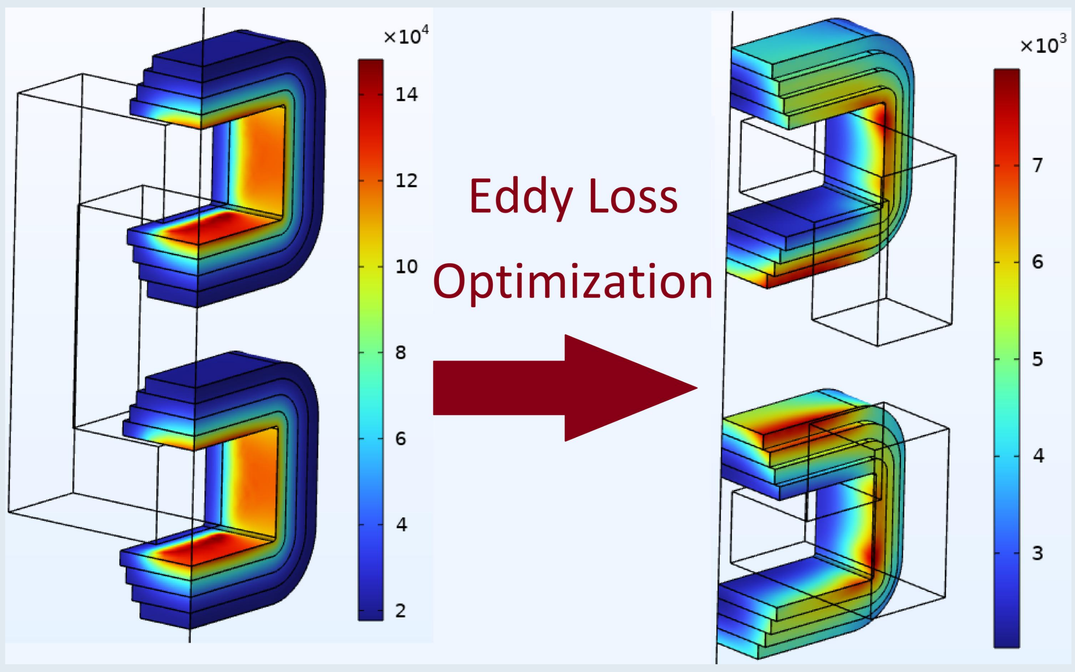
The Complex Permeability Model for Eddy Loss Calculation and Optimization of Adjustable Reactor

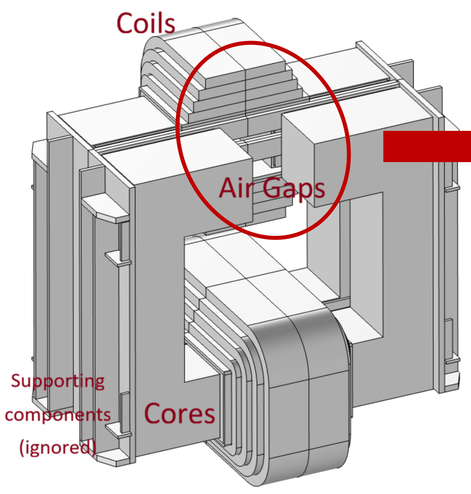
Abstract: The traditional adjustable insulation test reactor has a problem where the leakage magnetic field of the core intersect with the coils within large areas, which leads to huge coil eddy loss. Based on the **complex power density** theory of homogenized multi-turn conductor, this study appropriately adjusted the **High-frequency effective loss** calculation function of **COMSOL 6.4** and applied it to the calculation of coil eddy loss under the intersection of a strong external magnetic field. The main loss of the adjustable reactor were found and optimized. The **eddy loss** of the reactor coil was **reduced by 72%**, and the global loss was reduced by 40%.

