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Numerical Simulation of Thermal Behavior In a No-insulation Toroidal Magnet

Yi Zhang, Yuejin Tang, Zhong Xia, Chi Zhang, Li Ren

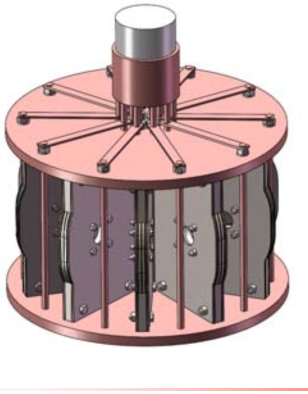
State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science & Technology, Wuhan, China

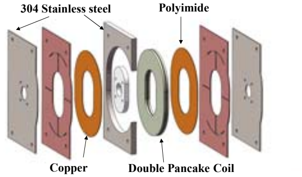
•*Abstract* —The toroidal field (TF) magnet in Tokamak system is required generate a high-steady field to confine and shape the high-temperature plasma. To secure high current density and high thermal stability, the no-insulation(NI) winding technique is used in the fabrication of TF magnet. During plasma operation, heat generated in the TF magnet due to the interaction with central solenoid(CS) coil, poloidal field(PF) coils and the plasma current. The heat generated in NI coils is complex due to the existence of current flow between adjacent turns, thus, it is necessary to calculate the thermal problems. This paper presents the thermal behavior of a NI toroidal magnet under different operating conditions, considering the effect of turn-to-turn contact resistance. The analysis procedure combine FEM and equivalent circuit model. This analysis has applicability and practical directive to the design of cryogenic cooling system for NI toroidal magnet.

I. Structure of the NI toroidal magnet

The NI magnet has 10 racetrack double pancake coils(DPCs) which arranged in toroidal shape. The superconducting tape for the DPC is the DI-BSCCO Type HT. Each DPC contains two copper cooling plates, three 304 stainless steel support structure, and two polyimide plate between the pancake coil and the cooling plates. The magnet is conduction cooled by GM cryo-coolers to the operating temperature of 14 K . The critical current is 395A and can generate a max parallel field of 1.02T.

A simplified operating condition is applied to investigate the thermal behavior of the TF magnet. The saturation time(99%) of magnet field in different charging rates are calculated, after compared the excitation loss of the total magnet, an optimized charging rate is obtained. Then, four PF coils are excited by triangular wave current to simulate the electromagnetic environment in fusion magnet. Finally, the temperature field in the DPC along with time is discussed



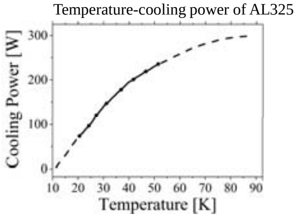


Designation	Parameter
Number of pancake coils	10
Inner radius R_i	50 mm
Operating temperature	14K
Critical current *Ic*	395A
Inductance	71.8 mH
Total Contact resistance R_c	207 μΩ
Max Parallel field	1.02T

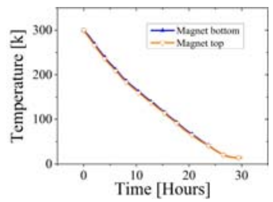
II. Cooling Process

The magnet is cooled by AL 325 to 14K in 30 hours. Due to the non-existent of insulation layer, the DPCs has a preferably isotropy of heat conduction, the maximal difference of temperature between the magnet top and bottom is 2K during the cooling process, in about 30 hours, the whole magnet reach 14K.

Temperature-cooling power of AL325

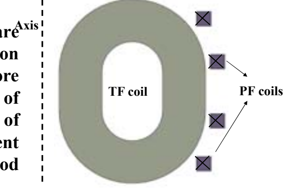


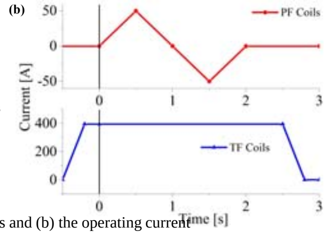
Temperature-time curve of magnet



III. Operating Conditions

The structure of the TF coil and PF coil are made to simplify based on the fusion Tokamak system. the time of charging before 0s is not to scale. In practice, the current of PF coil is complicated by feedback control of plasma current. In our analysis, the current of PF coil is triangular wave with the period of 2 s and the change rate of 100 A/s.

