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Numerical estimation on balance coefficients of central difference averaging method for quench detection of the KSTAR PF coils

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Abstract

A quench detection system of KSTAR Poloidal Field (PF) coils is inevitable for stable operation because normal zone generates overheating during quench occurrence. Recently, new voltage quench detection method, combination of Central Difference Averaging (CDA) and Mutual Inductance Compensation (MIK) for compensating mutual inductive voltage more effectively than conventional voltage detection method, has been suggested and studied. For better performance of mutual induction cancellation by adjacent coils of CDA+MIK method for KSTAR coil system, balance coefficients of CDA must be estimated and adjusted preferentially. In this paper, the balance coefficients of CDA for KSTAR PF coils were numerically estimated. The estimated result was adopted and tested by using simulation. The CDA method adopting balance coefficients effectively eliminated mutual inductive voltage, and also it is expected to improve performance of CDA+MIK method for quench detection of KSTAR PF coils.

Keyword: Balance coefficients, Central Difference Averaging, KSTAR, MIK, Quench Detection System

1. INTRODUCTION

Korea Superconducting Tokamak Advanced Research (KSTAR) consists of multiple low-temperature superconducting coils. A quench detection system is essential for stable and reliable operation in case normal zone abruptly appears and generated overheating. The quench occurrence might cause damage to the superconducting coils. Thus, several types of sensors such as temperature, pressure, flow and voltage were installed in KSTAR for quench detection [1, 2]. Among these above, voltage sensors which are bridge circuits and co-wound voltage strips provide the fastest reaction against quench occurrence. However, voltage quench detection methods pick up not only resistive voltage caused by quench but also inductive voltage from mutually coupled adjacent coils. The inductive voltage is an undesirable factor for accurate quench detection. Especially, KSTAR consists of enormous coils which have large inductance, and those coils experience a few kA pulse currents. This leads high inductive voltage to disrupt detection of resistive voltage caused by quench. Both the bridge circuits and the co-wound voltage strips were adopted to eliminate inductive voltages, however, these sensors are not perfectly effective in multiple coil system. Therefore, additional inductive compensation methods were required for more reliable quench detection. Recently, new voltage quench detection method, combination of Central ifference Averaging (CDA) and Mutual Inductance Compensation (MIK) for compensating mutual inductive voltage more effectively than conventional voltage detection method, has been suggested and studied [2-5]. Central Difference Averaging (CDA) was proposed for reduction of mutual inductive voltages of multiple coils [6]. The compensation of the mutual inductive voltage is achieved by subtracting average of the first and the third coil winding voltages from the second coil winding voltage. Mutual inductance compensation or MIK, where I and K stand for mutual coupling indexes of different circuits [7], can be executed by using microprocessor as active inductive voltage compensation by using mutual inductances of coils. Balance coefficients of CDA must be estimated and

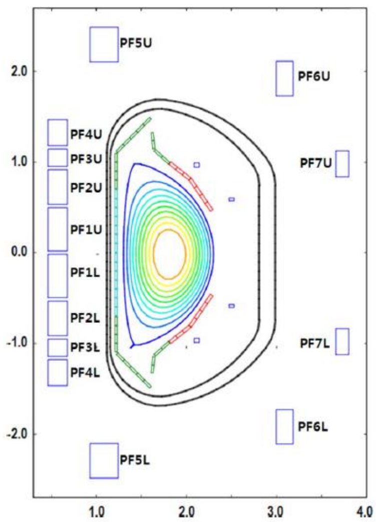

Fig. 1. Geometry of the KSTAR PF coil system.