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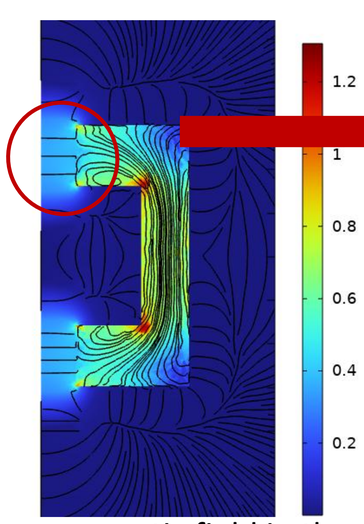
Introduction

The adjustable high-voltage test reactor has a large air gap in the core at small inductance, causing leakage magnetic field in the air gap to widely interact with the coil. This results in a large amount of coil eddy loss P_{eddy}. The losses of the reactor also include the coil conduction loss P_{cond} and the core loss P_{core}. It is necessary to first identify the main cause of the loss and optimize it accordingly in order to reduce the tempatrure rise during tests.



Traditional design of adjustable reactor

Leakage magnetic field in core air gap, interacts with coils,



Leakage magnetic field in the core gap

which leads to eddy loss in coils.

Theoretical derivation

Based on the complex power density theory, combining the complex Poynting vector in eq.(1) with the complex permeability μ in eq.(2), the expression for the reactor coil loss in strong external magnetic field is derived as in eq.(3), which can be written as the sum of two linearly superimposable parts: P_{eddy} and P_{cond}. On this basis, the imaginary part of μ , that is μ'' in eq.(4), can be derived by the average power density of the conductors and insulating medium of coils in eq.(3). The μ'' is used to modeling the homogenized coils in FEM, and can be calculated based on the geometric size, turns of the coil.

$$\nabla\cdot\tilde{p}=\frac{1}{2}\nabla\cdot(\mathbf{E}\times\mathbf{H}^*)=\frac{1}{2}\left(\mathbf{H}^*\cdot(\nabla\times\mathbf{E})-\mathbf{E}\cdot(\nabla\times\mathbf{H}^*)\right) \quad (1)$$

$$\mu=\mu'-j\mu'' \quad (2)$$

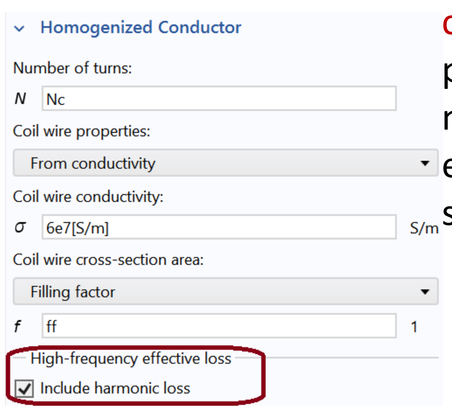
$$\mathbf{S}=j\frac{1}{2}\omega\mu_0|\mathbf{H}|^2a+\frac{1}{8}\pi\sigma\omega^2\mu_0^2|\mathbf{H}|^2r^4+\frac{1}{2}\frac{I_{cond}^2}{\sigma a}=j\mathbf{Q}+\mathbf{P}_{eddy}+\mathbf{P}_{cond} \quad (3)$$

Compare expressions

$$\mu''=\frac{N\pi\sigma\omega\mu_0^2r^4}{4S} \quad (4)$$

Model setup

By using COMSOL 6.4, check the "Include harmonic loss" option in the "homogenized conductor coil" nodes, and edit the complex permeability values to the results of eq.(5) to meet the requirements for calculating the coil eddy loss under the low-frequency external strong magnetic field.

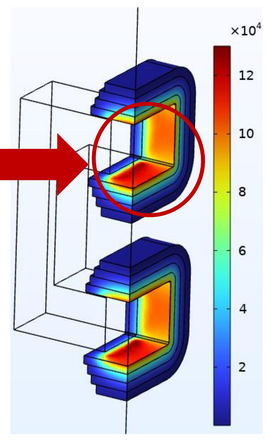


Name	Expression	Unit	Description
mf.coil1.hl_m_eff	0.9999992 - 0.0100825*i	1	Effective permeability
mf.coil1.hl_s_eff	6e7	S/m	Effective conductivity

