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*Far-Tech, Inc., San Diego, California

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ABSTRACT

Plasma control design approaches and solutions developed at DIII-D to address its control-intensive advanced tokamak (AT) mission are applicable to many problems facing ITER and other next-generation devices. A systematic approach to algorithm design, termed “integrated plasma control,” enables new tokamak controllers to be applied operationally with minimal machine time required for tuning. Such high confidence plasma control algorithms are designed using relatively simple (“control-level”) models validated against experimental response data and are verified in simulation prior to operational use. A key element of DIII-D integrated plasma control, also required in the ITER baseline control approach, is the ability to verify both controller performance and implementation by running simulations that connect directly to the actual plasma control system (PCS) that is used to operate the tokamak itself.

The DIII-D PCS comprises a powerful and flexible C-based realtime code and programming infrastructure, as well as an arbitrarily scalable hardware and realtime network architecture. This software infrastructure provides a general platform for implementation and verification of realtime algorithms with arbitrary complexity, limited only by speed of execution requirements. We present a complete suite of tools (known collectively as TokSys) supporting the integrated plasma control design process, along with recent examples of control algorithms designed for the DIII-D PCS. The use of validated physics-based models and a systematic model-based design and verification process enables these control solutions to be directly applied to ITER and other next-generation tokamaks.

1. INTEGRATED PLASMA CONTROL DESIGN PHILOSOPHY

We use the term “integrated plasma control” (IPC) to refer to a particular systematic approach to plasma control design. This approach is characterized by using validated physics-based models to design controllers, and verifying controller performance specifically by operating actual realtime implementations against sufficiently detailed simulations. IPC has also been used to refer to control schemes and corresponding design methods which take into account the relevant coupled interactions in the system. Taking this latter sense to be implicit in any systematic model-based design approach (and in the assumption that the controllers of interest are multivariable), we focus on the methods and tools required. It is essential that the approach make use of physics-based models in order to enable reliable application to more than one device and confident extrapolation to future devices. While initial physics models may be very complex, possibly implemented in large computer codes, practical control design considerations make it important to reduce such representations to lower-order, often linear or simple nonlinear models. These “control-level” models are then used for design, and the resulting candidate controllers are tested in simulations containing more detailed descriptions. One critical aspect of the final verification step is the use of simulations which interoperate with the realtime control hardware and software systems themselves. This capability allows confirmation of both control performance and correctness of algorithm implementation.

Development of the IPC approach and its related tools has been motivated at DIII-D by the demands of the advanced tokamak program. Advanced tokamaks are characterized by extensive use of active control in order to attain and stably sustain high values of both normalized beta, β_N, and high confinement, or H-factor. Operating at high β_N in particular necessarily implies operating near or beyond MHD stability boundaries, so that high performance active stabilization becomes essential. Another aspect of DIII-D operation which has driven the need for high confidence control design is the need to minimize experimental time used for control development. ITER [1] has even stronger motivation for such systematic control design and verification, as it is highly constrained in number of discharges that can be produced in its operational lifetime, and the consequences of poor control can be severe.

The final essential element of IPC is validation of the physics-based models against experimental data. Validation of control-level physics models in relevant operating regimes allows high confidence extrapolation to control designs for other devices.

2. TOKSYS: GENERIC SYSTEM FOR TOKAMAK CONTROL MODELING

A key enabling tool for integrated plasma control is a computational environment for producing models of new tokamak systems or physics, validating those models, and both designing and verifying controllers based on the models. The TokSys code suite provides this functionality for DIII-D and the devices that share versions of the DIII-D PCS [2]. The system is implemented in the Matlab/Simulink® environment, presently a commercial standard for control design, signal processing, and communications engineering. Use of a mature commercial product with a strong and sustained history and status as a broad-based standard in industry exploits a robust maintenance and support infrastructure, and can facilitate international, cross-institution interoperability. Examples of TokSys application include control-level models for axisymmetric and nonaxisymmetric MHD plasma responses, multivariable model-based MHD controller design, and verification of both algorithm implementation and control performance using TokSys simulations.

