§3. Hysteresis Losses in LHD Poloidal Coils

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AC losses in poloidal coils of the Large Helical Device (LHD) have been measured during single-pulse operations. Superconductors of the poloidal coils are Nb-Ti cable-in-conduit conductors (CICC) cooled by supercritical helium. In 2008, additional pulse power supplies were installed to enhance the output voltage of the power supplies for the poloidal coils in an effort to control the magnetic field structure more rapidly during plasma experiments. The maximum rate of field change increased to 0.06 T/s in the innermost conductor, which corresponds to a six-fold increase over previous operations. This enhancement also enables AC loss measurements to be made during more rapid pulse operations. In the 12th experimental campaign, coupling time constants were measured for the two coils, IV-U and IV-L[1]. We found a 2.5-fold difference in the constants even though the two coils were fabricated with exactly the same design. In the 13th experimental campaign, hysteresis losses were then measured during rapid pulse operations.

The loss can be measured by monitoring the enthalpy increase of the helium coolant between the inlet and outlet. The loss is always transferred to the coolant and the enthalpy of the coolant then increases. The coolant is always driven out from the outlet. Therefore, the heat loss can be obtained by $m\Delta H$ where m is the mass flow rate and ΔH is the enthalpy increase. Fig. 1 shows an example of time evolution of the temperature and the heat loss for the IV-L coil. After a single pulse operation, increase of $m\Delta H$ was observed for about 1500 s. The offset of 16 W corresponds to a heat leak by conduction and radiation, Q_L. Consequently, the integration of $m\Delta H - Q_L$ gives the total AC loss.

Fig. 2 shows the total measured loss per pulse operation cycle as a function of the inverse of the ramp time, $1/\tau_0$. The maximum current is fixed at 2 and 4 kA. Hysteresis loss, which is independent of the sweep rate can be estimated by extrapolating the slope of the data to $1/\tau_0 = 0$ by linear fitting. The coupling loss can be extracted by subtracting the extrapolated loss from the measured total loss. The estimated hysteresis loss is about 3, 7 and 10 kJ/cycle for the maximum currents of 2, 4 and 5 kA, respectively.

Fig. 3 shows the measured hysteresis loss as a function of the maximum current. The open circles indicate the calculated hysteresis loss using measured static magnetization in a short conductor[2]. The measurements show that the difference between the measured and calculated losses increases with increasing the maximum current. This suggests that an additional loss occurs in the coil. In the case of LHD poloidal coils, the solid-state-bonding technique is applied to the joints. Therefore, the joints maintain superconducting state. The superconducting coupling currents through the joints might result in an increase in hysteresis loss.

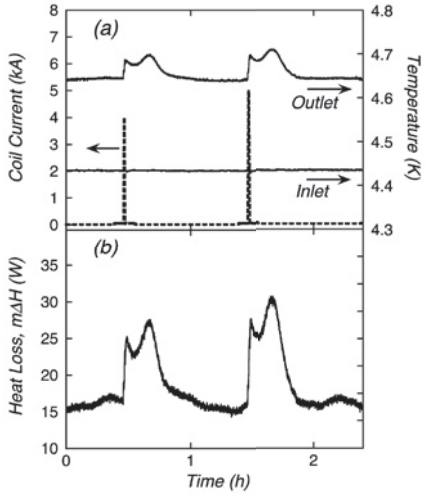

Fig. 1. Time evolution of (a) temperature and (b) heat loss during pulse operations.

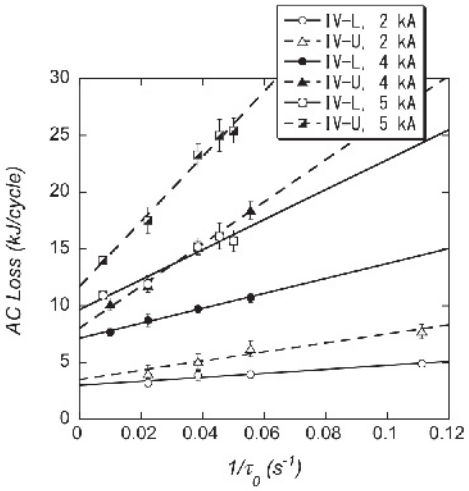

Fig. 2. Measured AC loss per pulse operation cycle as a function of the inverse of the ramp-up/down time.

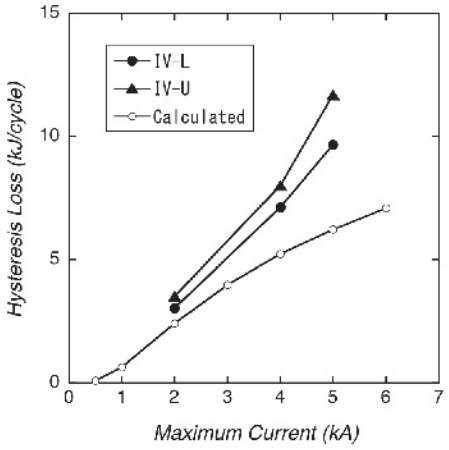

Fig. 3. Measured hysteresis loss as a function of the maximum currents.

1) Takahata, K. et al.: IEEE Trans. Appl. Supercon. **20** (2010) 517
2) Takahata, K. et al.: Fusion Eng. Des. **81** (2006) 2571