§3. Coupling Losses in LHD Poloidal Coils

Takahata, K.

Coupling losses in Large Helical Device (LHD) poloidal coils have been measured during operations with several different waveforms. The superconductors of the poloidal coils are cable-in-conduit conductors cooled by supercritical helium. In the experiments, the operating currents were simultaneously changed with a certain waveform, and the enthalpy increase due to the losses was observed at the inlet and outlet of the helium coolant. Inter-strand coupling currents through resistive contact points mainly caused the losses.

To evaluate the coupling losses with various waveforms, the normalized loss, Q^* is defined by using the following equation.

$$Q_c = A^*(B_m^2/\mu_0)Q^*V_m, \qquad (1)$$

where Q_c is the total coupling losses per coil, A^* the geometrical factor, B_m the maximum field, μ_0 the permeability, and V_m the volume of strands.

Figure 1 shows the results of the discharge experiments with the protection circuit for the IV coils. Q^* is plotted as a function of $1/\tau_0$, where τ_0 is defined as the decay time constant. When the coupling time constant of the loop current τ is fixed, Q^* is theoretically expressed as

$$Q^* = \nu/2(1+\nu), \qquad (2)$$

where $\nu = \tau/\tau_0$. The estimated τ is 0.32 s for IV-U and 0.12 s for IV-L at $\tau_0 = 8$ s. Theoretical lines are indicated as solid lines in the figure assuming the constant τ. However, the data do not agree with the theoretical lines. This means that τ is not fixed to the constant value. The coupling currents with a longer τ are considered to flow with long circulation loops.

To investigate the losses at a lower sweep rate, the experiments with a single triangular pulse and a ramp-up/down have been carried out. Figure 2 shows the experimental results for the IV-U coil. Q^* is plotted as a function of $1/\tau_0$, where τ_0 is defined as the time during which the current increases or decreases. For the ramp-up/down, Q^* is doubled. For reference, the theoretical curve is shown as a solid line in the figure, assuming the coupling time constant is fixed to 0.32 s, which is the previously obtained value in the exponential discharge experiments. The difference between the two waveforms is clearly confirmed, which means that the time constant close to τ_0 exists [1]. Consequently, the time constant reaches 1000 s.

A broad distribution of coupling time constants becomes evident after summarizing the experimental results. The time constants range from the order of 10 to 1000 s. Imperfect transposition in the cable can lead to long coupling current loops. The loop has a long time constant because of the large inductance. Here, the distribution of the time constants is assumed and the calculated losses are compared to the experimental data. First, the probability distribution of occurrence of the loop with a certain time constant is assumed to be uniform in the range of 10 to 5000 s. The normalized loss of Q^* is expressed as the value per unit volume. Therefore, the loss density is assumed to be proportional to $1/\tau$ because the length of the loop may be proportional to the time constant τ. Finally, the total loss is given by the introduction of the following probability density function with a variable of τ:

$$f(\tau) = 0.001/\tau \quad \text{at } 10<\tau<5000 \text{ s}$$
$$f(\tau) = 0 \quad \text{at } \tau<10 \text{ s or } \tau>5000 \text{ s}. \qquad (3)$$

The factor of 0.001 is determined by the fitting. The range of 10 to 5000 s is assumed to show the agreement between the measured and calculated data. The intrinsic coupling loss with the time constant of 0.32 s is always added as an intrinsic coupling loss. The calculated results are shown in Figs. 1 and 2 as dotted lines. The calculated results agree well with the experimental data. The results prove the existence of long coupling time constants with a broad distribution.

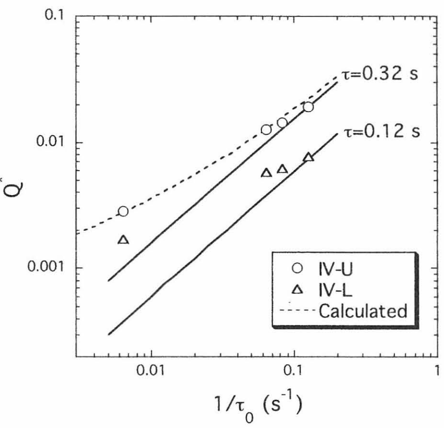

Fig. 1. Normalized coupling losses during the exponential discharge operations for the IV coils.

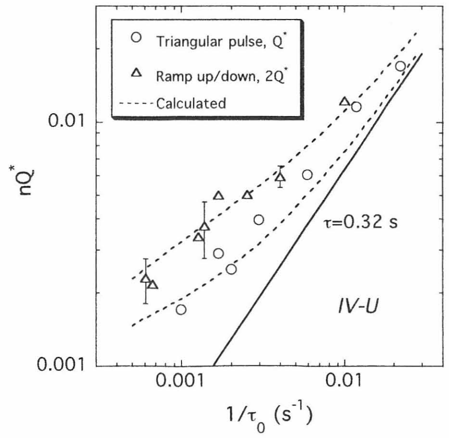

Fig. 2. Normalized coupling losses during single triangular and ramp-up/down operations for the IV-U coil.

Reference

[1] Takahata, K., Ann. Rep. NIFS (2000-2001) 80.