The key elements of TokSys are represented schematically in Fig. 1. System geometry and other relevant configuration information are typically described in machine-specific data files, in various formats. These files are interpreted and the data files needed for construction of the TokSys model are created in standardized formats by the define_data.m function. Those data are used by the make_tok_objects.m function to construct the system of magnetic mapping objects (for example mutual inductances among vessel elements, or between the plasma grid region and magnetic diagnostics) and other descriptors of the electromagnetic system. Data objects follow a standardized naming convention for ease of recognition: subscript “v” refers to vessel or other passive structure, “c” refers to active coils, “p” refers to the plasma circuit (or grid region), etc. TokSys is fully integrated with the EFIT equilibrium code, which provides reference equilibria for calculation of plasma responses. Codes exist in the TokSys suite for calculating a rigid R,Z plasma response (rzrig.m) or a nonrigid plasma response (nonrig.m), along with optional constraint choices for plasma current or flux conservation. A plasma circuit equation is constructed for resistive plasma current evolution and ohmic loop voltage drive. The collection of standardized data objects along with plasma response objects are then used by the build_tok_sys.m function to construct the actual state space system model for design of controllers or fundamental analysis.

Several scripts and functions are provided to support generation of controllers and control parameter estimators for the PCS. One approach to circular (or simply vertically elongated) plasma control provided in the PCS makes use of linear estimators for desired position (or shape) quantities, based on magnetic measurements. The make_predictors.m function calculates the weights on magnetic measurements to provide position or shape estimates, and the make_ctrlvecs.m function determines weights on voltage or current in each shaping coil that define the control response to a specific position or shape error signal. Control functions such as design_shpctrl.m can then be used to produce PID gains for good dynamic performance. A rich array of functions and scripts exists for design of state space controllers for the realtime EFIT-based scheme, which is the standard shape control, used in the DIII-D PCS. This scheme regulates the flux at various control points specifying the plasma boundary to be equal to the X-point (or a limiter point) flux value, and separately regulates the X-point (or limiter point) location.

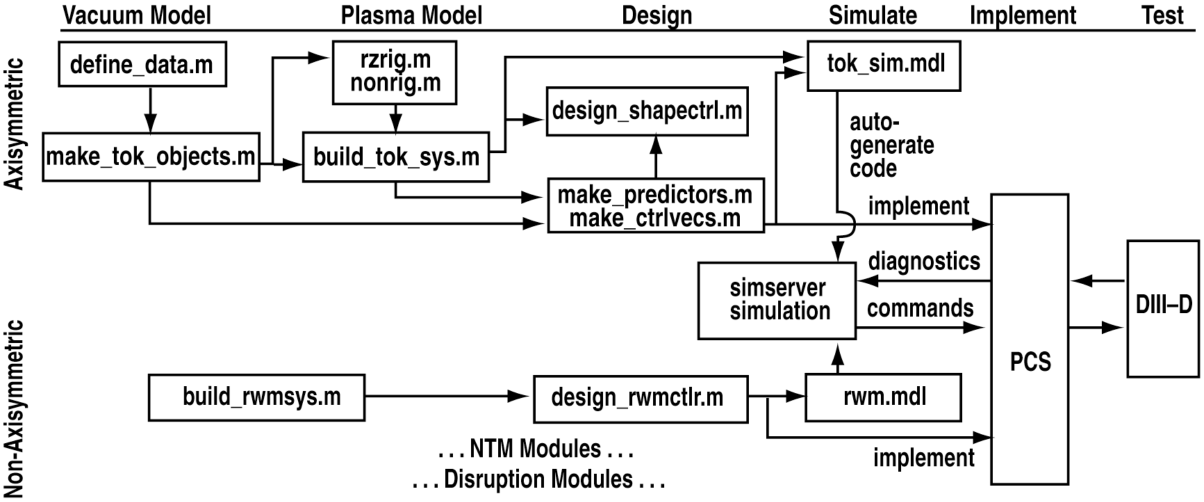

Fig. 1. TokSys elements schematic, a generic modeling and simulation environment in Matlab/Simulink enabling integrated plasma control.