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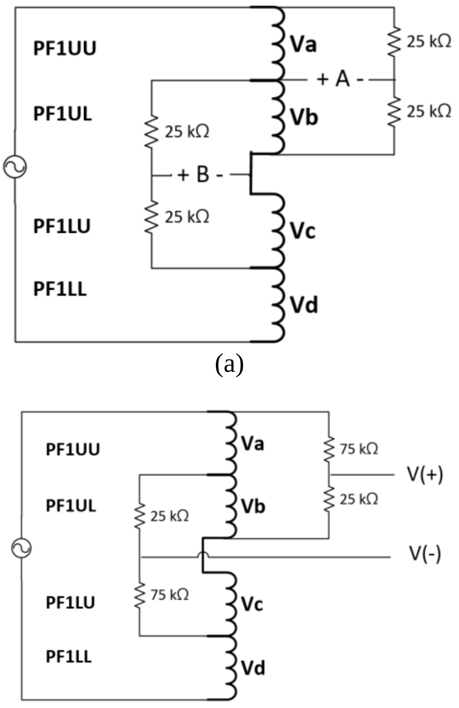
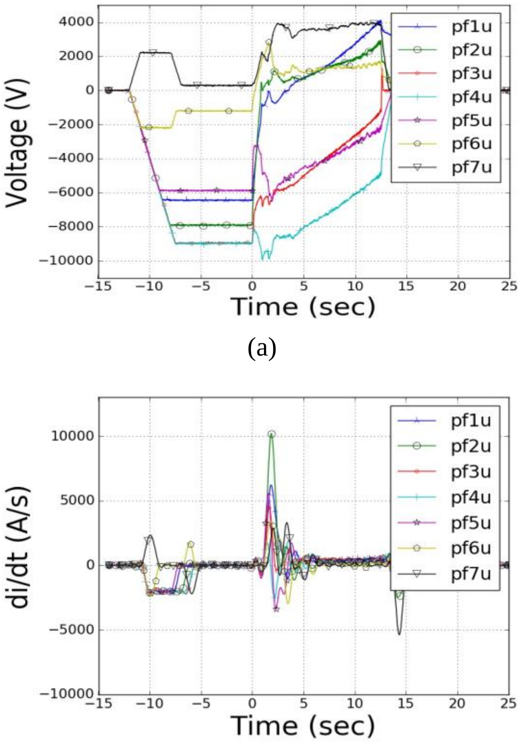


(a)

(b)

Fig. 2. (a) R-R type CDA circuit for PF 1 coil, (b) 3R-R type CDA circuit for PF 1 coil.



(a)

(b)

Fig. 3. (a) The currents of 7 upper coil windings for shot #15394, b) The di/dt of 7 upper coil windings for shot #15394.

adjusted preferentially for better performance of mutual induction cancellation of CDA+MIK method for the KSTAR Poloidal Field (PF) coil system [8]. In this paper, he balance coefficients of CDA for the KSTAR PF coils were numerically estimated. The estimated result was adopted and tested by using simulation. The simulation was carried out using current data of actual experiment and inductance matrix calculated from FEM tool in advance. The CDA method adopting the balance coefficients effectively eliminated mutual inductive voltage, and also it is expected to improve performance of CDA+MIK method for quench detection of the KSTAR PF coils.

2. NUMERICAL ESTIMATION ON CDA

2.1. Simple CDA

The KSTAR PF coil system is illustrated in Fig. 1. Fourteen coils are charged with eleven power supplies. Upper and lower of the PF 1 to PF 7 coils are vertically symmetric to the mid-plane. High accuracy resistors are installed in the PF 1 coil to verify efficiency of CDA method and CDA circuits are two types of wiring patterns as shown in Fig. 2 [5]. The CDA circuit is applied to the first, second and third coil windings of the PF 1 coil, where PF1U and PF1L are series-connected. The simple CDA of PF 1 upper part(CDAU) is calculated as shown in (1).

$$\begin{aligned} V_{CDAU} &= V_b - 0.5(V_a + V_c) \\ &= \{L_b - 0.5(L_a + L_c)\}\frac{di}{dt} + \{M_{ac} + M_{cb} + M_{db} \\ &\quad -0.5(M_{ba} + M_{ca} + M_{da} + M_{ac} + M_{bc} + M_{dc})\}\frac{di}{dt} \end{aligned} \quad (1)$$

The average of the first and the third coil winding voltage is subtracted from the second coil winding voltage so that the coefficient for the simple CDA was set as 0.5. Most of the self and mutual inductance terms are eliminated. However, the CDA does not perfectly cancel out inductive noise into an acceptable level [2]. For better cancellation of mutual inductive components, certainly the MIK needs to be combined with the CDA. Before applying the MIK to the CDA, the balance coefficients of the CDA for the KSTAR PF coils are required to be adjusted preferentially because the simple CDA is insufficient [5]. The balance coefficients could be estimated during CS load associated with an appropriate load rate, by balancing the CDA. However, the balance coefficients were not adjustable during current operation in case of KSTAR. Therefore, the balance coefficients were estimated through simulation ahead of experiment.

