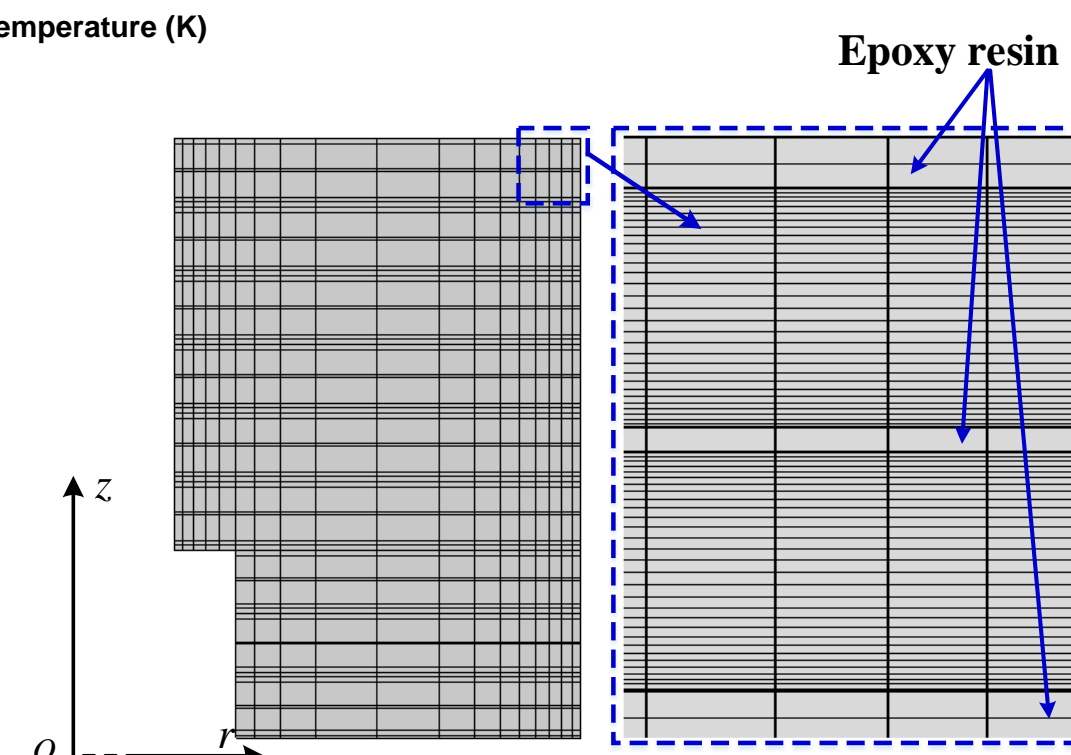
$$k = \sum_i f_i k_i \text{ (z-direction) or } \frac{1}{k} = \sum_i f_i / k_i \text{ (r-direction)}, \text{ and } C_{eff} = \frac{\Delta Q}{\rho_{eff} V \Delta T}$$



The thermal conductivity of the HTS tape in r-direction is much smaller than that in z-direction. The epoxy resin has the worst thermal conductivity.