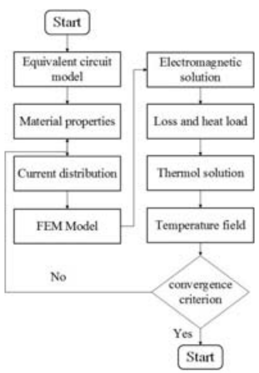




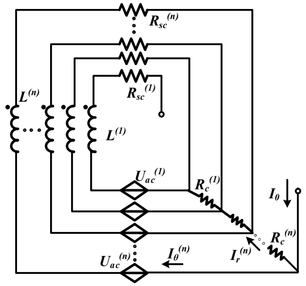
Schematic diagram of :(a) the coils and (b) the operating current

IV. Analysis Precedure and Model

Analysis precedure



Equivalent circuit model built by each turn



$$\rho=\frac{E}{J}=\frac{E_0}{J_C(B)}\left(\frac{J}{J_C(B)}\right)^{n-1}$$ where,

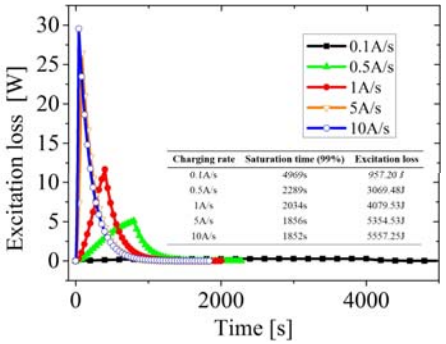
$$J_C(B)=\frac{J_{C0}}{\left(1+\frac{\sqrt{k^2|B_{\parallel}|^2+|B_{\perp}|^2}}{B_0}\right)^{\alpha}}$$

$$J_{C0}=\alpha\left[1-\left(\frac{T}{T_C}\right)^2\right]^{1.5}$$

Each unit of the equivalent circuit model contains the turn inductance, characteristic resistance in azimuthal direction and turn-to-turn contact resistance. The electromagnetic material properties can be obtained Maxwell equations and E-J power law characteristic of superconducting tape.

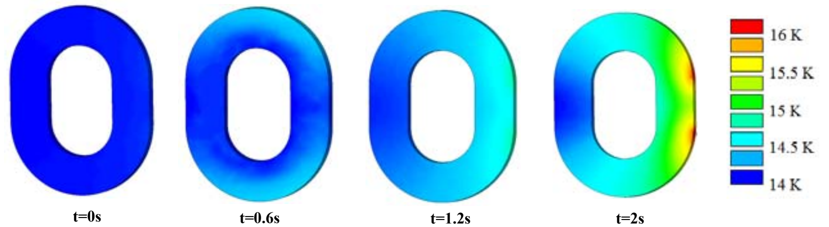
V. Results and Conclusion

a. Excitation loss



The excitation loss in the NI coil The turn-to-turn loss is two orders of magnitude higher than the hysteresis loss, which can be ignored. When the charging rate increases, the excitation loss will increase significantly , and the saturation time will decrease to a certain extent, after charging rate increase to 10A/s, the saturation time almost reach the minimum value.

b. Temperature distribution by time-step under the influence of the PF coils



The temperature field of DPC varying with time in a period is shown above. In earlier period(before 0.6s), the temperature raising appears in the top and bottom of outer layer, as the turn-to-turn current is higher and the critical current density is lower in outer layer. After 1.2s, the temperature near the outer current lead is significantly higher than other parts, that is because the current of the lead could not path through the turn-to-turn contact, the heat accumulations quickly. However, the temperature difference in the whole DPC is less than 2.3K, much uniform than a insulated colleague.

Conclusion:

In this paper, we describes the analysis procedure considering the influence of external magnetic field. The numerical simulation results show that: (1) when the magnet is charged in different rate, the saturation time and excitation loss will be different, thus, it is necessary to choosing a appropriate charging rate to meet the engineering needs and control the heat load; (2) when the magnetic field of PF coils influent the TF coils, the temperature distribution variation in the DPC is relatively uniform due to the exist of turn-to-turn contact, but still need to be considered to avoid quench. The simulation result can be used to predict temperature distribution along with the time variation, and could help us in understanding how to improve the design of the cooling system of NI magnet.