Various Simulink simulations have been developed for testing of control action separately in the case of each of the devices sharing the DIII-D PCS, as well as for some tokamak designs, including ITER. Final verification of implementation and control performance is accomplished in each of the PCS-controlled devices by connecting these simulations directly to the actual realtime PCS (including a version created to study ITER control issues). In addition to algorithm verification, this capability also allows control optimization in the presence of delays introduced by the digital control as well as the ability to study tradeoffs in algorithm performance versus computational speed. In order to study nonlinearities and other complex physics associated with the plasma itself, TokSys simulations can make use of detailed nonlinear core plasma evolution modules derived from the LLNL Corsica [3] or TRINITI DINA [4] codes. Use of these codes in TokSys provides examples of cross-institution code interoperability, an essential process to maximize efficient use of control resources among ITER Parties and the broader control community. It should be noted that the form of these simulations has not yet been standardized within TokSys to make a single structure generically encompass the needs and configurations of all devices. At the moment, each such simulation in TokSys is somewhat unique (although sharing many common features). Completion of a standardized, generic simulation tool will be essential for full sharing of design resources across institutions and design teams, particularly among the ITER Parties actively engaged in control design.

A set of nonaxisymmetric modeling modules has also been designed for DIII-D control development, including neoclassical tearing mode (NTM) and resistive wall mode (RWM) responses [5]. For example, build_ntm.m can be used to construct an NTM model system based on the Modified Rutherford equation, and setup_d3d_sim_build_ntm.m is used to define the simulator that is connects to the PCS to test actual algorithm implementations (see Section 3 for details of the RWM modeling system).

3. INTEGRATED PLASMA CONTROL APPLIED TO NTM AND RWM CONTROL DESIGN IN DIII-D

The TokSys environment includes several nonaxisymmetric MHD modules, which have been used for ongoing design and verification of various MHD control algorithms on DIII-D. One class of such algorithms to have benefited greatly from this approach is that of neoclassical tearing mode (NTM) control. The DIII-D gyrotron system is used to apply electron cyclotron current drive (ECCD) very precisely at the location of magnetic islands that form on rational q-surfaces at sufficiently high beta. Driving sufficient current within the islands can shrink them completely, stabilizing the mode [6]. Without such stabilization, these islands can degrade confinement, or in the worst cases, grow large enough to produce a discharge-terminating plasma disruption. The NTM control system can perform a complex search process, homing in on the correct alignment between the current deposition spot and the island, and maintaining the alignment once the island is suppressed [7]. The many parameters that specify the correct performance of this highly nonlinear algorithm are designed using TokSys models and simulations.

RWMs represent another area of intense research in MHD stability control at DIII-D. An array of external (“C-coil”) and internal (“I-coil”) nonaxisymmetric coils are used to apply magnetic fields with the same toroidal mode number (n=1 to date) as the dominant RWM in order to stabilize the mode and raise the plasma beta above its no-wall limit [8]. The I-coil array consists of a set of 12 water-cooled picture-frame coils mounted on the interior of the vacuum vessel beneath the protective carbon tiles. Six of these coils are evenly spaced toroidally above the outboard-midplane, and 6 identical coils are located at the same toroidal locations below the outboard midplane. The I-coils have better coupling to the plasma and less shielding by the vessel wall than the C-coils, and are thus favored for fast stabilizing control. Extensive experimentation and development have been done on understanding the physics and stabilization of these modes in DIII-D over the last decade [9], along with significant model-based control design and analysis [10,11]. Integrated plasma control design methods have been applied to model based controllers being prepared for experimental use in upcoming campaigns.