2.2. Balance coefficients of CDA estimation

For estimation of the balance coefficients of the CDA, an expected CDA voltage could be calculated with mutual inductances and derivatives of current by using V=Ldi/dt. Mutual inductance matrix was calculated with detailed dimension of the KSTAR PF coils by using FEM tool Infolytica Magnet [9]. One of factors that contributes voltages of coils is the derivatives of current(di/dt). However, di/dt of KSTAR current scenario is drastically variable as shown in Fig. 3 so that an assumption for estimation of the balance coefficients is inevitable.

TABLE I
MTUAL INDUCTANCE MATRIX OF PF 1 COIL.

Primary coil	Secondary coil			
	PF1UU (V_a)	PF1UL (V_b)	PF1LU (V_c)	PF1LL (V_d)
PF1UU	10.338	5.925	2.680	1.461
PF1UL	5.925	10.338	5.539	2.680
PF1LU	2.680	5.539	10.338	5.925
PF1LL	1.461	2.680	5.925	10.338
sum	20.404	24.482	24.482	20.404

The unit of each value is (mH)

TABLE II
IDUCTANCE SUM OF KSTAR PF COILS IN VIEW OF CDAU OF PF 1 COIL.

Primary coil	Secondary coil		
	PF1UU (V_a)	PF1UL (V_b)	PF1LU (V_c)
PF1	20.404	24.482	24.482
PF2	8.507	5.587	5.587
PF3	1.778	1.329	1.329
PF4	1.512	1.197	1.197
PF5	1.786	1.637	1.637
PF6	2.865	2.847	2.847
PF7	1.936	1.954	1.954

The unit of each value is (mH)

TABLE III
WEIGHT FACTORS OF V_A AND V_C BASED ON V_B FOR EACH COIL.

Weight factor	PF1UU (V_a)	PF1LU (V_c)
PF1	1	0.833
PF2	1	1.522
PF3	1	1.338
PF4	1	1.262
PF5	1	1.091
PF6	1	1.006
PF7	1	0.991
sum	7	8.045

The effects of current derivatives for each coil that contribute to voltage of each coil are assumed to be equal because current derivatives are irregularly changed. Even though mutual inductances between adjacent coils are high, current derivatives are occasionally too high to cancel effects of mutual inductances of adjacent coils. V_a, V_b and V_c as shown in Fig. 2 are used for estimation of CDA of PF 1 upper part (CDAU). For minimization of the CDAU voltage, (2) has to be satisfied so that V_a / V_b and V_c / V_b were deduced using the inductance matrix calculated from FEM tool.

$$V_b = 0.5\alpha V_a = 0.5\beta V_c \quad (2)$$

Table I shows calculated mutual inductance matrix of the PF 1 coil as used for the CDA voltage. An expected CDA voltage would be V= 24.49 mH x 1 kA/s - 0.5 (24.49+20.41) mH x 1 kA/s = 2.095 V from PF 1 inductance matrix when the PF 1 coil is solely operated at 1 kA/s. A higher coefficient needs to be multiplied on Va to minimize the CDA voltage. For minimizing the CDA voltage during only PF 1 coil operation, α and β are determined as 24.482/24.482 and 24.482/20.404, respectively. Therefore, the balance coefficients of CDA for the PF 1 coil are deduced as shown in (3).