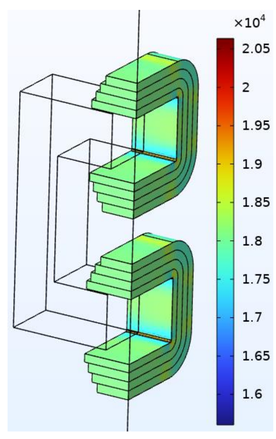
Edited complex permeability & conductivity

Calculation results

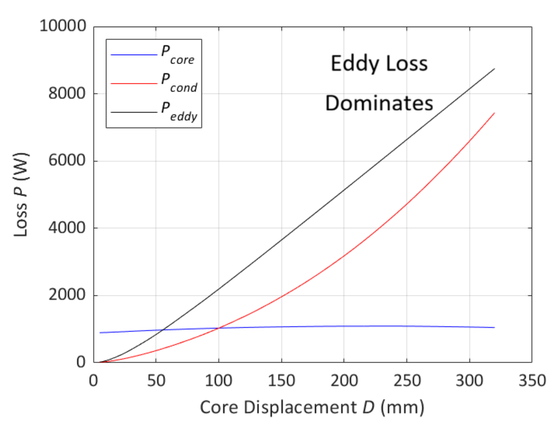
As shown below, P_{eddy} is dominant in most cases within the air gap range of 0 to 320mm, followed by P_{cond} , and then P_{core} (core loss, calculated by the Steinmetz formula). The P_{eddy} is concentrated in the vicinity of the air gaps. Therefore, P_{eddy} can be reduced by changing the position of the coils in order to moved the coils away from the air gaps.



P_{eddy}



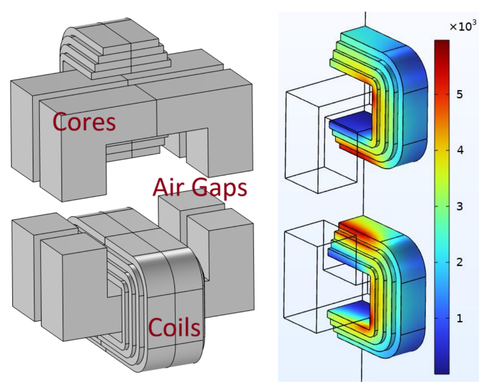
P_{cond}



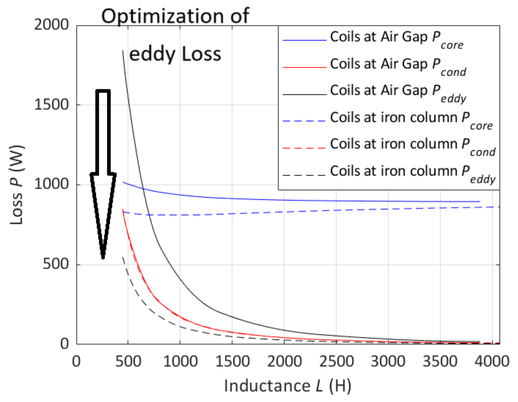
P_{eddy}, P_{cond} and P_{core} VS air gap width (core displacement)

Optimization design and comparison

Move the coils from the air gap edge of the iron core to the edge of the iron column without an air gap, as shown below. The loss calculation results show that, under the same inductance conditions, the P_{eddy} of the coil decreases by 62.92% to 72.75%, while the P_{cond} remains almost unchanged, the P_{core} increases slightly. The total loss of the test reactor decreases by 5.21% to 40.01%.



Optimized reactor and P_{eddy}



Power losses VS inductance

Conclusions and Prospects

Conclusion: Using the COMSOL 6.4, the complex permeability modeling and loss optimization design of the coil of adjustable test reactor under a strong magnetic field environment were completed.

Prospect: The optimization module will be used to optimize the shape and size of the reactor components, further reducing the loss. The optimization of the electric field and vibration will also be carried out.

Reference:
[1]. Zhao Zhigang, et al. Calculation Model of Winding Loss of Litz-Wire Based on Equivalent Complex Permeability[J]. Transactions of China Electrotechnical Society, 2024, 39(4):947-955.
[2]. Meeker D C .An improved continuum skin and proximity effect model for hexagonally packed wires[J].Journal of Computational & Applied Mathematics, 2012, 236(18):4635-4644.