Development of an inductive noise cancellation method for quench detection of the KSTAR CS coils by introducing improved plasma modeling

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Abstract. An inductive noise cancellation method, CDA+MIK, has been developed for better performance of KSTAR (Korea Superconducting Tokamak Advanced Research) CS (Central Solenoid) coils’ quench detection. The CDA+MIK method was evaluated in real operations of the KSTAR superconducting coils. An analysis of this evaluation considering mutual inductances only among CS and PF (Poloidal Field) coils showed insufficient reduction of the inductive noise in the quench detection signal. On the other hand a supplementary analysis taking into account of eddy currents induced on conductive structures and dynamic plasma evolutions capable to induce voltages showed better reduction even though the inductive noise was underestimated. This paper describes an improved plasma modelling by considering plasma’s volume and shape, and also application of the model to the experimental results.

1. Introduction

A quench detection system for fusion magnets such as Korea Superconducting Tokamak Advanced Research (KSTAR) is necessary because quench might cause damage to superconducting magnets. A fusion magnet, tokamak, consist of multiple coils so that the induced inductive noises picked up on voltage sensors interrupt detecting resistive voltage caused by quench [1, 2]. Especially Central Solenoid (CS) coils experience pulse current which causes huge inductive noises. The co-wound conductive strips and Wheatstone bridges have been installed in KSTAR to detect quench voltage effectively and protect coils from quench [3, 4]. For better inductive noise cancellation performance of quench detection system, the CDA (Central Differential Averaging) + MIK (Mutual Inductance Compensation) method has been developed and adopted in KSTAR PF (Poloidal Field) 1 coil [5 - 7]. However, test results considering only mutual inductances between PF (Poloidal Filed) coils show remnant inductive voltages. Therefore, Numerical Plant Modelling (NPM) has been developed to estimate the eddy currents induced on conducting structures and the dynamic plasma evolutions capable to induce inductive noises. The NPM analysis was additionally considered for improving performance of CDA+MIK. From the NPM analysis results, the MIK compensation is efficient so that the resultant voltages are converged to zero level, except the plasma current ramping-up and down phases. In those phases where the plasma current has a large change, the residual CDA voltages after MIK compensation showed quite high remnant inductive voltages comparing to present quench threshold voltage. The contribution from plasma current change has the largest value, compared with others such as conductor eddy currents, and the radial and vertical...
plasma movements. However, the inductive noises still remained due to possible reason of under-estimated plasma modeling [7].

Therefore, the assumption of plasma modeling should be revised to apply realistic plasma dynamics for more accurate analysis of plasma effects on CDA+MIK method. In the first version of the NPM, plasma shape effect is not taken into account for a simplified plasma model. In the developed NPM, more accurate plasma estimation such as a multi-filament model instead of single-filament model was used to verify the effects of plasma current density and shape. Also, time-varying mutual inductances were calculated to take into account time-evolving plasma.

2. Quench detection of KSTAR PF coils

Several types of sensors have been used for quench detection of KSTAR PF coils such as temperature, strain, and voltage sensors. However, a system based on the voltage sensors is defined as the quench detection system in KSTAR because voltage sensors provide the fastest response against quench. Other sensors are used for a secondary quench detection system which is a back-up system during malfunction of voltage sensors.

2.1. Conventional quench detection system

The co-wound conductive strips and bridge circuit were used for quench detection of KSTAR PF coils. Theses sensors are effective to cancel out self-inductive noises between each PF coil. To minimize mutual inductive noises, a comparison between bridge or co-wound voltages from upper & lower PF coils, which are symmetric to the mid-plane has been additionally used. Figure 1 shows location of KSTAR PF coils. From PF 1 to PF 4 coil correspond to Central Solenoid (CS) coil in KSTAR. This comparison method is efficient due to current operation of KSTAR PF coils which similar current flows on the each upper & lower PF coil during plasma test.

![Figure 1. Location of KSTAR PF coils](image)

2.2. CDA+MIK system for PF 1 coil

For better inductive noise cancellation performance, CDA+MIK system was installed in PF 1 coil as a feasibility study. The configuration of CDA+MIK system is shown in figure 2. High accuracy resistors 25 kΩ (=R) and 100 kΩ (=3R) were installed in PF 1 upper and lower coil to obtain CDA voltage which is expressed as equation (1).

\[ V_{CDA} = 0.5V_b - 0.25(V_a + V_c) \] (1)
The CDA compares voltage on three adjacent coil to reduce mutual inductive noises. To minimize remnant inductive voltage from CDA circuit, MIK was additionally implemented. The process of MIK is simply calculated as $V = L/(di/dt)$ where $V$ is voltage on each coil terminal, $L$ is coil inductance, and $di/dt$ is time derivative of current. The CDA+MIK process can be expressed by equation (2). $V_{x,\text{MIK}}$ represents calculated voltage on each coil terminal by MIK process.

$$V_{\text{CDA+MIK}} = 0.5(V_b - V_{b,\text{MIK}}) - 0.25\{(V_a - V_{a,\text{MIK}}) + (V_c - V_{c,\text{MIK}})\}$$

where

$V_{\text{CDA,measured}} - 0.5V_b - 0.25(V_{a,\text{MIK}} + V_{c,\text{MIK}})$

The CDA+MIK process can be expressed by equation (2).

