A Command Governor Approach to Plasma Shape Control

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Abstract— The paper deals with the application of the so-called Command Governor (CG) approach to the shape control of plasmas in thermonuclear fusion reactors. A primal internal loop controlling the plasma-wall gaps is designed first and a CG device is then tuned to modify, whenever necessary, the reference to the primal loop, taking into account constraints due to voltages saturations on the converters, currents limitations in the active coils, force limits on the mechanical structures, minimum clearance between the plasma and the vacuum chamber wall, maximum induced forces on coils. The reference signal modification is accomplished through an online optimization procedure which embodies plasma model forecasts computed along a finite time virtual receding horizon as usual in model predictive paradigms. The ITER (International Thermonuclear Experimental Reactor) tokamak is assumed as a case study. Numerical simulations are carried out on a numerical nonlinear model taking into account almost a hundred of constraints.

I. INTRODUCTION

In tokamak devices, plasma control has gained relevance due to increasing performance demand. To this extent, the ITER tokamak [1,2] is designed to obtain plasmas which are significantly elongated and vertically unstable, placed as close as possible to the metallic facing components. This ensures a good passive stabilization, due to the eddy currents induced in these metallic structures, and an efficient use of the available volume.

Since contact between plasma and walls is always a major concern in tokamak operations, adequate clearance must be guaranteed. Both vertical stabilization and plasma-wall clearance are obtained by regulating currents in a number of poloidal field (PF) coils surrounding the plasma ring (see Fig. 1 for a poloidal section of ITER). The poloidal field interacts with the plasma, modifying its position, current, and shape. The voltages applied to the PF coils are generated by a power supply driven by a feedback control system.

Usually plasma position and shape controllers have a quite simple structure and are mainly based on multiloop proportional integral derivative (PID) actions. To maximize the performance of the tokamak the distance between the plasma boundary and the vessel at some specific points (gaps) are controlled. To this reason multiple-input–multiple-output control approaches have been deeply investigated in the last decade [3, 4, 5]. The most successful are linear approaches which do not take into account the possibility that the physical variables of interests can exceed their operating limits. In [6] an attempt to deal with control inputs saturation is described. In facts during tokamak operations, not only voltages and currents, but also fields, electromagnetic forces, and shape parameters must belong to prescribed ranges.

The need to satisfy input and/or state dependent constraints is in general a relevant problem in control theory. Anti-Windup (AW), Bumpless methods, AW/LQR, AW/H₂, are feedback control methodologies dealing with the presence of input constraints in an indirect manner [7]. Recently, techniques based on invariant sets arguments and predictive control ideas [8, 9] have gained in popularity due to their inherent capability to take directly into account, in the design phase, the presence of constraint during the design phase. The control action is computed through the solution of a sequence of optimization problems based on the prediction of the plant state evolution. The objective is to jointly maximize the control performance and enforce the satisfaction of the prescribed constraints. On practical applications side, the interest towards such methodologies is growing in the last decade due to the availability of fast computing units [10, 11].

Some of the predictive control methodologies are mainly devoted to constraints fulfilment leaving to traditional regulation frameworks the control performance satisfaction (set point tracking, disturbance rejection, robustness issues etc.). Such a family of control strategies is known in the literature as the Command Governor (CG) approach. In this respect, the CG is a nonlinear device which is added to a primal pre-compensated plant designed so as to exhibit stability and good tracking performance in the CG absence. At each time instant \( t_k \), the CG computes a modified reference command which, if applied from \( t_k \) onward, does not produce constraints violations. Such a modified reference command is computed to minimize its distance from the actual desired reference signal, according to an online constrained procedure on a receding horizon finite time interval. Many mature assessments of the CG state of the art for linear systems can be found in [12-13].

The objective of this paper is to explore the possibility to apply a linear model based CG framework to the plasma shape control in a tokamak. Preliminary results on this approach were presented in [14] where however performance have been verified only by means of linear simulations. In the following paper nonlinear numerical results are proposed on ITER to show the effectiveness of
the CG control strategy.

II. THE PLASMA RESPONSE MATHEMATICAL MODELLING

Three main subsystems need to be considered to obtain a control oriented model of a plasma in a tokamak: the plasma, the control circuits, and the passive conductors.

The model is governed by Maxwell’s equations in their quasi-stationary form where the electric field does not vary too rapidly and the current density is divergence free with the constitutive relationships. In axi-symmetric geometry with cylindrical coordinates \((r, \phi, z)\), the magnetic field and current density vectors \(B\) and \(J\) can be expressed in terms of two scalar functions, namely, the poloidal magnetic flux per radian \(\psi(r, z)\) and the poloidal current function \(f = \mu I_{pol}/2\pi = rB_{\phi}\), \(B_{\phi}\) being the toroidal field, and \(I_{pol}\) the poloidal current.

At the time scale of interest for current, position, and shape control, because of the low plasma mass density, inertial effects can be neglected. Hence at equilibrium, the plasma momentum balance becomes \(J \times B = \nabla p\), that can be rewritten as the well known Grad-Shafranov equation [15]

\[
\Delta \psi = \frac{r}{\partial r} \left( \frac{\partial}{\partial r} \left( \frac{1}{\mu_0 r} \frac{\partial \psi}{\partial r} \right) + \frac{\partial}{\partial z} \left( \frac{1}{\mu_0} \frac{\partial \psi}{\partial z} \right) \right) = -f \frac{df}{d\psi} - \mu_0 r^2 \frac{dp}{d\psi} \tag{1}
\]

\(\mu_\ast = \mu / \mu_0\) being relative magnetic permeability.

