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Plasma q-profile control in tokamaks using a damping assignment passivity-based approach

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ABSTRACT

The IDA-PBC based on PCH model for tokamak q-profile is investigated. Two scenarios are carried out. The first one is the resistive diffusion model for the magnetic poloidal flux. The second one is extended with the thermal diffusion. A feedforward control is used to ensure the compatibility with the actuator physical ability. An IDA-PBC feedback is proposed to improve the system stabilization and convergence speed. The controllers are validated in the simulation using RAPTOR code and tested in TCV, the result is analyzed and the followed discussion proposed the required improvement for the next experiments.

1. Introduction

A tokamak is a facility constructed with the shape of a torus (or dough-nut) in which a plasma is magnetically confined and heated in order to produce nuclear fusion reactions (see Fig. 1 for a schematic view and the Wesson's classical monograph, Wesson, 2004, for a large comprehensive reference textbook). It aims at producing energy from the controlled nuclear fusion reactions. However many challenges remain to prove the scientific feasibility of this goal and then to move towards a fully functional plant. A suitable control model for these plasma dynamics is then a success key in the fusion research. There are many different objectives in tokamak plasma control (Ariola & Pironti, 2008; Pironti & Walker, 2005). One of them consists in handling the MHD (Magneto-Hydro-Dynamics) instabilities and improve the plasma confinement, while maintaining some current, temperature and pressure density profiles. Hence the goal is to reach some specific non-uniform profiles of the 1D plasma safety factor q-profile (equivalent to the inverse of plasma current density), an important parameter for both plasma stability and performance.

In this context the 1D resistive diffusion equation for the magnetic flux in the plasma (Blum, 1989, chap. 6) is a commonly used control model. Readers could refer to Witrant et al. (2007) for investigations on this model for control purposes or to Ouarit, Brémond, Nouailletas, Witrant, and Autrique (2010) for application to model-based predictive control. A similar model has been used to solve the current profile optimal tracking problem (Ou et al., 2011) or to design robust controller for the poloidal magnetic flux profile (Ou, Xu, & Schuster, 2010). Feedback control using Lyapunov approach (Argomedo, Prieur, Witrant, & Brémond, 2012), or sliding mode (Gaye et al., 2011) is also proposed. Note also that two-time scale extensions have already been considered for simultaneous magnetic and kinetic (temperature) profile control in tokamak (Moreau et al., 2008).

This model also takes into account the plasma resistivity variations and the bootstrap current[1] described in Wesson (2004). Both of these effects are large and very sensitive to the plasma temperature. When this dependence is considered, scaling laws are usually used to determine the system parameters (resistivity and bootstrap current), see Boyer, Barton, and Schuster (2013) or Moreau, Crisanti, and Litaudon (2003). However, to the best of our knowledge, there is no work proposing the design of feedback controls using both the plasma resistive diffusion equation and the

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[1] A magnetohydrodynamic coupling effect which produces an extra current density.

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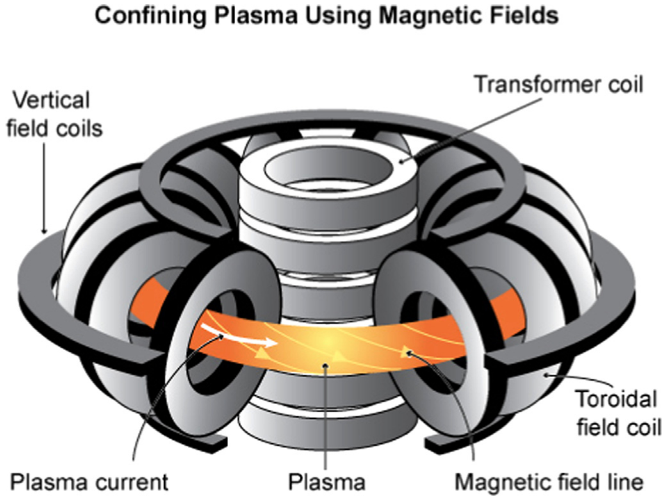

Fig. 1. Schematic view of a tokamak with the electrical solenoids: the magnetic field generated by the three magnets makes the plasma gas ions following helicoidal trajectories along the torus.

plasma thermal equation (here roughly modeled using a heat transport equation), as well as the corresponding interdomain couplings and actuators in both magnetic and thermal domains to achieve a better safety factor profile regulation.