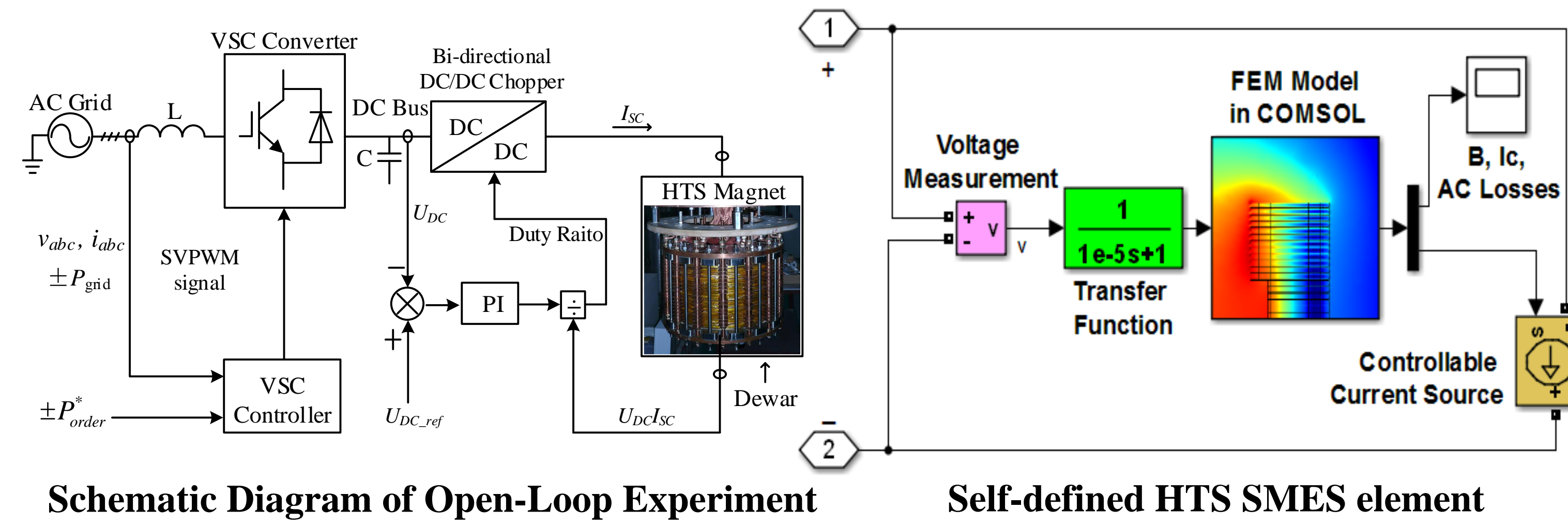


Effective specific heat of the HTS coils were almost the same near 20K.



The temperature of outer boundary of the epoxy resin on each DPC is set to 20K. Eddy current losses of the cooling structure has not be concerned.

