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Progress and improvement of KSTAR plasma control using model-based control simulators

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ABSTRACT

Superconducting tokamaks like KSTAR, EAST and ITER need elaborate magnetic controls mainly due to either the demanding experiment schedule or tighter hardware limitations caused by the superconducting coils. In order to reduce the operation runtime requirements, two types of plasma simulators for the KSTAR plasma control system (PCS) have been developed for improving axisymmetric magnetic controls. The first one is an open-loop type, which can reproduce the control done in an old shot by loading the corresponding diagnostics data and PCS setup. The other one, a closed-loop simulator based on a linear nonrigid plasma model, is designed to simulate dynamic responses of the plasma equilibrium and plasma current (I_p) due to changes of the axisymmetric poloidal field (PF) coil currents, poloidal beta, and internal inductance. The closed-loop simulator is the one that actually can test and enable alteration of the feedback control setup for the next shot. The simulators have been used routinely in 2012 plasma campaign, and the experimental performances of the axisymmetric shape control algorithm are enhanced. Quality of the real-time EFIT has been enhanced by utilizations of the open-loop type. Using the closed-loop type, the decoupling scheme of the plasma current control and axisymmetric shape controls are verified through both the simulations and experiments. By combining with the relay feedback tuning algorithm, the improved controls helped to maintain the shape suitable for longer H-mode (10–16 s) with the number of required commissioning shots largely reduced.

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1. Motivation

Tokamak operation costs are high, even for the tokamaks with full superconducting coil capability: annual operation requires dedicated machine preparation process longer than the time for the conventional tokamaks, including the cool-down procedure [1]. As a consequence, the practically allowed runtime for plasma experiments is usually 8–12 weeks per year for KSTAR tokamak [2–4]. The experiment schedule for applying any novel designs in the plasma control is more demanding and risk-taking if the design is not practically verified within the existing control constraints of the diagnostics and actuators. Control software development benefits if we have a suitable simulation environment to test newly developed algorithms against the known constraints. The constraints can be either from possible conflicts with the existing algorithms

during the development, or from the hardware limits that could give the control an immediate stop if violated. The ability to check against the plant system limitations is especially efficient when dealing with the superconducting coil actuators, for preventing loss of superconductivity which is usually caused by accumulated coupling AC loss through excessive PF coil current drive and current saturations at the end of the discharge.

The complexity of the plasma control system (PCS) is also a good reason to implement a future shot designer, which is a user interface that can save desired plasma control system settings for future applications to an incoming experiment shot. Usually the number of available control setpoints is huge for a tokamak. The number of feedback items for the KSTAR PCS increased to more than 30 items from the 4 items in the first year [5]. Practically the operators need to set up more than 100 entries for a shot design from scratch.

Hence an approach of offline optimization methods using simulations becomes essential for better utilizing controls in the limited runtime slot. The first attempt using a model-based approach has been taken for improving the axisymmetric magnetic controls to

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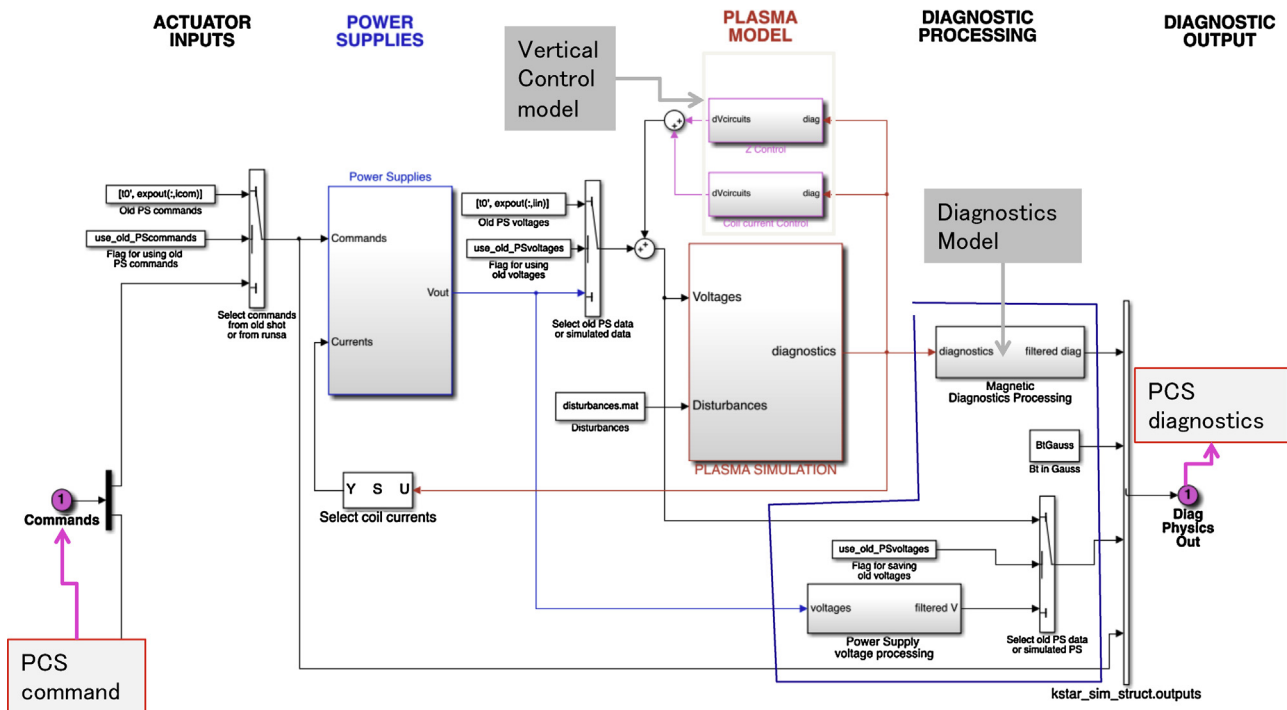 E-mail address: hahn76@nfri.re.kr (S.-h. Hahn).