On the other hand, most of these models already possess a Hamiltonian structure which is considered essential by plasma physicists since the fundamental laws governing charged particle dynamics are Hamiltonian. Therefore the preservation of the Hamiltonian structure provides some confidences that the truncations used to derive the fluid model have not introduced unphysical phenomena. The presence of the Hamiltonian structure has the additional benefit of providing important tools for calculations such as the MHD energy principle, solvability conditions for the equilibrium equations, and Casimir invariants. A model based on a port-Controlled Hamiltonian (PCH) formulation of the plasma TMHD (Thermal-Magneto-Hydro-Dynamics) in tokamaks is proposed in Vu and Lefèvre (2013). This model implies to modify the safety factor control problem into an equivalent magnetic field profile control problem. Spatial reduction and discretization methods, inspired from Moulla, Lefèvre, and Maschke (2012) and developed in Vu, Lefèvre, Nouailletas, and Brémond (2013), allow to reduce this 3D TMHD model to a finite dimensional PCH model. These symplectic reduction and discretization methods preserve the qualitative spectrum properties. Another consequence is that the finite-dimensional PCH model has the same invariants (for instance the total energy density) and model structure as the infinite-dimensional ones. Stored and dissipated energies in the finite dimensional model are simply approximation of the actual ones in the original distributed parameter model. Therefore, this finite-dimensional PCH model is the ideal one for the design of a high performance IDA-PBC (Interconnection and Damping Assignment - Passivity Based Control) controller (Ortega, van der Schaft, Maschke, & Escobar, 2002). This general control design, taking advantage of the Hamiltonian structured model, aims not only at sharping the total energy of the closed-loop system, but also at modifying the interconnection and dissipation structures of the original one. The controller achieves the robust stabilization by the passivity property of the desired closed-loop Hamiltonian model.

Here, the proposed IDA-PBC controller allows stabilizing 1D profiles of the safety factor q at the desired references directly by two actuators: the voltage V_{loop} at the boundary of the plasma[2] and the distributed non-inductive current-drive heating source J_{ext}. Besides, a third actuator, the external heating source S_{heat},[3] will be used as supplementary actuator which modifies the plasma temperature, hence indirectly some physical parameters such as the resistivity η profile or the bootstrap current.

Challenges in this control problem arise not only from the time variation of some parameters usually badly estimated (such as the resistivity or diffusivity for instance), but also from the technological constraints and non-linearities in the actuator models. In the considered facilities, the distributed controls J_{ext} and S_{heat} have specific spatial profiles, possibly depending from the control variable values themselves. In fact, the controllable inputs are rather the total external current power P_{ext} and the total external heating power P_{heat}. The consequence is that the system is a finite rank input–output control system with both boundary and distributed control actions. The finite dimensional coupled control model may thus be considered as an under-actuated system in the sense that the number of actuators is less than the number of system states (more details on under-actuated PCH systems could be found in Ortega & Spong, 2002). Hence, only a limited (finite dimensional) set of safety factor profiles is reachable. In this work, the available control signals are used to regulate the q-profile at a finite number of points. On one side, the corresponding q-profile on the whole spatial domain for the radial coordinate as well as the corresponding feedforward control are both computed in order to guarantee their compatibilities with the systems constraints. On the other side, the designed IDA-PBC feedback control aims at improving the system stabilization and convergence rate as well as at attenuating the approximation errors. Nevertheless, an integrator is still necessary to cancel the static error on the safety factor profile.

Two scenarios are figured out in the sequel. In the first one the PCH model equivalent to the resistive diffusion equation is used with two control signals V_{loop} and P_{ext} to regulate the q radial profile at two positions. In the second one, the magneto-hydrodynamic couplings and the thermal-electromagnetic model are investigated. A third control signal P_{heat} is used in order to reach a given reference value for the q radial profile at a third point. The simulation results will be presented, they are based on the RAPTOR code (cf. Felici & Sauter, 2012; Felici et al., 2011) for the TCV (Tokamak of Variable Configuration at EPFL, Lausanne, Switzerland) tokamak real-time control system. Besides, based on these previous simulation tests, the IDA-PBC controller has also been implemented and tested on the real TCV experimental facility.

This paper is organized as follows. In Section 2, the IDA-PBC design methodology is revisited and adapted to the specific studied case. In Section 3, the model plant is clearly explained, the control problem is revealed and the solution is proposed. The resistive diffusion model (cf. Vu et al., 2013) is firstly used as a control model in Section 4. A non-linear feedforward control takes into account the system constraints and a simple “linear” IDA-PBC feedback control is discussed with the help of some practical considerations. Some simulations and experimental results are also figured out. In Section 5, the coupled TMHD system (cf. Vu & Lefèvre, 2013) is then used as a control model for the IDA-PBC controller design. The same methodology is adapted for the new coupled system in Section 5.2 and the control law is tested only on simulation and compared to the previous one in Section 5.4. The paper ends with a brief conclusion and some prospects for the future works.

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[2] The loop voltage produced mainly by the central solenoid shown in Fig. 1.

[3] The external current drive J_{ext} and the external heating source S_{heat} are both the effects from various antenna systems around the tore.