Using dynamic input allocation for elongation control at FTU

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1. Introduction

Currently, the horizontal positioning system at FTU (Frascati Tokamak Upgrade) relies on the use of two magnetic windings. The first one, called V winding (V stands for “vertical” as the winding generates a vertical field), runs in open loop using a preprogrammed feedforward reference. The second one, called F winding (F stands for feedback, as only this winding among the two runs in feedback configuration), operates in closed-loop and ensures asymptotic regulation and satisfactory disturbance rejection on the horizontal plasma position based on a suitable estimate of the actual position based on the magnetic measurements. Fig. 1 shows a cross section of the FTU vessel with indications of the V coils (right) and of the F coils (left) and of the arising magnetic fields. The reason why the V winding is not involved in the feedback stabilization task is that its power supply is very slow (it has stringent rate saturation constraints on the allowable output current). Therefore, it cannot be directly used for this stabilization task. On the other hand, the F winding is also responsible for plasma compression, called elongation (namely the ratio between the main vertical and the main horizontal plasma axes). Moreover, there is a known affine (therefore nonlinear and invertible) curve which well approximates the relationship between the current flowing in the F coils and the arising plasma elongation. Classical linear control techniques cannot be used within this setting to guarantee elongation control without resulting in a perturbation for the horizontal position control loop. As a matter of fact, only the F coil can affect the plasma elongation and the V coil alone is incapable of guaranteeing a sufficiently large bandwidth due to its maximum allowable rate. Therefore, with a linear approach the only way to avoid the rate saturation of the V winding is to design a slow enough control, in order to remain inside the bounds also in the worst case, thus resulting in a too conservative solution.

Within this setting, in this paper we employ the dynamic allocation scheme of [1] to combine the action of the V and F windings, which are redundant as seen from the viewpoint of the horizontal position and achieve the horizontal regulation goal as a primary task and regulation of the current flowing in the F coils as a secondary task, namely without perturbing the position loop at all. This secondary task results in ensuring a desired elongation because of the direct relationship between the achieved elongation and the current flowing in the F coils. In particular, once the current in the F coils can be suitably regulated, it is possible to achieve a prescribed desired elongation by suitably inverting the known affine curve relating the F coils current to the corresponding plasma elongation. The paper is organized as follows: in Section 2 we give the problem statement, in Section 3 we describe the allocation scheme and give simulation results and in Section 4 we describe the experimental results.

2. Problem statement

The control system currently running at FTU for the horizontal position control of the plasma is represented in Fig. 2. This control scheme and the corresponding static and dynamic functions have been identified in the recent work [2] where the nonlinear instabilities induced by the F coils power amplifier when operating at low currents have been addressed and resolved. As shown in Fig. 2, before the insertion of the darkest allocator block, the requested current from the V power amplifier was only the preprogrammed (or feedforward) action, whereas the F winding was driven by the preprogrammed signal plus the contribution com-
The magnetic fields generated by the V (right) and F (left) coils at FTU. The view shows a cross section of the vacuum vessel and the poloidal circuits. The plasma current and the F and V currents are orthogonal to the section shown, with direction that changes from shot to shot, depending on the selected magnetic configuration and the consequent adjustable coils wiring.

from the PID feedback controller whose input corresponds to the flux difference $\Delta \psi$ between the two preprogrammed radiusies (the inner and outer ones), thus resembling the horizontal plasma position (see [3] for details).

With this scheme in place, the actual current flowing in the F winding during the experiment depends on the PID controller output and therefore on the type of disturbances acting on the experimental system. In most experiments the experience of the physicists leads to a current of roughly 4 kA in the flat-top phase, which induces a desirable elongation (typically around 1.03, 1.04). However, any external disturbance that requires a significant action from the PID controller (such as impurities, radiofrequency heating or similar events) causes a significant change in the steady-state F current and therefore an undesirable elongation. Among the many reasons why it is desirable to obtain an elongation higher than 1.03 is that smaller elongations make it difficult to identify certain plasma parameters from the magnetic measurements (due to the symmetries), thus compromising the plasma equilibrium reconstruction. The amplitude and rate saturation limits for the current in the V and F coils correspond respectively to:

$$I_{V,\text{max}} = 25 \text{ kA}, \quad I_{V,\text{max}} = 54 \text{ kA/s}. $$

$$I_{F,\text{max}} = 12.5 \text{ kA}, \quad I_{F,\text{max}} = 830 \text{ kA/s}. $$

(1)

From the above it appears that the F winding is less powerful than the V winding, but much faster therefore more adequate for the fine feedback control of the plasma horizontal position. Nevertheless the slow V winding could be used to slowly take over the F coils effort and make the F winding available for the lower priority task of the elongation control. To this aim, the dynamic allocation scheme proposed in [1] and in particular its extension outlined in ([1], Remark 3) allowing a nonzero reference value for the plant input can be directly applied to this problem as clarified in the next section.

The simplified plasma model for the plasma horizontal position control system and the dynamic allocator interconnection (darkest blocks).
The saturation level of $\sigma_M(\cdot)$ has been selected as $M_d = 3800$ to induce a desirable large signal slope compatible with the limits in (1) and the saturation level of $\sigma_M(\cdot)$ is $M = 2000$ so that the allocator can only use a limited amount of input authority. Moreover, according to the FTU parameters, $K_V$ and $K_F$ are selected as $K_V = -1.187e - 6$ and $K_F = -2.75e - 7$.

