§4. AC Losses in LHD Poloidal Coils

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AC losses in LHD poloidal coils have been investigated in order to predict a temperature increase during pulse operation in phase II. The losses in a cable-in-conduit conductor include hysteresis loss in superconducting filaments, inter-filament coupling loss in strands and inter-strand coupling loss. In the poloidal coils, the inter-strand coupling loss will be dominant. In the present study, the coupling losses were measured during various types of operation in LHD: a single trapezoidal pulse, ramp up, ramp down and fast discharge with exponential current decay.

The coupling losses were normalized by the following equation.

$$Q_c = A^*(B_m{}^2/\mu_0)Q^*V_{st}\,, \qquad (1)$$

where Q_c is the loss per cycle, A^* a factor determined by the conductor structure, B_m the maximum field, Q^* the normalized dimensionless loss and V_{st} the strand volume. Q^* can be obtained by a circuit model and depends on the ratio of a time constant of coupling current to sweep time, τ/T, and a waveform. The decay time constant is applied to T for fast discharges. When $\tau/T \le 0.1$, Q^* for a single trapezoidal/triangular pulse agree with nQ^* where n=2 for ramp up/down and n=4 for exponential decays. Therefore the measured data of nQ^* are plotted as a function of $1/T$ in Fig. 1 for the upper IV coil (IV-U) and Fig.2 for the lower IV coil (IV-L). When τ is smaller than T, the normalized loss becomes

$$nQ^* = 2\tau/T\,. \qquad (2)$$

Under this condition, nQ^* will be proportional to $1/T$.

The results clarified some interesting features as follows:

[1] It should be noted that the losses of IV-U were approximately twice higher compared with IV-L. The differences cannot be explained for the moment because both coils have the same structure.

[2] The apparent coupling time constant increased with decreasing $1/T$. For IV-U, τ of 0.35 s was obtained from the equation (2) for the fast discharges. However τ increased up to 2 s for the slow ramp up/down operation.

[3] The losses depended on the waveform in the low $1/T$ region. Figure 3 shows the theoretical nQ^* for two different waveforms. When $\tau/T \ge 1$, nQ^* are different between the waveforms. Therefore the experimental results indicated that long coupling time constants more than 1000 s appeared. The behavior of [2] can be explained by the long time constant.

[4] It is clear from Fig. 3 that nQ^* for the single triangular has a peak when $\tau \approx T$. On the other hand, the experimental data shows the increase of apparent τ in a wide range of $1/T$ from 0.001 to 0.01 s^{-1}. The coupling currents should have a wide variety of time constants.

[5] Disturbances of cabling periodicity may be responsible for inter-strand coupling with long time constants.

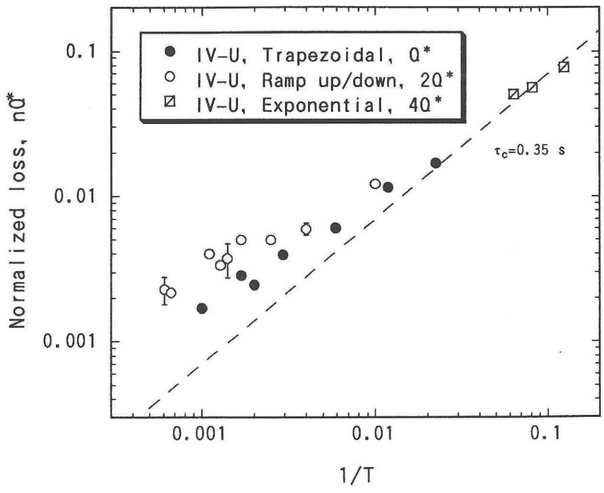

Fig. 1. Normalized losses in the IV-U coil during various types of operation: Single trapezoidal pulse, ramp up, ramp down, and exponential decay.

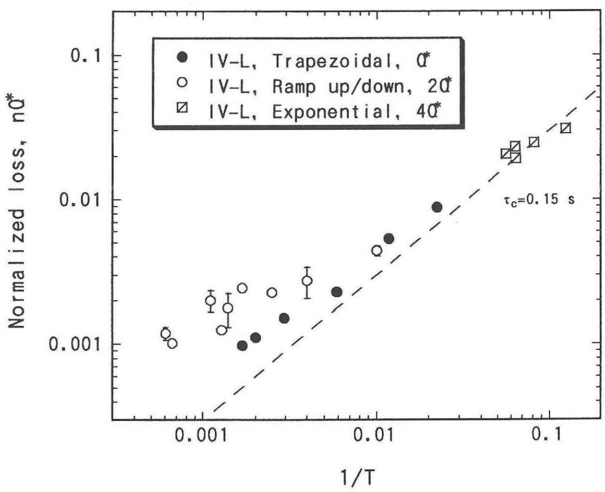

Fig. 2. Normalized losses in the IV-L coil.

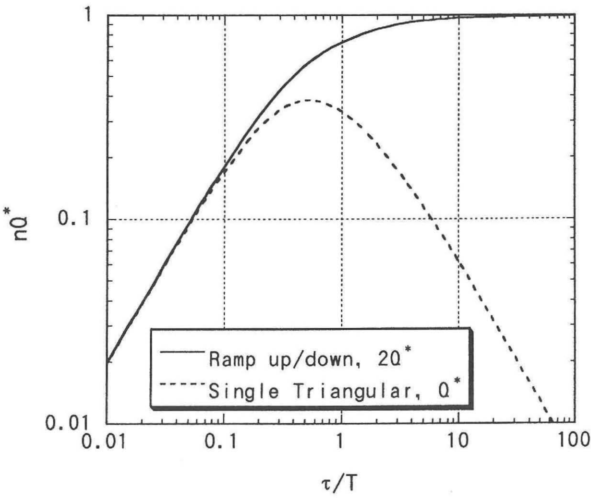

Fig. 3. Theoretical normalized losses during ramp up/down and a single triangular pulse excitation.