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** See annex of F. Romanelli et al, "Overview of JET Results", (Proc. 22nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).*

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ABSTRACT

This paper reports on a recently proposed dynamic allocation technique that can be effectively adopted to handle the current saturations of the Poloidal Field coils with the eXtreme Shape Controller. The proposed approach allows to automatically relax the plasma shape regulation when the reference shape requires current levels out of the available ranges, finding in real-time an optimal trade-off between shape control precision and currents saturation avoidance. In this paper the results attained during preliminary analysis are presented, showing the advantage arising from the use of the dynamic allocator, versus the bare use of the eXtreme Shape Controller.

1. INTRODUCTION

The need for achieving better performance in present and future tokamak devices is pushing plasma control to gain increasing importance in tokamak engineering. High performance in tokamaks is achieved by plasmas with elongated poloidal cross-section. A strong motivation to improve plasma control are the need of maximize the plasma volume within the available space, and heat flux control in the divertor region. In particular, the ability to control the plasma shape with an accuracy of few centimeters is an essential feature of any plasma position and shape control system. The eXtreme Shape Controller (XSC, [1, Ch. 9]) allows to accurately control highly elongated plasmas at the JET tokamak [2] by driving the current in the Poloidal Field (PF) coils. The XSC enables high accuracy control of the overall plasma boundary, specified in terms of a given number of plasma shape descriptors, i.e., gaps, strike-points and x-point. In its present implementation, the XSC does not handle current saturations in the PF coils. Indeed, each operating scenario is carefully designed [3] in order to avoid PF currents saturation in the presence of the envisaged disturbances (i.e. plasma current, poloidal beta and internal inductance variations). A dynamic coil Current Allocator (CA) based on the technique originally proposed in [4] has been recently proposed to manage current limit avoidance with the XSC [5]. The CA exploits the redundancy of the PF coil system to obtain “almost the same plasma reference shape” with different PF currents combinations. Hence, in the presence of disturbances, it aims at avoiding the current saturations by “relaxing” the plasma shape constraints. Furthermore, the CA guarantees an optimal tradeoff, at the steady-state, between shape loss and distance of the coil currents from their saturation limits. The paper is structured as follows: in Section 2 some theoretical results are briefly recalled and the allocation scheme is described, in Section 3 two test cases are presented in order to show the effectiveness of the proposed approach.

2. THEORETICAL FRAMEWORK

The proposed CA is based on the dynamic input allocation scheme first proposed in [4] for input redundant systems, then generalized to underactuated ones in [5]. In the former case, thanks to the redundancy, there exist, at least at steady state, infinite combinations of the inputs that give the same desired output: the allocator makes Preprint submitted to Fusion Engineering and Design August 27, 2010 the control system converge to the best of these combinations, according to some cost function. In the latter case there not exists in general an inputs combination that gives the desired output.

Indeed, the XSC control algorithm minimizes a quadratic cost function for the plasma shape error in order to obtain at steady state the output that best approximates the desired one. However, since the XSC algorithm does not take into account the current limits into the actuators, it could happen that the requested combination may be not actually available. In order keep the currents within their limits without degrading too much the plasma shape, the allocation scheme proposed in [5] finds an optimal trade-off between these two objectives, specified in terms of an adequate cost function.

Consider the plant described by the linear timeinvariant system:

$$\dot{x} = Ax + Bu + B_d d \tag{1a}$$

$$y = Cx + Du + D_d d \tag{1b}$$

where $x \in \mathbb{R}^n$, $u \in \mathbb{R}^{n_u}$, $d \in \mathbb{R}^{n_d}$ $y \in \mathbb{R}^{n_y}$. In this application the control input u is represented by the 8 currents flowing in the PF coils (the current in the P1 circuit is excluded, since this circuit is used to control plasma current), while the controlled outputs y are represented by the n_y shape parameters (gaps, X-point and strike points); typically $n_y \geq 30$. The disturbance vector d holds the poloidal beta β_p and the internal inductance li.

The plant is controlled by an a-priori given linear controller:

$$\dot{x}_c = A_c x_c + B_c u_c + B_r r \tag{2a}$$

$$y_c = C_c x_c + D_c u_c + D_r r \tag{2b}$$

where $x_c \in \mathbb{R}^{n_c}$, $u_c \in \mathbb{R}^{n_y}$, $yc \in \mathbb{R}^{n_u}$, $r \in \mathbb{R}^{n_r}$, under the interconnection conditions:

$$u_c = y \tag{3a}$$

$$u = y_c \tag{3b}$$

In the considered case the a-priori given controller is the JET XSC. Assuming that the matrix transfer function $P(s) = C(sI - A)^{-1}B + D$ from u to y has no pole at $s = 0$, let $P^* := P(0)$.