$$V_{CDAU} = V_b - 0.546V_a - 0.454V_c \quad (3)$$

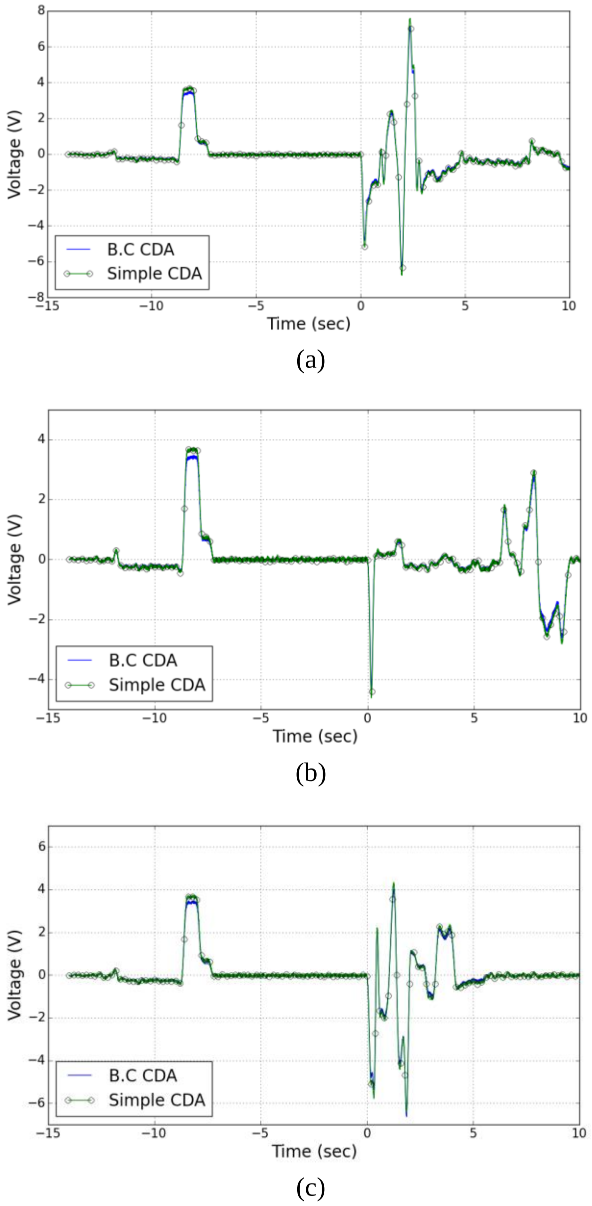


Fig. 4. Comparison of simple CDA and balance coefficients CDA (B.C CDA) for (a) shot #14337, (b) shot #14357 and (c) shot #14388.

However, all of the coils must be taken into consideration because every coil is operated in KSTAR plasma scenario. The current of each coil is almost identical so that only seven coils, from PF 1 to PF 7, are considered to be calculated the balance coefficients on CDA. Table II shows inductance sum of the KSTAR PF coils in view of CDAU of the PF 1 coil. The ratio of voltage, V_a / V_b and V_c / V_b, were calculated as weight factors for each coil as shown in Table III. The balance coefficients are calculated and deduced as 0.535 and 0.465 by means of summation of weight factors for each coil. Therefore, the balance coefficients of CDA are estimated as shown in (4). From the result, an influence of V_a on the CDAU is higher than that of V_c.

$$V_{CDAU} = V_b - 0.535V_a - 0.465V_c \quad (4)$$

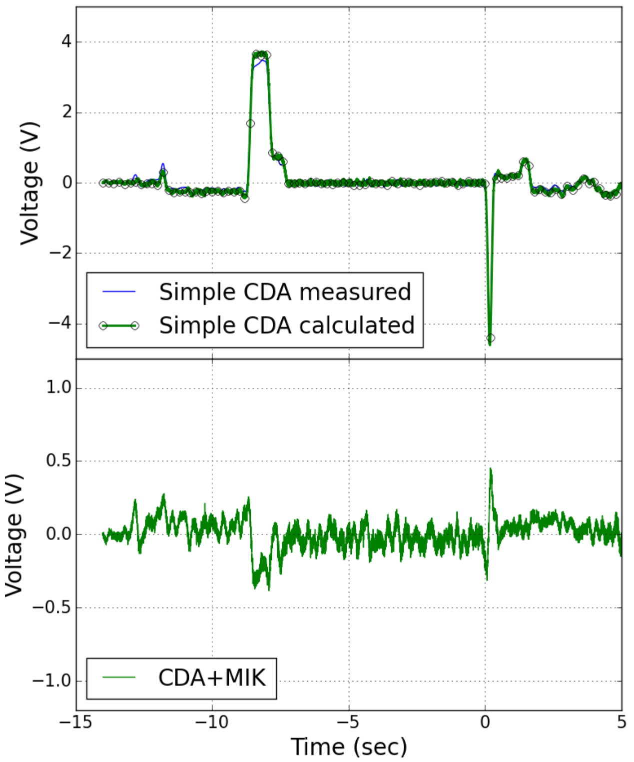


Fig. 5. Comparison voltage of measured simple CDA and calculated MIK(upper) and CDA+MIK result(lower) for Shot #14357.

