A generalized plasma shape and position controller for the TCV tokamak

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1. Introduction

The most promising technological solution to maintain the environment required for thermonuclear controlled fusion for energy production is the tokamak concept, where current flowing through a dedicated set of coils is able to confine a plasma from the reactor walls. The TCV tokamak [1], featuring an elongated vessel and a set of 16 independently powered coils is extremely flexible for testing advanced plasma shapes. Improved performance of the plasma discharge in terms of energy confinement time and MHD stability is indeed obtained by shaping the plasma in an elongated cross section [2]. Elongated plasmas are vertically unstable and feedback stabilization of vertical dynamics is a standard feature in present-day tokamaks [3]. In TCV, shaping and position control is performed with the same poloidal field coils used as actuators. Controlling the vertical position with the magnetic field generated by a dedicated set of coils therefore limits the number of pre-calculated coil current references that can be tracked exactly and consequently lowers plasma shaping performances. Furthermore, standard feedback control of coils currents is not able to correct disturbances to the plasma shape (e.g. from ELMs or external heating) in real time.

To overcome these limitations, an advanced shape controller algorithm based on the isoflux scheme was recently implemented, integrated within the digital control system, and tested for accessing advanced configurations, in particular negative triangularity and snowflake plasmas [4]. In principle, the shape and position controller is able to optimize the 16 PF coils for exact shape and position control. In this architecture, however, shape control and position stabilization make use of the same control signal: the flux errors coming from a real time equilibrium reconstruction code [5], which introduces a computational delay in the feedback loop. This delay makes routine use of the advanced shape controller challenging, as the delay is comparable to the vertical instability growth rate. When active during a shot, the shape controller is de facto required to also stabilize the vertical instability. The extra delay requires fine online tuning of the controller over many shots for standard plasmas while the most elongated ones simply cannot be stabilized, limiting the parameter range of applicability.

The goal of the present study is to develop a generalized control architecture for shape and position control, with the objective of being available as a tool for standard operation. This requires a separation of the problems of vertical stabilization and control of the plasma shape.

2. Modelling

Offline control system design requires a model of the studied plant. This is mandatory in particular for stabilization studies when the number of available experiments (shots) is limited. The RZIp model [6] describes the coupled electromagnetic dynamics of plasma, vessel and coils system. Such model includes circuit equations for coil, vessel and plasma, coupled with vertical and radial plasma force balance, where the plasma is treated as a fixed current distribution that can move rigidly in the vertical and radial direction. The inputs to the system are the voltages applied to the coils while the outputs are the magnetic measurements corresponding to the currents in conducting elements, which are the system states. The system is linearized around an operating point and is therefore suited for control design applications, and was already used for plasma vertical stabilization studies in TCV [7]. Taking the Laplace transform of the system equations for an elongated plasma identifies a single unstable mode, which represents the vertical instability. The plant was designed including mutual decoupling and resistive compensation (matrices R_a and M_{aa} in Fig. 2.2). It was possible to obtain a reduced model of the system in order to comprehend in an intuitive way the coupled dynamics of the full system. A second order SIMO system was derived for the vertical dynamics of the system, where an input $u \in \mathbb{R}$ acts as a voltage command for the coil combination $T_z \in \mathbb{R}^{16}$ while the outputs are the vertical position of the plasma z and an equivalent current obtained as the projection of coil currents $I_a \in \mathbb{R}^{16}$ along T_z as $I_z = T_z^T I_a \in \mathbb{R}$. The reduced model proved to be a useful tool for approximating the general dynamics.

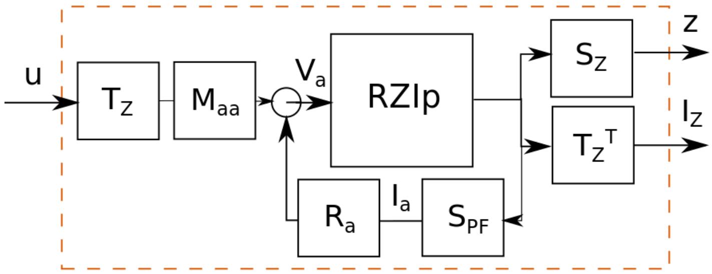

Figure 2.1: Block scheme of the plant featuring mutual decoupling and resistive compensation.