One control scheme which has been designed and implemented is to make the control voltages applied to each n=1 connected pair of the set of 12 I-coils depend on estimates of the RWM mode amplitude from magnetic diagnostics. The mode amplitude estimate is calculated using the Far-Tech, Inc. matched filter derived from the vector magnetic diagnostic signals predicted by a linear MHD stability code [12]. The matched filter is thus completely physics-based, with no empirical data or experiment-specific adjustments. The plasma-conductor models presently used for design under this scheme employ the Far-Tech eigenmode representation of the DIII-D passive structure and plasma coupling, allowing low-order model-based controllers to be designed [11]. Surface current eigenmodes representing vessel currents are derived by solving an eigenvalue equation of the form

$$\nabla_s \cdot \left[\frac{\eta}{\Delta} \left(\vec{\nabla} v\right)^2 \nabla_s K_m \right] = -\left(\vec{\nabla} v\right)^2 \lambda_m K_m \quad , \qquad (1)$$

where $K_m(l,\phi) = \kappa_m(l) e^{-in\phi}$. The Laplacian operator is defined by $\nabla_s = \hat{l}\,(1/R)(\partial/\partial l)R + \hat{\phi}\, in/R$ in the (v, l, ϕ) coordinate system corresponding to (radial dimension, poloidal length, toroidal angle). The eigenvalues $\{\lambda_m\}$ are effectively surface resistances corresponding to the eigenmodes and having units of resistivity/length^3. The Far-Tech matched filter and eigenmode-based RWM model presently used in TokSys represent another example of cross-institution interoperability of models, enabled as in the case of Corsica and DINA by the use of the Matlab/Simulink standard.

The TokSys RWM system results in a first order matrix circuit description [10]:

$$M_{ss} \dot{I}_s + R_{ss} I_s + M_{sp} C_{pp} M_{ps} \dot{I}_s = V_s \quad . \qquad (2)$$

where I_s and V_s denote currents and voltages in stabilizing conductors respectively, including both the vacuum vessel and the active control coils. C_{pp} is a scalar coupling coefficient between the modal perturbed surface current K_p and the plasma surface flux, ψ_p. These two quantities are thus related through $K_p = C_{pp}\psi_p = C_{pp}(M_{ps}I_s)$, so that C_{pp} completely determines the open loop growth rate of the instability.

Transforming Eq. (2) to standard state space form allows design of high-order controllers which can exceed the performance available from simple proportional-derivative (PD) controllers. As illustrated in Fig. 1, and similar to the axisymmetric modeling structure of TokSys, this state space model is produced by the function build_rwmsys.m. The design code design_rwmctrlr.m allows design of PD, linear quadratic Gaussian (LQG), and various robust controllers. The PD design facility provides a full gain space search to optimize the desired performance of a PD design. We select PD gains near the center of the stable region to maximize robustness (by one measure). Figure 2(a) shows open loop uncontrolled growth of a mode with growth rate of γ=120 rad/s, as well as the time history resulting from enabling this PD controller once the mode has grown to 0.2 G in amplitude, successfully stabilizing the mode. Figure 2(b) shows a similar simulation using an LQG controller with similar dynamic response to the PD, based on the same γ=120 rad/s open loop system, also successfully stabilizing the mode. However, Figs. 2(c) and 2(d) compare the same two controllers under (higher beta) conditions in which γ = 800 rad/s. Both controllers having been designed at low beta (γ = 120 rad/s), the LQG controller provides stability over a wider range of growth rates including this value, while the PID controller fails to stabilize at the higher growth rate.