Rogowski coils were installed to measure current derivatives of all PF coils, and mutual inductions among each PF coil were calculated by an electromagnetic FEM analysis tool ‘MagNet’.

![Diagram](image)

**Figure 2.** The configuration of CDA+MIK system

### 3. Plasma modeling

The NPM was introduced to evaluate the eddy currents induced on conducting structures and the dynamic plasma evolution. The eddy currents of within conducting structures can be induced during plasma tests because a time-varying magnetic field applied to a conductor. Plasma evolution is able to affect the CDA circuit of coil winding because plasma can be modeled as a toroidal current filament. Those two components can be calculated with NPM analysis.

#### 3.1. NPM code

The NPM code has been developed based on the RZIP response model which is a well-established and verified plasma dynamics modeling [8, 9]. RZIP is a linearized plasma equilibrium response model, which assumes that a small variation on a control coil leads small linear variations on the plasma evolution and the eddy currents on conducting structures. The plasma data such as the plasma currents ($I_p$), the radial movement of plasma column ($R_p$), and the vertical movement of plasma column ($Z_p$) is basic parameter for RZIP model.

In the NPM code, plasma and conductor combined circuit equation is formed for self-consistent dynamic modeling of both plasma and other current sources. Plasma is modelled as a toroidally current-flowing element. Possible plasma-conductor interactions are plasma current change ($dI_p/dt$), plasma movements ($dR_p/dt$ or $dZ_p/dt$ with constant $I_p$), plasma shape change ($d \Psi/dt$), and plasma state change such as Magneto–Hydrodynamic (MHD) event and the transition from low confinement state to a high confinement state ($d \Psi/dt$). The governing equations of the NPM code are (1) Plasma radial force balance.
(RP), (2) Plasma vertical force balance (ZP), (3) Plasma flux conservation (IP), and (4) Combined plasma and conductor circuit equations. Detailed explanation of the governing equations are shown in [7].

Eddy current induced on conductors can be calculated from other measured components. From the analysis results, induced voltage from eddy current effects were negligible for most of shots. Calculated induced voltage from plasma current (IP) is the largest except that of PF coil effects.

3.2. Development of NPM code

The simplified single-filament and improved multi-filament plasma modeling are shown in figure 3 and 4, respectively. The plasma model in an initial version of the NPM code with simplified single-filament model was assumed to have uniform plasma current density. Also, plasma shape was assumed to be rigid as a specific ellipse type regardless of plasma dynamics even though plasma shape and volume is varying in practice. Plasma was assumed to be a point source so that center point of plasma shape was used for mutual inductance calculation. At this sequence, estimated initial plasma data was used to calculate inductances. That is, mutual inductance matrix is a static value and does not change regardless of actual plasma dynamics. In the previous NPM analysis with this assumption, the inductive noises still remained due to possible reason of simplified plasma modeling [7].

Therefore, plasma modeling and analysis method are improved to verify accurate plasma effects on CDA+MIK method. Firstly, plasma data (RP and ZP) is reconstructed by considering current density. Conventionally, plasma data (IP, RP and ZP) was obtained from KSTAR Plasma Control System (PCS) using real-time control. In practice, IP is measured directly by using a mirnov coil probe, and RP and ZP are evaluated from a finite set of magnetic pick-up probe measurements. However, a plasma equilibrium reconstruction method using on a least square optimization technique was used, instead of the simplified linear plasma response relations in this study. The magnetic measurements consist of the contributions from plasma itself and external current sources. Here, the external current sources can be not only PF coil currents, actively controlled for plasma equilibrium, but also passively driven eddy currents on conducting structures. Therefore, the plasma equilibrium parameters are obtained by finding a solution that minimize the total error between measured and evaluated magnetic fluxes. Multiple filament plasma model was developed so that volume and shape of plasma will be indirectly considered. The plasma is assumed to consist of 8 fixed located multi-filament, and each current on 8 section is reconstructed. The RP and ZP are determined by averaged center of eight plasma segment.