3. Development of decoupled shape and position controller for the TCV tokamak

A new control architecture was developed, inspired by same approach that was developed for EAST tokamak and which is foreseen as well for ITER [8] [9]. A series of fundamental observations were made based on the aforementioned reduced model. As a first point, control on vertical velocity alone was proven not sufficient to stabilize the unstable system. In previous designs of TCV vertical controller, to achieve vertical stabilization, a proportional control loop was closed on the vertical estimator zI_p. In the new proposed scheme, this proportional loop is replaced with a proportional feedback of the error in $I_z = T_z^T I_a$, where T_z is the coil current direction assigned to vertical position control. Since both signals are provided by fast linear estimators rather than nonlinear equilibrium reconstruction [2], it is possible to avoid computational delay and thus obtain a larger phase margin for the control loop. On the other hand, using I_z and not directly the vertical estimator zI_p has the drawback of reducing again the phase margin. There is therefore a trade-off between velocity and performance of the closed loop response. A second important observation derived from the reduced model was the necessity of a counterintuitive positive feedback loop for I_z, which was proven correct both in simulations and in experiments. The main motivation lies in the combined effect of different DC gain of the unstable reduced plant in the channels $u \rightarrow zI_p$ and $u \rightarrow I_z$ and of the presence of RHP zeros in the reduced model. Before each shot, the proportional gain of the new controller is estimated with loop shaping techniques using the complete model and the present parameters, thus making use of former operators experience on vertical stabilization with the analog system.

4. Experimental results and closed loop simulations

After verification in closed loop simulations, the decoupled controller was tested in TCV experiments. Once the decoupled controller is turned on in the digital control system, the plasma moves to a new equilibrium position as the vertical dynamics is stabilized while the vertical position is not directly controlled. This control scheme is in principle able to allow tracking of all PF coils currents. During shots, it is however observed that the equivalent current I_z is not perfectly tracked: the error e_{Iz} as a combination of various currents errors does not move to zero from the value before the inclusion of the controller. This was effectively explained with a simulation of the closed loop system, showing that errors in the pre-shot calculated feedforward voltages act as a disturbance on the PF coils currents loop. The model predicts correctly the effect of increasing the proportional gain in the I_z control loop to reduce the steady state error, which is observed in a series of successive shots. In conclusion, frequency decoupling is obtained: the plasma column is vertically stabilized at high frequencies and all currents references in the coils can be tracked at low frequencies. This means that the shape controller can now act on a stable system at slower time scales. The next steps will be the inclusion of the shape controller during a full shot and the test of the generalized shape and position controller for reliable access to advanced configuration during experimental runs.

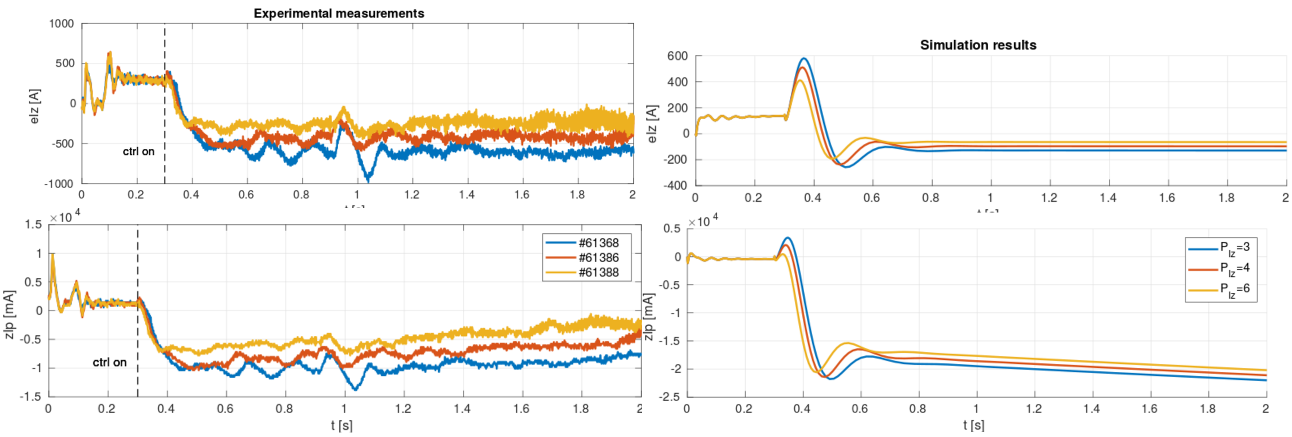

Figure 4.1: Comparison of closed loop experimental results and simulations. Before the activation of the decoupled controller (at t = 0.3 s) the position is tracked while I_z is not. After t = 0.3 s the plasma moves to a new position while the disturbance effect can be corrected increasing the proportional gain for I_z control.

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