An input allocator block can be designed, described
by the relations:

$$\dot{\ } = -\rho w B_0^T [I \quad P^*] \nabla J^T \tag{4}$$

$$y_a = B_0 w \tag{5}$$

where B_0 is a suitable full column rank matrix, $\rho > 0$ specifies the convergence speed and $J(u^*, e^*)$ is a suitable cost function (see [5] for more details) measuring the trade-off between the modified steady state value of the PF currents u^*, and the associated plasma shape error $e^* = r^* - y^*$. The CA is interconnected to the unconstrained closed-loop via the equations

$$u_c = y - P^* y_a,$$

$$u = y_c + y_a \tag{6}$$

as can be seen in Fig. 1.

In particular for this application the following cost function has been used (for brevity, the superscript * indicating the steady-state is omitted):

$$J(u, e) = \sum_{i=1}^{n_u} a_i dz(\bar{u}_i)^2 + \sum_{i=1}^{n_y} b_i (e_i)^2 \tag{7}$$

where the $\bar{u}_i$*'s* are the inputs normalized in the range $[-1, +1]$, $dz(\bar{u}_i) = \text{sign}(\bar{u}_i) \max\{0, |\bar{u}_i| - 1\}$ is the deadzone function, $a_i \geq 0$, $i = 1, \ldots, n_u$ and $b_i > 0$, $i = 1, \ldots, n_y$ are weight coefficients.

Such a function has the following features:

- penalizes separately each $\bar{u}_i$ and e_i;
- it does not penalize $\bar{u}_i$ as long as $\bar{u}_i \in [-1, +1]$;
- penalizes ei quadratically (hence large values of ei are penalized much more than small values);
- penalizes ¯ui quadratically when $\bar{u}_i \notin [-1, +1]$.

The above points imply that priority is given to keep the plasma shape errors ei's small, with relative weights specified by b_i's, as long as the normalized currents $\bar{u}_i$'s satisfy $\bar{u}_i \in [-1, +1]$; meanwhile, when the $\bar{u}_i$'s are sufficiently outside the interval $[-1, +1]$, if the ai's are sufficiently big with respect to the b_is, then priority is given to keep the $\bar{u}_i$'s close to the interval $[-1, +1]$, even at the price of larger e_i's. In such a way, normalizing the currents with respect to safety ranges smaller then the physical ones, the shape tracking effort is automatically relaxed when the currents exceed these safety values.

From the point of view of convergence and stability, if the cost function in (7) is used then, generalizing the results in [5], exponential convergence can be easily established for sufficiently small values of the parameter ϱ.

3. SIMULATIONS

The problem of saturation avoidance for the shape control system at JET can be dealt with in the theoretical framework described in Section 2. The CA described in Section 2 has been integrated with the XSC and simulated with the linear model of the plasma.

The following two test cases are presented in this section:

Case A

in this case the CA is adopted to move the PF currents far from their saturation limits, in order to operate a given scenario in a safer way;

Case B

in this case the CA allows to operate a given scenario at higher plasma current without saturating the currents in the PF coils.

3.1. TEST CASE A

The JET Pulse No: 78668 at t = 13.4 s is considered in this test case. The equilibrium values of the plasma current, poloidal beta and internal inductance are I_{Peq} = 3.4MA, β_{Peq} = 0.29, and l_{ieq} = 0.91. In the considered configuration the currents in PFX and in the shaping circuits are very close to their limits. Indeed, their equilibrium values are equal to I_{PFX} = 29.2kA and I_{SHP} = 32.7kA, while their upper bounds are equal to $I_{PFX_{max}}$ = 32.9kA and $I_{PFX_{max}}$ = 38kA.

In this case the CA has been used to limit the currents in both the PFX and the shaping circuits. In particular, PFX can range in the interval [4.9, 28] kA, while the shaping current is limited in the range [9.5, 28.5] kA. Furthermore, Ip is kept constant equal to 3.4MA. The plasma shape achieved in steady–state is shown in Fig.2, while the currents in the PF coils are reported in Fig.3. In this simulation the plasma shape at t = 13.4s has been set as reference for the XSC. The error in the outer upper zone can be reduced by increasing the PF limits up to 90% of the available operative space.