Secondly, procedure of mutual inductance calculation was revised to consider current density and time evolution of plasma. Plasma is assumed to have non-uniform plasma current density as same as real plasma dynamics as shown in figure 4. To apply actual time-varying plasma dynamics, calculated inductances are time-variant as well based on the plasma changes. The mutual inductance matrix is re-calculated based on the variation of plasma volume and shape by 0.1 ms time interval.
4. Analysis results and discussion

A Mega-Ampere (MA) plasma shot (#21523) in 2018 KSTAR campaign was analyzed. Figure 5 shows the plasma data ($R_P$ and $Z_P$) comparison of different plasma modeling for shot # 21523. The shape of plasma current is varying in radial direction more than vertical direction. The radial position of plasma in case of weight-averaged by the plasma current is lower than that of measured value. This shows current density of plasma inner region is higher so that $R_P$ values are closer to the center axis. Figure 6 shows calculated mutual inductances during NPM, where ‘T-V M’ is time-varying mutual inductance, and ‘Rigid M’ is a static mutual inductances. PF1UU, PF1UL, and PL1LU represent each PF 1 coil section for CDA calculation as shown in figure 2. The trend of time varying mutual inductance is increasing due to closer plasma center point to PF coils during plasma evolving.

Figure 5. The plasma data comparison of different plasma modeling for shot # 21523: (a) radial plasma position ($R_P$) and (b) vertical position of plasma ($Z_P$)
Figure 6. Calculated mutual inductances during NPM analysis: ‘T-V M’ is time-varying mutual inductance, and ‘Rigid M’ is a static mutual inductances. PF1UU, PF1UL, and PL1LL represent each PF 1 coil section for CDA calculation. Note that the blue curve overlays the green one.

Figure 7 shows CDA+MIK analysis results of shot #21523, and the time evolution of $I_P$ is shown in the first row, $R_P$ and $Z_P$ in the second row, all PF coil currents in the third row, and the measured CDA voltage in the fourth row with the calculated MIK voltage induced by only PF coils. The voltage trend of $V_{MIK}$ is similar to that of measured CDA voltage, however, not exactly same at plasma ramp up and down phase. This shows inductive noises are not completely cancelled out during plasma discharge.

Figure 7. CDA+MIK analysis for a 1 MA plasma shot (#21523) in 2018

Figure 8 shows induced voltage comparison by plasma data between two modeling. The causes of induced voltages from plasma can be divided into three components such as plasma current ($V_{Ip}$), radial position ($V_{Rp}$), and vertical position ($V_{Zp}$). The averaged $V_{Ip}$ with developed model are 0.157 V and
0.155 V, whereas those of $V_{Ip}$ with simplified model are 0.109 V and 0.095 V during plasma ramp-up and down phases, respectively. The induced voltage caused by plasma current is estimated as 1.5 times larger in case plasma position was weight-averaged by the plasma current density and varying mutual inductances were used. In case of the $V_{Rp}$ and $V_{Zp}$, induced voltages are estimated as about 2.5 times larger. This results show revised plasma modeling estimated contribution of plasma effects on CDA larger than simplified modeling.

Comparative NPM analysis results between two modeling for shot #21523 are shown in figure 9. The averaged voltage difference between $V_{CDA-NPM-Simplified}$ and $V_{CDA-NPM-Developed}$ is 0.1 V during plasma ramp up and down phases. This leads the induced voltage from plasma data of developed modeling can reduce remnant inductive noises after CDA+MIK process more than simplified model. The inductive noises were reduced averagely 0.2 V comparing to CDA+MIK result ($V_{CDA-MIK}$) in case of developed model, whereas 0.1 V was reduced in case of simplified model. That is, the remnant inductive voltage based on the results considering only PF coils was reduced by 0.2 V, and this indicates plasma effects on CDA+MIK method was estimated as 0.2 V. The developed plasma modeling can reduce quench threshold voltage as 0.2 V comparing to CDA+MIK results. However, there still inductive voltage remained. This results may represent plasma effects are still under-estimated. This plasma modeling still adopt a single filament assumption, so that better noise cancellation can be possible if plasma information is totally volumetric data. Further detailed analysis will include multi-filament modeling.

![Figure 8](image_url)

**Figure 8.** Comparison of induced voltage by plasma data between two modelling: (a) $V_{Ip}$, (b) $V_{Rp}$, and (c) $V_{Zp}$.
5. Conclusion

A NPM has been developed by considering plasma current density and plasma evolving for more accurate plasma modeling. The compensated voltage only considering PF coils shows that inductive noises are not completely cancelled out during plasma discharge. The previous NPM analysis in which plasma is assumed as a single-filament and having rigid motion also represents remnant inductive noises. Therefore, the NPM was developed in this study by two assumptions: (1) revised plasma data ($R_p$ and $Z_p$) considering current density, and (2) time-variant mutual inductances. The developed NPM analysis result shows remnant inductive voltage was reduced by average 0.1 V compared to that of previous NPM analysis which shows plasma effects might be still under-estimated. Further detailed analysis will include multi-filament modeling to determine plasma effects on CDA+MIK method.

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