§5. Reconsideration of Evaluation of Balance Voltages during Normal Zone Propagation in the LHD Helical Coils

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Propagation and recovery of normal zones were observed several times in a pair of helical coils, which are H1 and H2 coils, of the Large Helical Device. Each the coil is divided into three blocks, which are named H-I, H-M, and H-O from the inside. Since the current center shifts from the superconducting wires to a pure aluminum stabilizer at the normal zone, imbalance voltages between H1 and H2 are induced in all the blocks. The cross-sectional position of the conductor in which the normal zone propagates can be estimated from the difference of the imbalance voltages among the blocks. In the previous study, the conductor positions were estimated at the first or last turn in the third and fourth layers of the H-I under the assumption that the resistive voltage is proportional to the length of the normal zone. This assumption is not precise because of the transient high resistivity due to the slow current diffusion. Considering the transient resistivity of the normal zone, the position of the normal zone propagation is reconsidered.

When a normal-zone propagates, the current diffuses into the aluminum stabilizer from the superconducting strands. An inductance change is induced by the geometrical shift of the current. In this case, no mechanical work is induced. Hence, this is equivalent to add a new circuit.[1)] When a normal-zone propagates in the I-block, the voltage drop due to the resistance of the normal-zone e_R is expressed by

$$e_R = e_I - \frac{B_{Ix} I_M}{B_{Mx} I_I} e_M \equiv e_I - \alpha e_M \quad (1)$$

where e_j and I_j are the balance voltages and the currents of j (I, M) block, respectively. B_{jx} is the magnetic field density by j-block across the additional circuit by the current shift. The ratios of magnetic field at each turn by M-block to that by I-block are shown in Table I.

The resistive voltages during propagation of a normal zone were measured in a model coil using voltage taps as shown in Fig. 2. The time constants for the decreasing resistance in propagating and recovering are 59 and 441 ms, respectively. The time constant in recovering is obviously longer than the theoretical value, which is four times of that in propagating. It might be affected by the power supply for the model coil. In the cases of one-side propagation, the recovery starts before the current deeply diffuses into the aluminum. The voltage drop can be fitted using the duration of propagation, t_r. The calculated resistive voltages using Fig. 1 with t_r=0.06 and 0.08 s are shown in Fig. 2, in which the resistive voltages evaluated by (1) are also shown for α=0.7 and 0.9. Since the profile at a=0.7 is in good agreement with the calculation, the normal zone is considered to have propagated in the first layer of the H-I, which is agreement with the evaluation of measured data with pickup coils along the helical coils.[2)]

Table 1 Max. and Min. ratio of the magnetic field in the overturning direction by M-block to that of by I-block.

Turn	L8	L7	L6	L5	L4	L3	L2	L1
T3	-1.87	-4.95	6.4	1.78				Max.
	-2.74	-16.7	3.76	1.62				Min.
T4	-1.67	-3.54	19.1	2.36	1.24			
	-2.36	-7.40	5.84	2.00	1.19			
T5	-1.56	-2.94	746	3.07	1.45	0.94		
	-2.14	-5.20	-121	2.40	1.35	0.93		
T6	-1.48	-2.57	2380	3.85	1.60	0.96		
	-1.98	-4.23	-92.8	2.86	1.47	0.95		
T7	-1.42	-2.36	530	4.93	1.81	1.09	0.79	
	-1.88	-3.64	-2691	3.33	1.63	1.06	0.78	
T8	-1.37	-2.20	-6.21	6.40	2.02	1.17	0.81	
	-1.80	-3.31	-32	3.86	1.77	1.13	0.80	
T9	-1.34	-2.10	-5.35	8.09	2.22	1.25	0.87	0.69
	-1.74	-3.09	-17.6	4.43	1.90	1.19	0.86	0.67
T10	-1.31	-2.03	-4.81	10.16	2.37	1.31	0.89	0.68
	-1.70	-2.95	-13.2	4.91	2.01	1.24	0.89	0.67
T11	-1.30	-1.98	-4.54	12.14	2.47	1.34	0.90	0.68
	-1.67	-2.85	-11.2	5.27	2.07	1.26	0.89	0.67
T12	-1.29	-1.96	-4.39	13.41	2.52	1.35	0.90	0.68
	-1.65	-2.80	-10.5	5.51	2.11	1.27	0.90	0.67
T13	-1.28	-1.95	-4.35	13.94	2.54	1.36	0.91	0.68
	-1.65	-2.78	-10.2	5.58	2.12	1.28	0.90	0.67

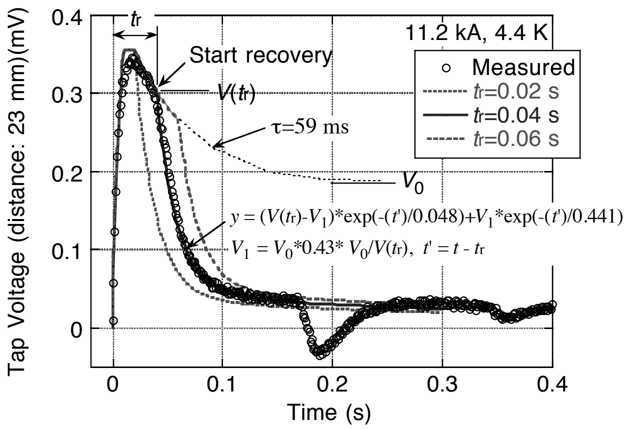

Fig. 1. Fit curve for voltage drop of the LHD-HC conductor during propagation and recovery of a normal zone.

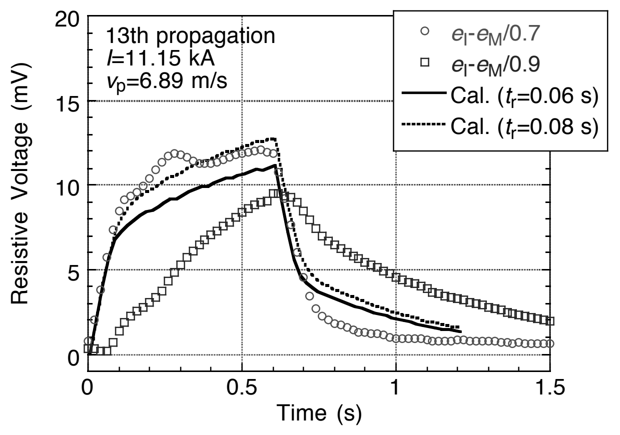

Fig. 2. Calculated normal component of voltage during the 13th propagation of a normal zone in the LHD helical coil.

1) Imagawa S. et al., *IEEE Trans. Appl. Supercond.*, vol. 13 (2003) 1484.

2) Imagawa S. et al., *IEEE Trans. Appl. Supercond.*, vol. 21 (2011) 2316.