GA-A24776

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This is a preprint of a paper to be presented at the 23rd Symp. On
Fusion Technology, Venice, Italy, September 20–24, 2004, and to
be printed in the *Proceedings*.

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Work supported by
U.S. Department of Energy
under DE-FC02-04ER54698 and DE-AC02-76CH03073

GENERAL ATOMICS PROJECT 30200
JULY 2004

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DIII-D Integrated Plasma Control Tools Applied to Next Generation Tokamaks

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Abstract. A complete software suite for integrated tokamak plasma control has been developed within the DIII-D program. The suite consists of software for real-time control of all aspects of the plasma, modeling, simulation and design tools for analysis and development of controllers, a flexible and modular architecture for implementation and testing of algorithms and many fully validated models. Many elements of the system have been applied to and implemented on NSTX and MAST. The DIII-D realtime plasma control system together with the integrated modeling and simulation suite have been selected for operational use by both the KSTAR and EAST tokamaks, and are also being used at General Atomics to investigate control issues for ITER.

1. Introduction

The DIII-D Plasma Control System (PCS) [1,2] has evolved to satisfy expanding DIII-D requirements for over a decade, is now operating at both NSTX [3] and MAST [4], and is being adapted for use by KSTAR [7] and EAST [8]. A parallel modeling/simulation effort [5,6] is integrated with this environment and the combination provides a framework for development, validation and implementation of algorithms for tokamak plasma control.

The functional layout of the overall architecture is shown in Figure 1. Plasma control during experimental operations is provided by a multi-CPU computer running the PCS software (1A⇔2A). For “hardware-in-loop” simulations, switch S1 can be set to allow the PCS hardware to drive a model based Simulation Server (SimServer) (1A⇔2B). For complete software simulation of the PCS and tokamak, essential for new tokamaks like KSTAR, EAST and ITER, a closed loop simulation including a software version of the PCS (1B ⇔ 2B) is used. This software version of the PCS contains the same user interface and data storage (MDSplus) as is normally used for tokamak operation and allows for complete off-line simulation of the tokamak, including post processing of shot data using conventional plasma diagnostic programs like EFIT [9]. The PCS software contains all control laws required for plasma operation, including the isoflux and real-time EFIT shape reconstruction algorithims [10].

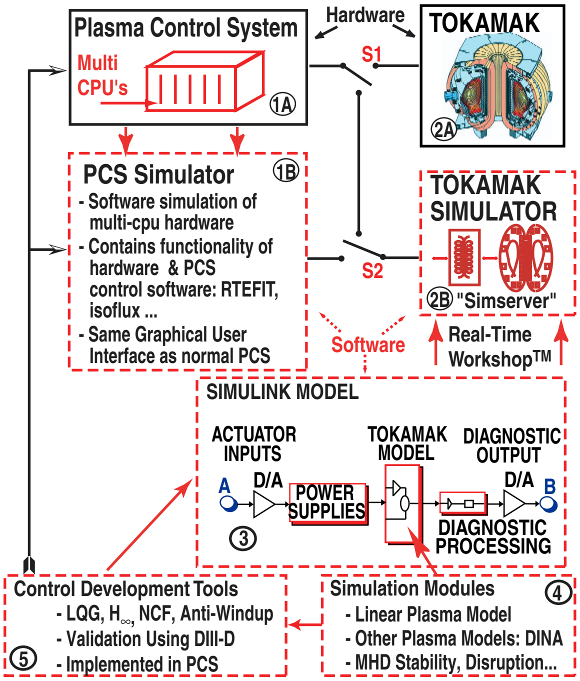

Fig. 1. DIII-D derived PCS and model/simulation framework. Solid boxes are hardware; dashed boxes are software. Switches S1 and S2 allow for: (1A⇔2A) experimental tokamak control, (1A⇔2B) "hardware-in-loop" simulations and (1B⇔2B) complete closed loop software simulation.

The SimServer executable (2B) is generated from a Simulink^{TM} model (3) containing all components essential for a complete simulation of the plasma dynamics being studied, including power supply actuators, tokamak model and diagnostic output. All model elements are validated based on DIII-D and other machine results. The primary shape control model includes PF power supplies, the passive/active conductor system, a linearized plasma model, and magnetic diagnostic outputs. Other models (4) are available which can be added to the simulation, such as the nonlinear, plasma evolution code, DINA [11], or modules to simulate non-axisymetric phenomena such as neoclassical tearing modes and resistive wall modes suppression [5].

Controller development (5) relies on similar models and readily available Matlab^{TM} control development algorithms. Controllers can be operated in closed loop within the Simulink^{TM} environment prior to implementation in the PCS. Preliminary testing of the PCS implementation is done using the complete software simulator (1B ⇔ 2B) for initial tests and for machines in the design stages, and final testing of controller implementation uses the "hardware-in-loop" functionality of the environment (1A⇔2B).