3.2. TEST CASE B

In this case we have considered the JET Pulse No: 78668 74177 at t = 8.8s. For this equilibrium we have I_{Peq} = 4MA, β_{Peq} = 0.16, and l_{ieq} = 0.75. In this operative scenario plasma current is limited by the current in the D2 circuit, that is close to its saturation limit. Indeed, the equilibrium value of the current in the D2 circuit is equal to $I_{D2_{eq}}$ =–33.5kA, which is close to its lower saturation limit (–37kA). The CA has been used to limit I_{D2} in the range [–31.45,–5.5] kA, and to increase the plasma current up to 4.5MA (see Fig.4). The CA keeps the current in D2 within its new limits, while the plasma shape error increases in the upper zone (see Figs.5 and 6). It is worth to remark that the plasma current variation is seen as a disturbance for the shape control.

CONCLUSIONS

A dynamic allocation technique has been proposed to handle the current saturations of the PF coils to improve the JET plasma shape control. All the analyses carried out have shown that the CA improves the performance of the XSC in terms of shape tracking and it allows to manage in the currents saturation in a flexible way.

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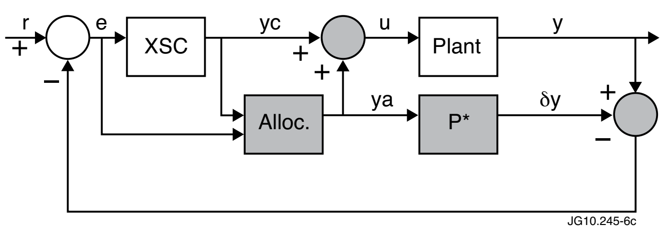

Figure 1: Block diagram of the control system with the insertion of the allocator block.

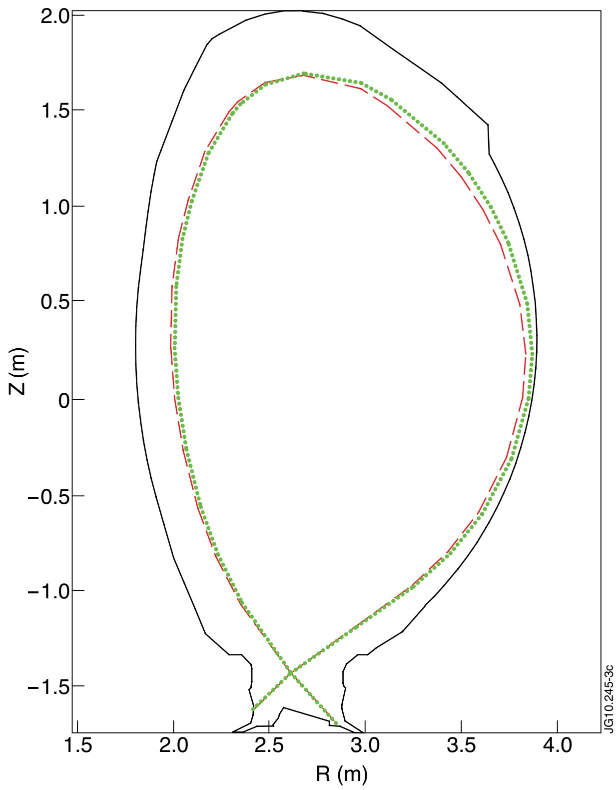

Figure 2: Test Case A. Plasma shape when the CA is used to move both PFX and the shaping current far from the saturation limits. The plasma shape at t = 13.4s has been set as reference for the XSC. The shape reference is the red trace, while the green trace is the simulated shape.