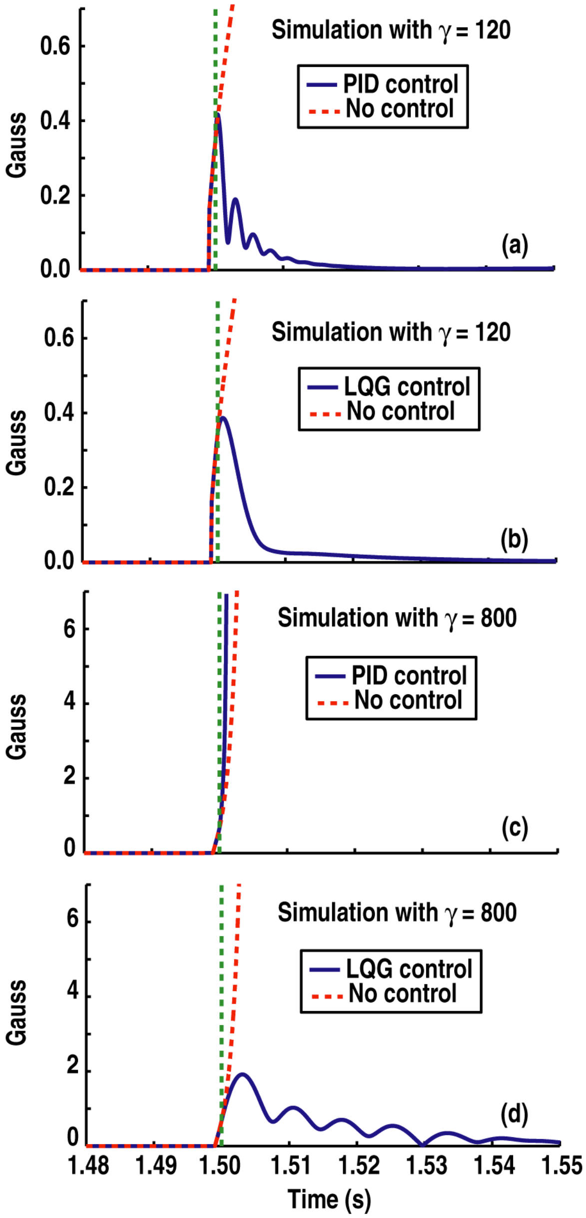

Fig. 2. Comparison between PD controller and LQG controller for RWM stabilization. The LQG controller is able to stabilize the mode for larger growth rates than the PD controller.

Figure 3 shows a TokSys Simulink module used to test performance of RWM controllers under more realistic power supply representations, including delays and voltage saturation. This simulation can also connect to the actual PCS software in order to verify implementation accuracy and control function. Figure 4 shows results of such a simulation, comparing responses of a PD controller implemented in the PCS to step commands for different choices of proportional gain, Gp. The figure shows that under realistic power supply voltage saturation and response dynamics choosing a Gp too high results in unstable oscillation of the closed loop system.

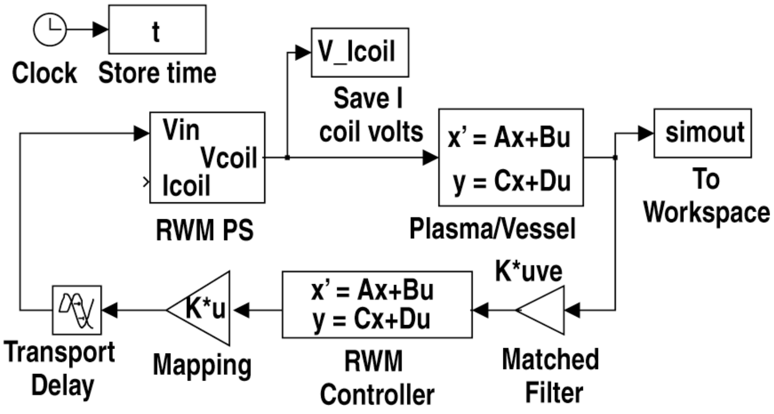

Fig. 3. Simserver model for testing of RWM control performance.

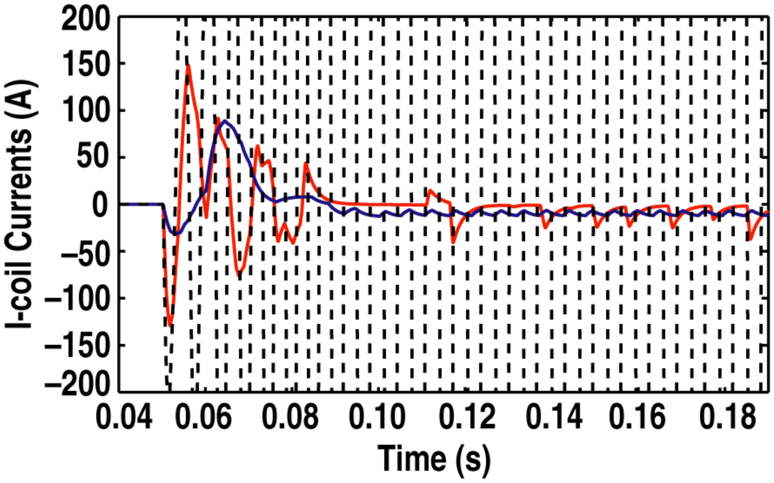

Fig. 4. Results of simserver simulation of RWM control algorithm designed based on Far-Tech eigenmode model. The simulation shows that poor choice of proportional gain G_p can drive the closed loop system into instability. Blue curve is for $G_p = 1$, red for $G_p = 6$, and dashed for $G_p = 12$. (Figure expanded to show stable response.)