2. Model Development / Validation

The primary shape simulation/modeling tool relies on a linearized plasma model derived from perturbation of an equilibrium plasma, produced by EFIT or other equilibrium code, combined with a set of modified circuit equations and is cast in a state-space description:

$$\dot{I} = AI + Bu, \; y = CI + Du,$$

where I is the state vector of the system (coil, passive elements, and plasma current), y is the model output vector (diagnostic signals & ideal plasma variables), and u is the input voltage. This model generation technique has been extensively validated based on DIII-D experimental data [6]. Other models such as power supply and diagnostic signal processing have varying degrees of complexity depending on the machine being simulated.

Figure 2 shows examples of the modeling and validation tools applied to NSTX. Fig. 2(a) shows the overall geometry used to establish the electromagnetic model; experimentally determined plasma shape evolution during an unregulated Vertical Displacement Event (VDE) is also shown. Figure 2(b) shows the vertical instability growth rate of the unstable mode as predicted by a linearized plasma model based on equilibria reconstructed during the VDE shown in Fig. 2(a). The experimental growth rate of 31 rad/s compares favorably with the model generated 25 rad/s. Figure 2(c) shows model versus experimental response for a single coil vacuum excitation test. These types of validation studies are essential for existing machines and provide a basis for model extrapolation to future machines.

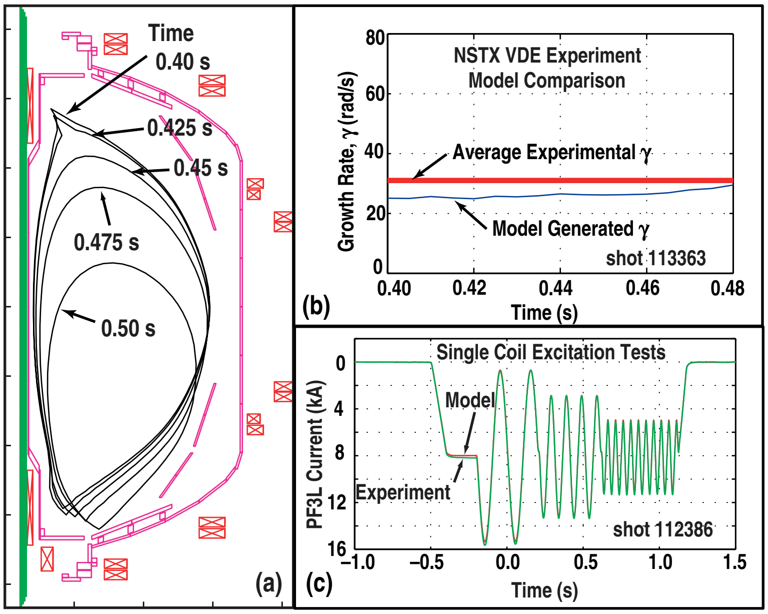

Fig. 2. Model and validation results for NSTX. (a) shows the coils and passive geometry along with the plasma boundary associated with the VDE studied in (b). (b) shows the experimental average VDE growth rate and comparisons with model growth rate predictions for the plasma shown in (a). (c) shows comparisons between experiment and model for single coil excitation tests with coil voltage as input.

3. Controller Design

The integrated control environment makes use of Matlab$^{\text{TM}}$ design tools to develop, test and implement shape controllers for various machines. Controllers ranging from simple to complex have been developed for many next generation machines along with DIII-D. In particular, a multiple-input-multiple-output (MIMO) controller was developed based on Normalized Coprime

Factorization design tools in Matlab to control a simulator of the ITER shape control system. The simulator consisted of simple power supplies with saturation, delay and rate-limit components connected to the poloidal field (PF) coils and including interactions with an axisymmetric model of the passive structure. A simple linearized plasma model was used to simulate the plasma response based on the reference ITER equilibrium. Control was applied to the 12 PF coils to regulate plasma current and six gap measurements [12]. Figure 3 shows controller performance based on an initial 10 cm Z-perturbation to the system. The control algorithm stably brings the gaps to zero within approximately 1s.

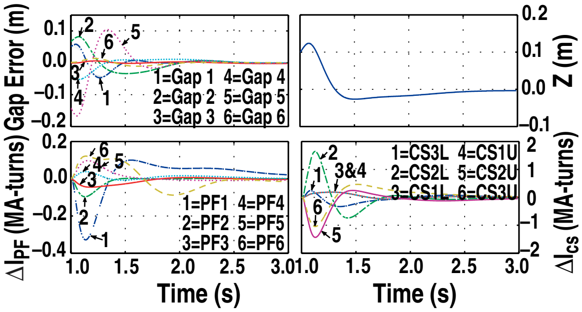

Fig. 3. Response of simulated ITER gaps to an initial 10 cm plasma displacement using a MIMO controller.