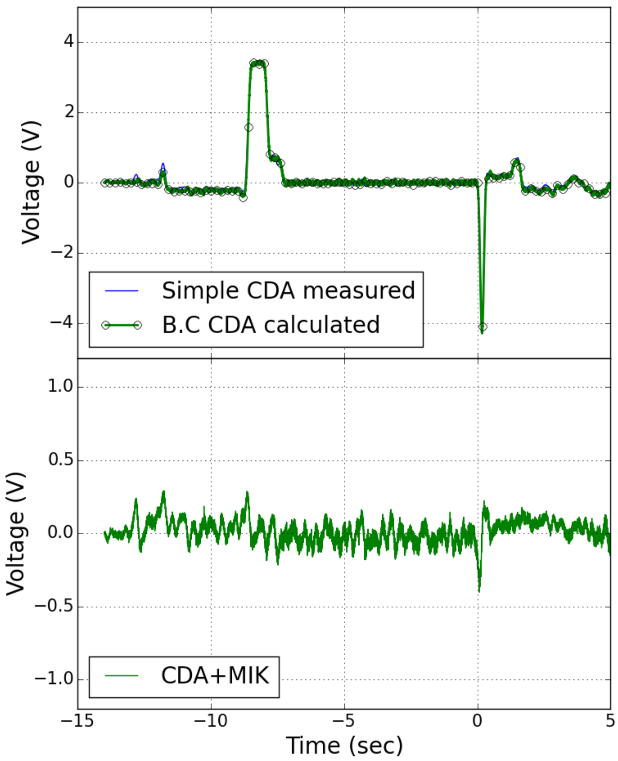


Fig. 6. Comparison voltage of measured simple CDA and calculated MIK adopting balance coefficients(upper) and CDA+MIK result(lower) for Shot #14357.

3. SIMULATION RESULTS

3.1. CDA

CDA simulation was carried out to verify effectiveness of calculated balance coefficients before practically applied to the CDA in KSTAR. Simulated CDA voltage was determined with inductance matrix and actual current data of KSTAR operation. Three shots differently operated were randomly chosen and comparison graphs of the simple CDA and the CDA adopting the balance coefficients (B.C CDA) are shown in Fig. 4. From the result of simulation, adjusting the balance coefficients of the CDA effectively compensated mutual inductive components than simple CDA method. The maximum voltage was about 0.3 V reduced averagely. Plasma is generated after zero second so that voltage after zero second may be caused by the effect of plasma and eddy current. Adjusted balance coefficients on CDA is efficient to detect quench occurrence because quench detection threshold of the KSTAR PF coils is 0.5 V.

3.2. CDA+MIK

Calculated balance coefficients would be adopted on CDA+MIK method for the KSTAR PF coils quench detection system. However, adjusting balance coefficients on CDA is not yet adopted so that effectiveness of calculated balance coefficients should be estimated. Thus, we could expect the effectiveness through comparative study on actual test result of simple CDA and the balance coefficients CDA. The balance coefficients on CDA should be adopted in the MIK as well. Fig. 5 shows comparison voltage of measured simple CDA and calculated MIK and CDA+MIK results as well. Fig. 6 shows comparison voltage of measured simple CDA and calculated MIK adopting balance coefficients and CDA+MIK result. From the result, even though result of the CDA adopting the balance coefficients has not been measured yet, differences between the MIK adopting the balance coefficients and measured simple were lower than those of simple coefficients MIK. This means the result of CDA+MIK method with the balance coefficients would be effectively minimized and compensate mutual induction.

4. CONCLUSION

The balance coefficients of CDA was numerically calculated for better performance of cancelling out mutual inductive components so that reliability of quench detection system in the KSTAR PF coils was improved. The balance coefficients are calculated with inductance information of KSTAR PF coils. The CDA adopting balance coefficients more effectively compensate mutual induction than simple CDA. Furthermore, results of CDA+MIK adopting the balance coefficients was estimated to present better performance than those of simple coefficients through simulation.

The balanced coefficients of CDA resistor in KSTAR PF coils system will be adopted following this study in the near future.

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