Fig. 4 represents two simulations of the closed-loop depicted in Fig. 2 and described above. In the first simulation (light dash-dotted) the control system is run without the allocator (namely the darkest block in Fig. 2 is disconnected). In the second simulation (dark solid) the allocator is connected and the reference signal $I_{F, ref}$ is selected as the dashed line in the upper plot. From the simulation it appears that the allocator successfully guarantees graceful and slow convergence of the F current to the desired value, while no difference is seen at the plant output $\Delta \Psi$ (the dark and light curves are on top of each other there). The lowest plot of the figure shows the plasma current value, taken from experimental data.

3.3. Extension to elongation control

Since the F winding generates a magnetic field that is not perfectly vertical then, in addition to moving the plasma horizontally, it produces a slight compression of the plasma, thus affecting its elongation. In particular, the steady-state elongation $e$ induced by the F coils current can be computed, also based on the plasma current $I_p$ as

$$e = f(I_F, I_p)$$

$$e = e_0 - k_e \frac{I_F}{I_p}$$

where $e_0 = 1.01$ and $k_e = 4.55$. This formula suitably describes elongation behaviour for typical FTU plasmas. A graphical representation of the relationship between $e$ and $I_F$ is shown in Fig. 5.

The static map is affine and depends on $I_p$ so that a family of curves is shown in Fig. 5, parametrized by $I_p$. 

Fig. 4. Simulation of the closed-loop with (dark solid) and without (light dash-dotted) allocator.

Fig. 5. The static map relating $e$ to $I_F$.

Fig. 6. Comparison between shots number 31710 (light dash-dotted) without the allocator and 31724 (dark solid) with the allocator.

Fig. 7. Comparison between shots number 31724 (light dash-dotted) with $M_d = 5000$ and 31726 (dark solid) with $M_d = 3800$. 

Fig. 6. Comparison between shots number 31710 (light dash-dotted) without the allocator and 31724 (dark solid) with the allocator.

Fig. 7. Comparison between shots number 31724 (light dash-dotted) with $M_d = 5000$ and 31726 (dark solid) with $M_d = 3800$. 

Fig. 5. The static map relating $e$ to $I_F$. 

Fig. 6. Comparison between shots number 31710 (light dash-dotted) without the allocator and 31724 (dark solid) with the allocator.
By inverting Eq. (5) one obtains \( I_F = f^{-1}(e, I_p) \) which can be used, together with \( I_{F\text{,ref}} = f^{-1}(e_{\text{ref}}, I_p) \) to extend the allocator in Eq. (3) and Fig. 3 to regulate the plasma elongation to a desired profile \( e_{\text{ref}} \), based on the real-time measurement of the current elongation \( e \).

4. Experimental results

The control scheme outlined in the previous section has been experimentally implemented on the FTU control system by being preliminarily tested on the virtual control system described in [4] for code validation. A key tool for the successful experimentation has been the use of the anti-windup solution described in [2], which allows now to request low currents from the F coils without losing closed-loop stability. Indeed, to enforce the desired F current reference (or elongation) the dynamic allocator can sometimes require currents below the circulation current threshold thereby requiring the anti-windup action (see [2] for details). In all the experiments the allocator works in a time window during the flat-top phase, because the simple model that it is based on adequately describes the real process only in these conditions. To this aim, an activation signal raises from 0 to 1 at time \( t = 0.4 \) and linearly goes back to zero between times \( t = 1.4 \) and \( t = 1.5 \).

In Fig. 6 two identical experiments are compared: shots number 31724 (dark solid) and 31710 (light dash-dotted) where the allocator is active and inactive, respectively. The allocator works in current mode with a constant reference of 3000 A for the F current (dashed line in the upper plot). It can be seen that the F current (top plot) follows the constant reference, while the V current is modified accordingly to make the allocator action invisible at the output.

The oscillations on the V coils in the middle plot of Fig. 6 reveals that the allocator action is too aggressive. Therefore, in Fig. 7 the same shot of the previous figure is compared to another shot number 31726 where a smaller value for the rate saturation limit \( M_d \) has been selected (\( M_d \) was selected as 5000 A/s in shot number 31724 and as 3800 A/s in shot number 31726). Reduced oscillations are seen after the saturation level reduction as seen in the dark solid curve of the figure.

Finally, in Fig. 8 preliminary results are shown where the allocator works in elongation mode, and the elongation reference \( e_{\text{ref}} \) corresponds to the dashed curve in the lower plot. The dashed curve in the upper plot shows the signal \( I_{F\text{,ref}} \) computed from \( e_{\text{ref}} \) while the light dash-dotted curve shows the signal \( I_F \) computed from \( e \) (the solid dark curve shows instead the actual current flowing in the F coils). From the lower plot, where the plasma elongation is reported in dark solid, it appears that the control system exhibits a steady-state error. This was later found to be caused by a coding problem of the algorithm which will require further experimentation. Nevertheless, this experiment reveals that the allocator can successfully assign a prescribed plasma elongation and the arising experiment is consistent with the results predicted in simulation.

References