4. Simulation

Simulation of controller and system response is essential for implementing new controllers and for exploring stability and control aspects of new devices. A simulation of the EAST vertical control system was performed within the Simulink environment using a model including a linear power supply driving the internal PF coils, passive structure elements and a linearized double null plasma model. A single pole power supply with a response time of 0.7 ms was used in the analysis. The open loop vertical growth rate of this system is 560 rad/sec. A proportional/derivative controller was utilized with feedback on an ideal Z position measurement through a 60 μs filter. Figure 4 shows the system response to a 10 cm initial vertical displacement request based on several controller gain set points. Reasonable performance is achieved with G_p~2000 V/m and G_d ~ 4 V/(m/s) and produces a response time of order 1ms with voltage and power demands of 1.1 kV and 2.5 MW, respectively. These values are within power supply specifications.

5. Implementation and Test

Complete software simulation of the PCS in closed loop with a tokamak simulator (SimServer) is extremely valuable for existing machines like DIII-D, NSTX and MAST. For new machines like KSTAR, EAST and ITER this simulation capability provides insight into PCS design specifications, provides a means of validating controller designs, allows for overall control testing and pre-commissioning, and provides a means for gaining operational experience prior to commissioning.

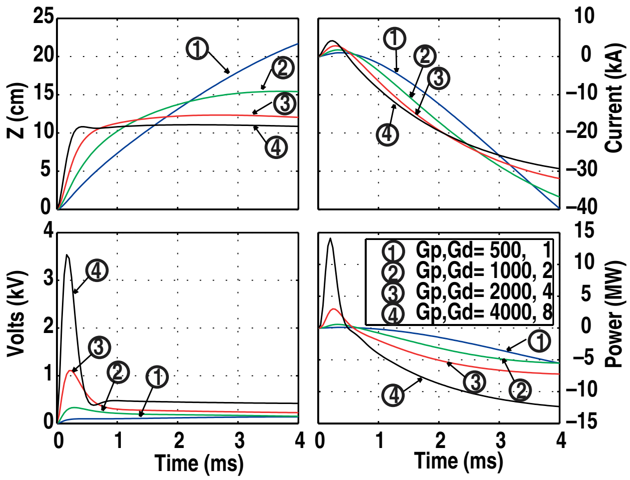

Fig. 4. Closed loop simulation of the EAST plasma response to a 10 cm vertical displacement for different gain settings for a proportional (G_p) and derivative (G_d) controller.

Figure 5 shows a full PCS/SimServer simulation of the KSTAR PCS operating with a simple R, Z, I_p controller connected to a tokamak model constructed to emulate the expected plasma position control aspects of the KSTAR machine. The simulator includes ideal power supplies, a linearized plasma/conductor system, diagnostics, filters and simulated experimental noise. Vertical stability is provided through derivative feedback using the vertical Internal Control (ICV) coils and proportional feedback using the superconducting coils. Radial control is provided by proportional control using the radial IC coils (ICR). The simulation commanded by the PCS is seen to follow the requested linear ramp of the major radius in the presence of diagnostic saturation, delays, rate limits, anti-alias filters and the actual PCS response. The large voltage requirement associated with the vertical position coil is primarily a function of the unstable vertical mode and the simulated experimental noise.

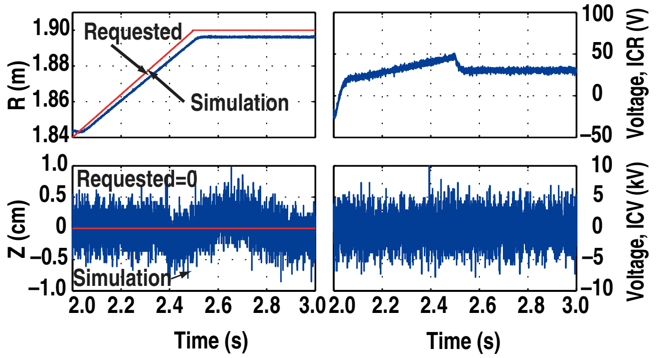

Fig. 5. PCS/SimServer simulation of KSTAR including all time delays, saturation, filtering and simulated experimental noise. Voltages shown are for the IC coils (vertical and radial) used for primary control.

6. Summary and Conclusions

A flexible, modular and extensible tokamak plasma control environment has been developed within the DIII-D program. Components of this environment are being applied to present and next generation devices for design of high reliability controllers and for implementation of the realtime PCS. The PCS and other elements of the integrated plasma control suite provide the necessary infrastructure and modeling tools needed to meet the advanced tokamak control mission of these devices in the years to come.

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Acknowledgment

Work supported by U.S. Department of Energy DE-FC02-04ER54698 & DE-AC02-76CH03073.