3. Field-Circuit coupled Analysis

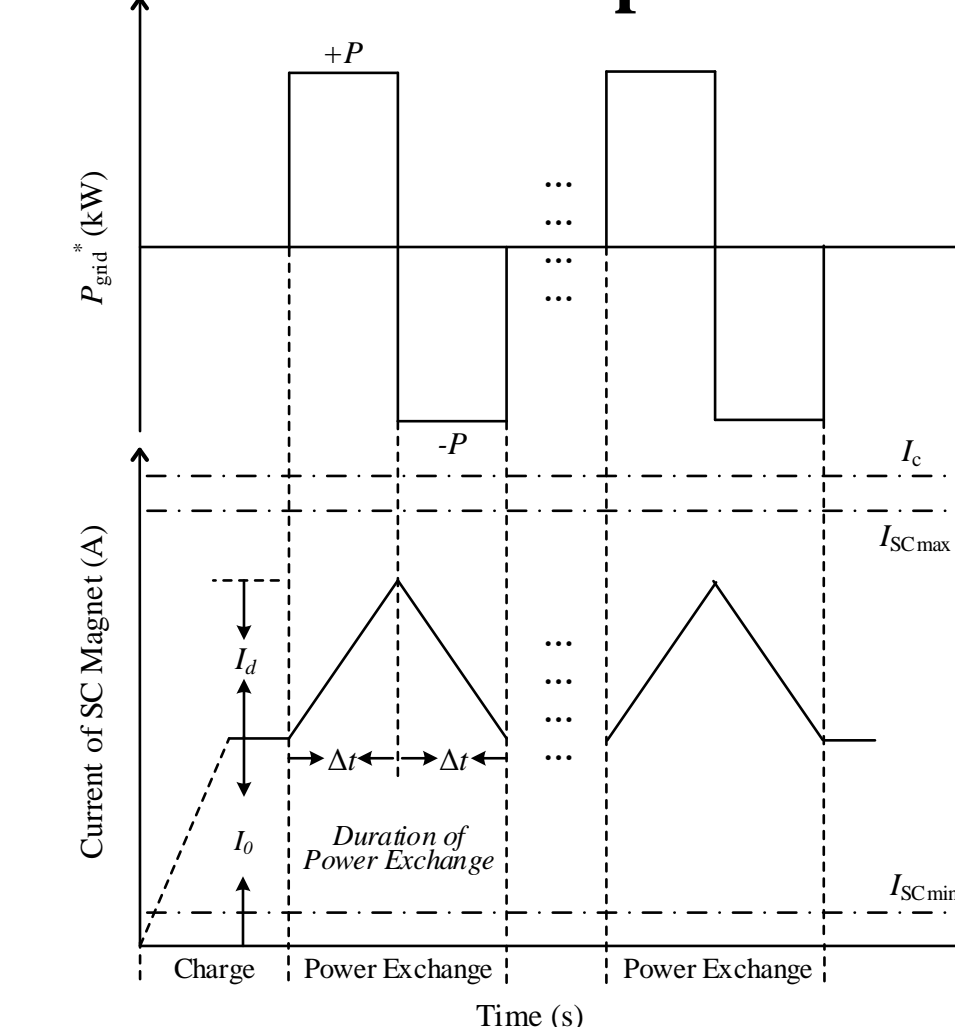


Transient equivalent $L(t)$ and $R(t)$:
$$L(t) = \frac{2 \times \int B(t) \times H(t) dV}{I(t)^2}, \quad R(t) = \frac{2 \times \int E(t) \times J(t) dV}{I(t)^2}$$

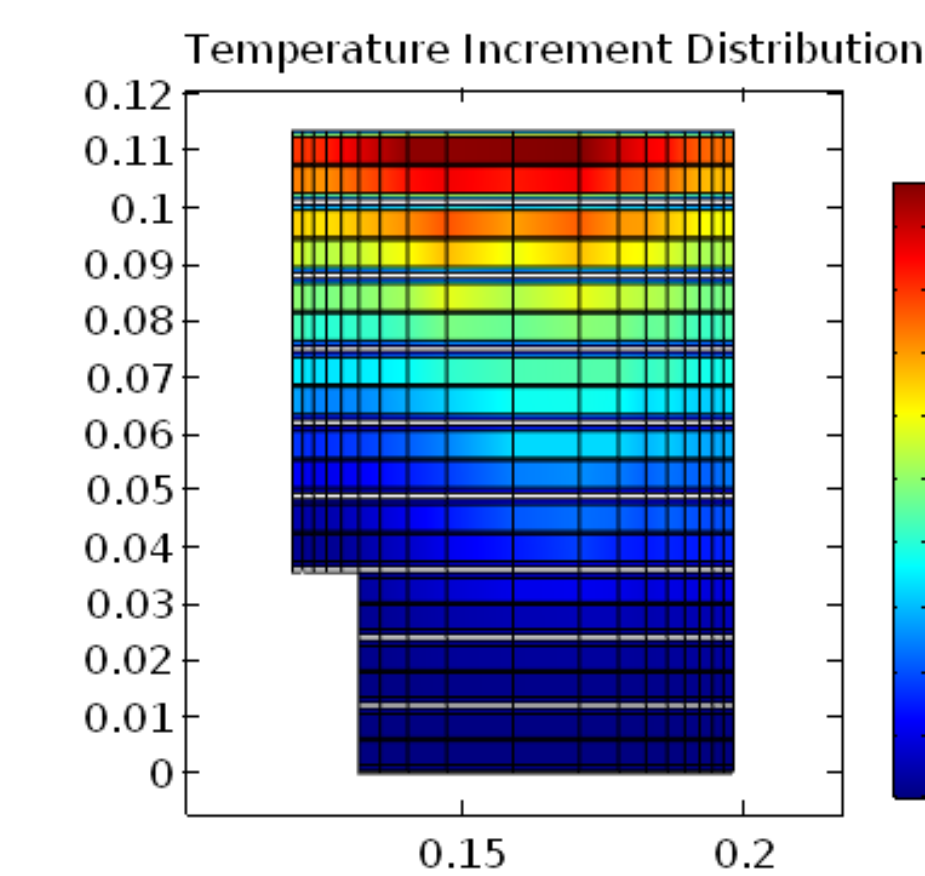
For the SMES controlled by VSC the power balance is described: $d \cdot U_{dc} \cdot i(t) + i(t)^2 R(t) = P_{ref}$

