§3. Monitoring and State Estimation of the LHD Coil

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The normal zone expansion mode of the LHD coil is relatively complex. According to Yanagi et al., the behavior of the normal zone in the helical coil of the LHD includes, (1)expansion, (2)reduction, and (3)keeping constant level with one directional traveling[2]. For such a complex phenomenon, a highly sophisticated quench protection system is necessary. So, the authors propose a quench protection scheme taking into consideration (1)the resistive voltage of the coil, (2)the velocity of the normal zone expansion, and (3)the effective stored heat in the coil.

The state of the coil can be estimated using; (1)the resistive voltage V_{res}, (2)velocity of normal zone expansion, or (3)effective stored heat. Among them, the resistive voltage V_{res} has a fundamental importance. It is almost proportional to the heat dissipation (Watt) in the coil. Through a careful observation of the resistive voltage (Fig. 1), we can conclude that the quench decision should be done as soon as possible if the resistive voltage exceeds the criterion voltage of 40 mV. This value corresponds to the normal zone length of 35 m for the coil current of 11.45 kA. Because the length of the conductor for 1 turn of H-I coil is 35 m, this value means the normal transition of 1turn length.

The velocity of normal zone expansion is also an important factor for the decision of quench. It is almost proportional to the derivative of the resistive voltage of the coil. In general, derivative of coil voltage includes large noises. However, in the case of H-I coil the noise can be suppressed by a smoothing process applying a moving averaging technique. In Fig. 2, we can recognize a clear large signal just after 2600 s. In this case, the appropriate quench decision threshold value for the velocity of normal zone expansion should be 3 m/s.

Effective stored heat in the coil is another important factor. This factor is obtained by an integration of the resistive voltage. So, fundamentally this factor is strong to noises. According to the experimental data shown in Fig. 3, the threshold value of quench for this factor would be 50 J.

As mentioned above, the criterions of the quench decision for each factor are summarized in Table 1[2]. Applying these criterions to the experimental data shown in Fig. 1, 2, and 3, we can actuate the emergency shutdown process about at t = 2601 s well before the full quench.

Thus, the authors proposed a quench protection scheme introducing some intelligent data processing techniques on the voltage signal of the helical coil of the LHD system. The conclusions are summarized as follows.

(1) A careful noise reduction effort to obtain a reliable resistive voltage is essential.

(2) Other than the resistive voltage, the velocity of normal zone expansion, and the effective stored heat would be effective as new criterion for the quench.

(3) Applying these new quench decision criterions for the LHD system, a full quench can be avoided.

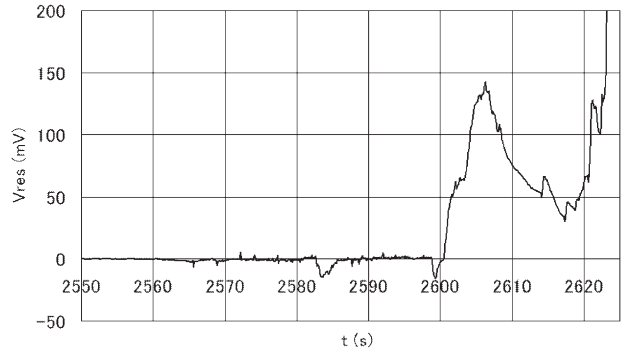

Fig. 1. Resistive voltage of H-I coil.

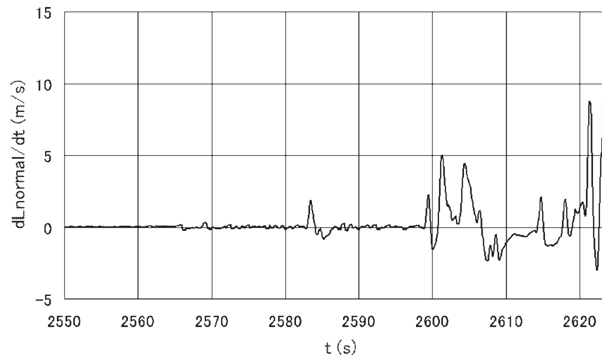

Fig. 2. Normal zone expansion velocity of H-I coil.

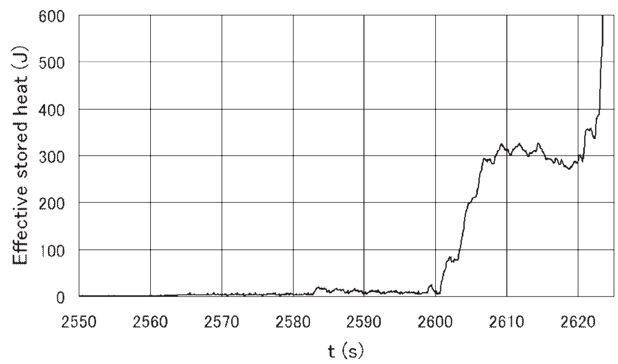

Fig. 3. Effective stored heat of H-I coil.

Table 1. Quench decision criterion of H-I coil.

Resistive voltage	40 mV
Normal zone expansion velocity	3 m/s
Effective stored heat	50 J

Reference

1) N. Yanagi, S. Imagawa, Y. Hishinuma, et al., IEEE Transactions on Applied Superconductivity, 14, (2004) 1507-1510.
2) T. Ishigohka, T. Mito, S. Imagawa, N. Yanagi, H. Sekiguchi, S. Yamada, "Protection of LHD coils by intelligent observation of voltage signals", Presented at ITC-15, Dec. 2005.