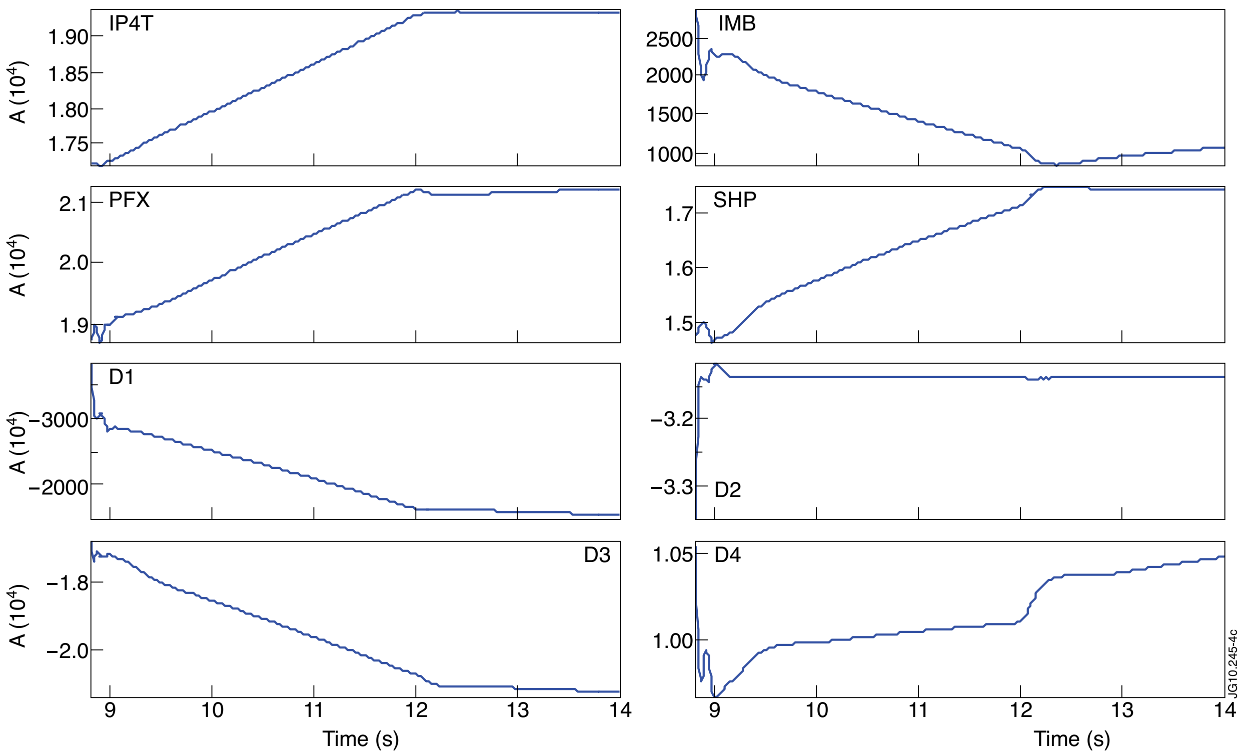

Figure 3: Test Case A. PF currents when the CA is used to move both PFX and the shaping current far from the saturation limits. Note that both the PFX and the shaping currents are kept equal their new upper bounds, in order to minimize error on the plasma shape tracking.

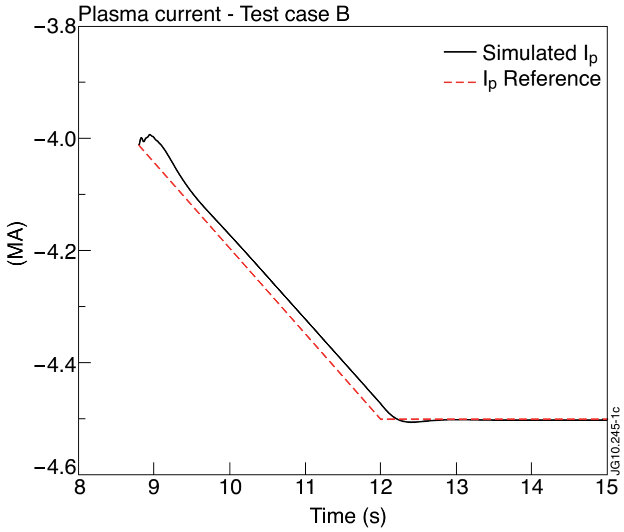

Figure 4: Test Case B. Plasma current variation. The plasma current is increased up to 4.5MA.