The initial current of the element can described as:
$$i(t) = I_0 e^{-\frac{R(t)}{L(t)} t} + \frac{u(t)}{R(t)} \times \left(1 - e^{-\frac{R(t)}{L(t)} t} \right)$$

Value of the current step is related to the previous one:
$$i(t) = \frac{u(t)}{R(t)} + \left(i(t - \Delta t) - \frac{u(t)}{R(t)} \right) \times e^{-\frac{R(t)}{L(t)} t}$$



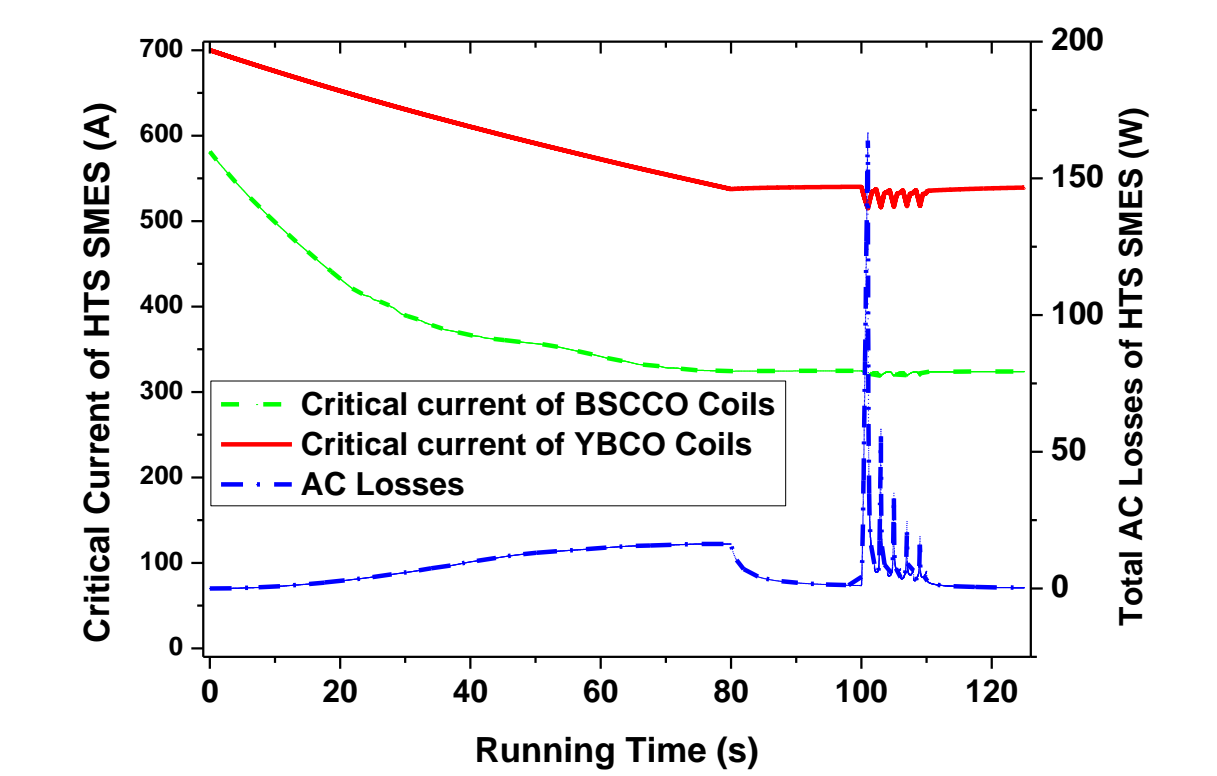
grid power order and SC magnet current



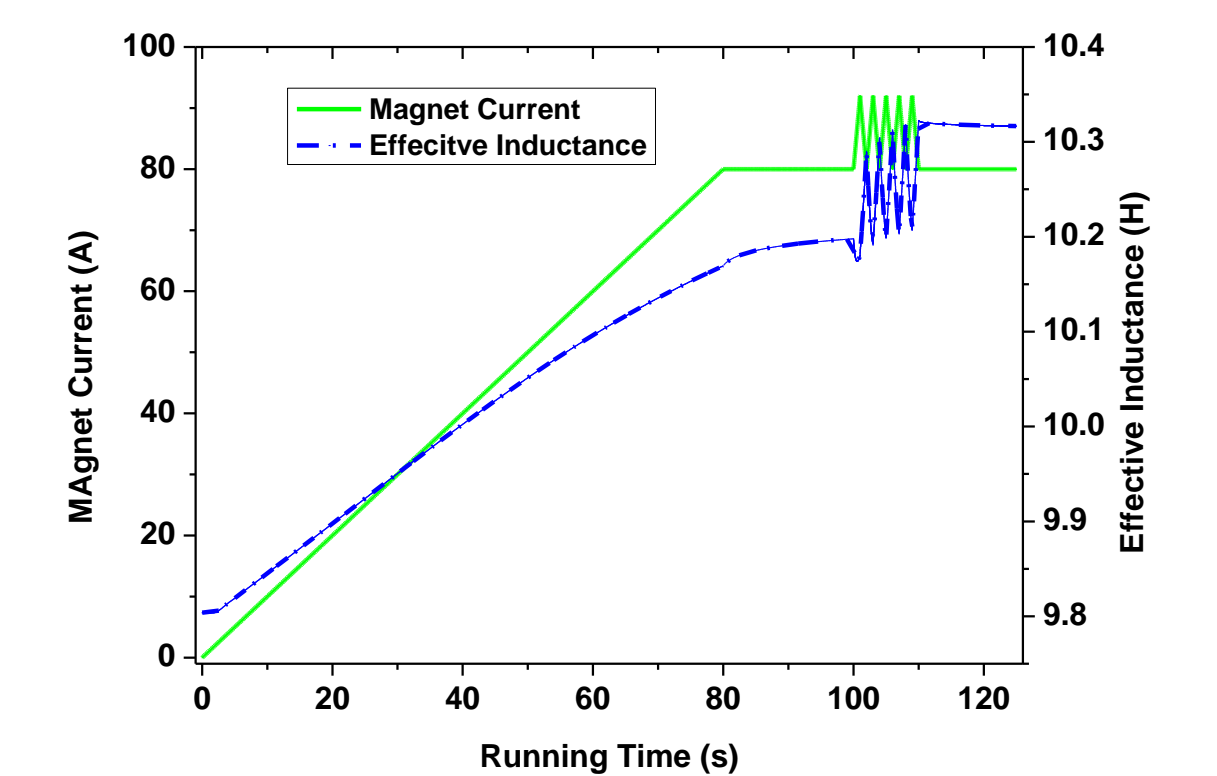
Temperature increment distribution at 102s

The end coils of the SMES magnet suffered a higher AC Losses, the temperature rise is concentration.

The HTS SMES element can be identified by a controllable current source. The output is a function about the voltage drop across the self defined block.



The transient effective inductance of the HTS SMES changed with the change of current.



The more significant the current changes, the greater the losses. The actual operating current fluctuation is far greater than the ideal condition, AC losses will be more obvious.

4. Conclusion

The coupling simulation and modeling method for HTS SMES used in power grid has been introduced detailed in this paper. A homogeneous thermoelectric coupling model based on the PDE and heat transfer modules is proposed. The state of the HTS magnet could be monitored comprehensively during the whole power switch process. Under the ideal condition, the AC losses and the temperature rise are not seem apparent, more details concerned the actual current fluctuation will be illustrated through in the manuscript. The effective resistance and the temperature increment will not be neglected.