4. PCS FAULT RESPONSE ARCHITECTURE AND ALGORITHMS

The DIII-D PCS incorporates a highly flexible architecture for fault detection and response, which finds a variety of experimental use at DIII-D and other devices using the PCS. In EAST [13] tokamak operations, for example, the PCS assists in protecting the superconducting coils from overcurrents by directly detecting excursions close to a current limit or identifying a large error signal level, then signaling a fault condition to the machine control. DIII-D experimental needs often use the fault response system in different ways. For example, in high performance discharges, it is frequently necessary to change from one control phase to another if the physics goals of a discharge are not being met. Switching to a soft landing shot termination in the presence of a robust 2/1 NTM serves to limit the neutron inventory expenditure after the confinement (and thus physics interest) is destroyed by the NTM and also avoids an NTM-induced disruption. Similarly, switching to a control phase with different programmed heating can produce profiles with different MHD stability characteristics than the initial target, depending on modes and confinement quality initially produced.

The method used in the DIII-D PCS and its derivatives is to execute a set of fault algorithms, whose only purpose is to detect and respond to faults in device operation, in parallel with the feedback control algorithms. Such parallel execution is trivially implemented in the highly parallel PCS. When a fault is detected, the response by all control loops is coordinated by the fault response logic. Several different response scenarios can be chosen, depending on the severity of the fault. The philosophy of the PCS architecture is to support a layered response by the supervisory (machine) control: to try to continue the shot, if it makes sense to do so; to perform a controlled shutdown, e.g., ramp the PF currents to zero, if it is safe to take the time to do this; or to perform an uncontrolled shutdown if danger to the device does not allow for a controlled shutdown. In fact, the architecture supports switching between different scenarios, depending on the decision logic incorporated into the fault algorithm within each scenario. No fault detection logic is incorporated in any individual feedback control loop, although data computed within these loops is sometimes passed to the fault algorithms. This centralization of fault detection and response makes it much easier to coordinate appropriate responses and has the added benefit of reducing code complexity and maintenance.

The PCS also supports coordination of fault responses with supervisory or machine control. Signals received from external systems through digital I/O circuits can be used to notify the PCS of an externally detected fault, which may require a response by the PCS. At EAST, the PF power supply systems notify the PCS if their internal controls detect a fault. The digital I/O can also be used to support detection by the machine control of a fault within the PCS. At DIII-D, a “watchdog timer” circuit is written on every control cycle by the PCS. If the PCS fails to update this watchdog circuit, a timeout will occur and trigger a fault condition.

5. SUMMARY AND CONCLUSIONS

A systematic approach to control design and verification such as the integrated plasma control process, will be essential to the success of ITER and many next-generation devices. Such machines cannot afford to expend limited experimental operations time to develop control algorithms and may also have severe machine safety constraints that require high confidence control verification prior to operational use. The TokSys suite of codes and its interoperability with the DIII-D PCS provide an example of this systematic design approach that addresses many of the characteristics needed for ITER. TokSys tools have been used to design controllers for DIII-D and other devices sharing the DIII-D PCS, in many areas including axisymmetric control, MHD stabilization, and fault detection and response. Design and analysis of RWM control algorithms provides an illustration of the approach and array of computational tools available. Recent RWM analysis has shown that state space control algorithms with fully populated control matrices can improve on the performance attainable by PD controllers and has produced candidate designs for use in DIII-D in upcoming campaigns. Successful application of such model-based controllers in RWM stabilization experiments will help demonstrate the efficacy and readiness of the approach to answer the needs of ITER.

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