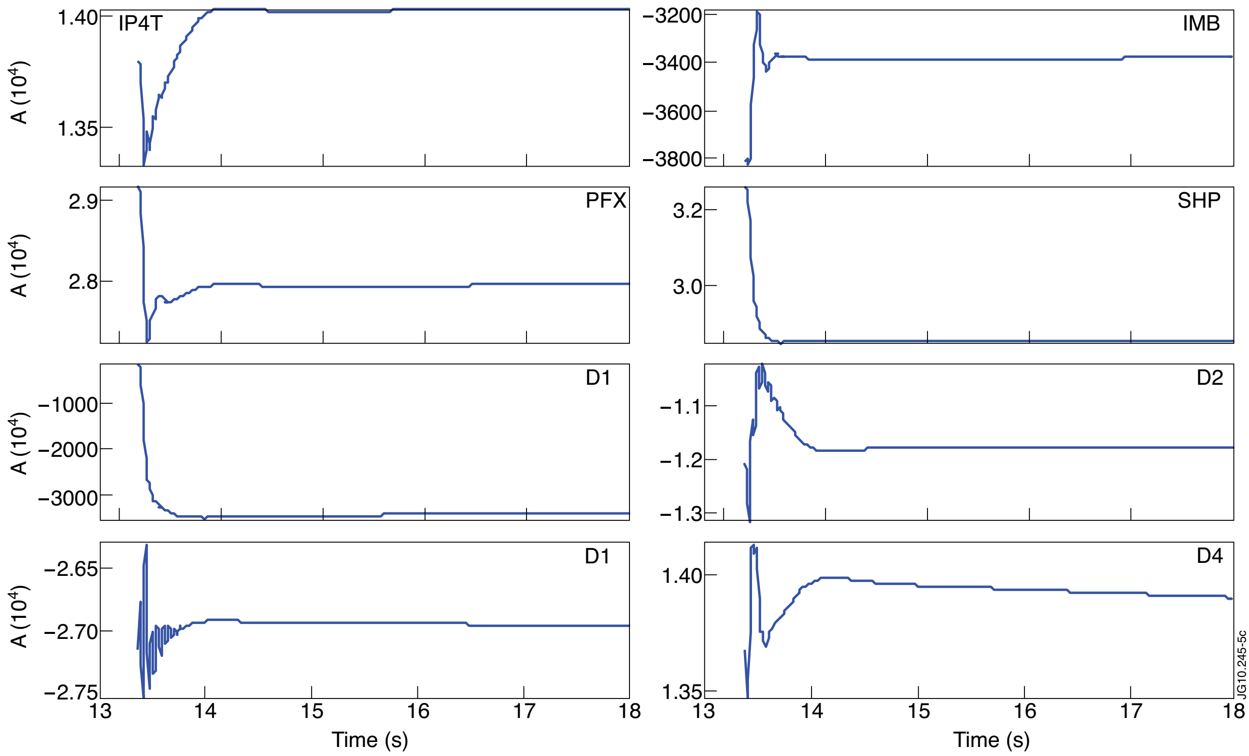

Figure 5: Test Case B. Current in the PF circuits when I_p is increased up to 4.5MA and the CA is switched on. Note that the current in D2 is kept in the range [−31.45;−5.5] kA.

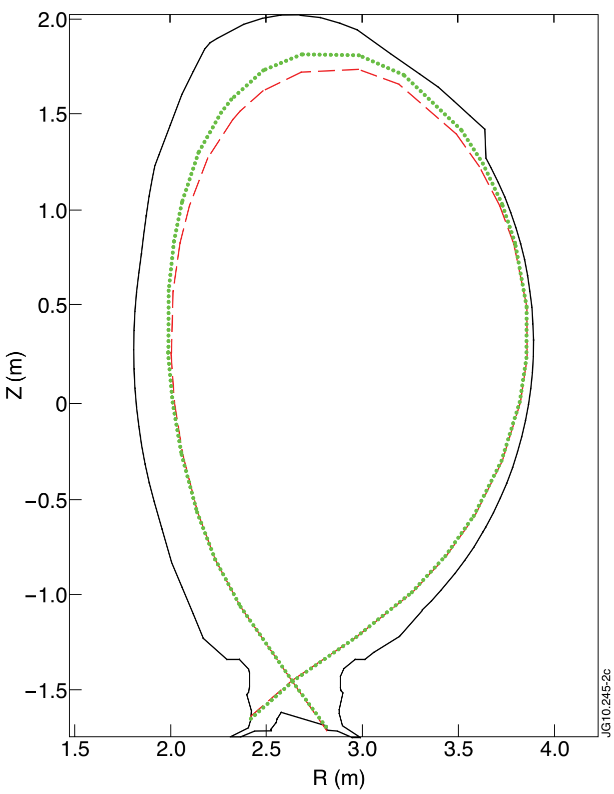

Figure 6: Test Case b. Plasma shape when Ip is increased up to 4.5MA.
The shape reference is the red trace, while the green trace is the simulated shape.