Fig. 1. Structure of the closed-loop simulator for axisymmetric plasma magnetic controls. (For interpretation of the references to color in text, the reader is referred to the web version of the article.)

maintain the diverted shape for a longer H-mode discharge. In the next section, the structure and the verifications of the simulators are summarized. Application highlights of the developed simulator are described in Section 3.

2. Structure and validations of simulators

2.1. The open-loop simulator

Two kinds of the PCS simulator have been implemented for KSTAR. The first one is an open-loop type, called as "data simserver". The data simserver provides archived data of a shot to the PCS software in place of diagnostics input, hence the PCS software re-runs the old shot to recalculate the output of the PCS under a new algorithm or operator setup. The data simserver has been most frequently used to rerun the PCS for old shots to check if we can get better shot setup for the particular shot with the modified operator setup. For example, it is used to test and give a working real-time EFIT [6] snap setup when given diagnostics hardware constraints are changed during the operations.

Another advantage of the data simserver is that the PCS users can verify their ideas through the PCS software even when a useful plasma model is not available. The data simserver helps to develop and analyze hardware-related algorithm changes. For example, it can be used to add a new physics parameter estimator (like radial position estimator used in [5]) using existing diagnostics, hence it can help to add/change a control output of the actuator according to the new criterion that the estimator gives.

2.2. The closed-loop simulator

On the other hand, the closed-loop simulator resembles the plant more in a sense of that it provides system responses of plant/plasma caused by the PCS commands as a form of corresponding diagnostics. Hence it is possible to design and simulate the feedback loop using this type of simulator. An axisymmetric magnetic response model is implemented in this closed-loop type

simulator (typically called as "simserver") in order to give the PCS data representing simulated changes of the plasma due to prior PCS commands.

2.2.1. Structure and implementations

Following the method originally developed in DIII-D control simulator [7,8], the simserver is written using Simulink software under Matlab/TokSys [9] environment. Fig. 1 shows the structure of the Simulink simulator redesigned in 2012. When the simulation is controlled by the PCS, the PCS commands come to the input port in the left. The blue block, 'Power Supplies (PS)', simulates each power supply voltage responses to a given voltage command in time. A linear response model accounting for the pure delays/rise time is implemented in the block for the PS voltage output. A state-space plasma response model is implemented in the red block, using the coil power supply voltages as the input. The plant model consisting of 70 toroidal conductors are included in the model to generate the current responses due to the given voltages. The gray blocks, "Vertical control model", are an idealized model of the vertical position control, including the estimator of the vertical position and the PD loop. Simulated diagnostic input is fed to the diagnostics model blocks, representing signal-conditioning apparatus (e.g. hardware filters) in the diagnostics data acquisition system. Most channels are modeled as low-pass filter boxes with different corner frequencies based on the measured frequency response of each component.

A setup script is also written using Matlab in order to provide user inputs essential to build the component models. The inputs for building the response model are provided from a user-specified old shot through an automated Matlab script under the TokSys environment. The script gets the user-specified inputs such as shot number, set of magnetic equilibria, and the diagnostics data vectors in time. After reading the inputs, the script analyzes the equilibrium set to extract information necessary to build a linear, non-rigid plasma response model [10] inside the red block. This model also needs the magnetic responses by perturbations on both the plasma energy (β_p) and plasma current distribution, characterized using