In the usual approximation that the electromagnetic interaction of the plasma with the surrounding passive structures and active coils is assumed axi-symmetric the plasma equilibrium is described by the following partial differential equation problem

\[
\Delta \psi = -f \frac{df}{d\psi} - \mu_0 r^2 \frac{dp}{d\psi}, \quad \text{in plasma region} \tag{2a}
\]

\[
\Delta \psi = -\mu_\ast J_{ext}(r, z, t), \quad \text{in conductors} \tag{2b}
\]

\[
\Delta \psi = 0, \quad \text{elsewhere} \tag{2c}
\]

with the initial and boundary conditions

\[
\psi(r, z, t) = \psi_0(r, z), \quad \psi(0, z, t) = 0, \quad \lim_{r \to \infty} \psi(r, z, t) = 0. \tag{2d}
\]

\(J_{ext}\) is the toroidal current density in the external conductors and coils. The above equations are used to calculate the poloidal flux \(\psi\) function at time \(t\) provided that the plasma boundary can be determined, the toroidal current density in the PF is known and the functions \(p(\psi)\) and \(f(\psi)\) are defined. The plasma boundary is determined by means of an iterative numerical procedure. Functions \(p(\psi)\) and \(f(\psi)\) can be expressed in terms of global plasma parameters, for example \(I_p, \beta_p\) and \(L_t\), namely plasma current, poloidal beta and internal inductance. As for the toroidal current density \(J_{ext}\), it can be expressed as a linear combination of the PF circuit currents. Therefore, the magnetic flux and the plasma configuration can be determined when prescribing the currents vector including poloidal field and plasma currents along with \(\beta_p\) and \(L_t\). The time evolution of these currents is then governed by a circuit equation driven by voltages in the active circuits. Also induced eddy currents in the metallic structures can be modelled by means of circuit equation with coupling terms with the plasma and active coils currents.

Solutions of problem (2) can be numerically found by means of Finite Element Methods (FEMs) [16]. In [17] the procedure adopted to linearize the plasma model response is described which finally approaches to a linear plasma-circuit dynamics in the form:

\[
L \delta i + R \delta i = \delta V + L_T \delta \omega \tag{3a}
\]

\[
\delta y = C \delta i + F \delta \omega \tag{3b}
\]

where \(V\) is the vector of voltages applied to the circuits (zero for passive coils), \(R\) is the circuit resistance matrix, and \(L\) is the matrix of self and mutual inductances between the plasma, the coils, and the equivalent circuits of the passive structures, \(I = [I_{p}, I_{pol}, I_{ext}]^{T}\) is the vector of PF, passive, and plasma currents respectively, and \(w = [\beta_{pol}, l]^{T}\) is the vector of external disturbances; \(y\) is a vector of outputs, \(C\) and \(F\) are output matrices, \(\delta z\) denotes the variation of the variable \(z\) with respect to a nominal condition.

When passive metallic structures are discretized with a FEM approach, a high number of corresponding passive currents has to be accounted for in the model. Hence for control design purpose it is very important to obtain a reduced order model. Model reduction can be achieved by means of a modal decomposition, followed by the selection of the unstable mode and of the stable modes corresponding to the time constants falling in the range of the closed loop characteristic times. All the controllers discussed in this paper have been designed on reduced models although they have been tested on high dimensional models.

III. THE CONTROL PROBLEM AND THE PRIMAL CONTROLLER

The proposed controller has three main objectives: (i) vertical stabilization, i.e. control of the vertical speed of the plasma centroid, which in ITER is mainly achieved driving the P3-P4 coils currents (see Fig.1); (ii) plasma current control, which is achieved by controlling the transformer pattern of currents which are chosen so as to induce plasma current without changing plasma shape; (iii) shape control, i.e. control of a certain number of plasma-wall gaps.
The control inputs in ITER are eleven voltages which drive the P1÷P6, CS3U, CS3L, CS2U, CS2L coil currents, CS1L and CS1U being driven in series. A first SISO (single input–single output) proportional control is designed to guarantee vertical stabilization assuming the time derivative of the vertical centroid position $z_{pl}$ as controlled/measured variable, and a combination of $V_{P3}$ and $V_{P4}$ voltages as input. A second SISO PI controller is then designed to control plasma current.

The primal controller is then completed with a multivariable PI controller for shape control (see Fig. 2). This external loop is designed so as to include also a model reference (see [17] for details).

IV. THE COMMAND GOVERNOR STRATEGY

In its most common formulation [12,13] and according to the scheme depicted in Fig. 3, the CG approach takes into consideration a discrete time, pre-compensated linear time-invariant plant having the expression:

$$
\begin{align*}
x(t_{k+1}) &= \Phi x(t_k) + G\delta(t_k) + G_d d(t_k) \\
y(t_k) &= H_x x(t_k) \\
c(t_k) &= H_c x(t_k) + L\delta(t_k) + L_d d(t_k)
\end{align*}
$$

(4)

where $t_k = t_0 + k\tau$, $k \in \mathbb{Z}_{[0,t_0]}$, $t_0$ and $T_0$ being the initial time instant and the sampling interval respectively; $x(t_k) \in \mathbb{R}^{n_x}$ is the state vector including plant and primal controller states; $\delta(t_k) \in \mathbb{R}^{n_\delta}$ is the command input vector which would coincide with the reference signal $r(t_k) \in \mathbb{R}^{n_r}$, if no constraints were present; signal $d(t_k) \in \mathbb{R}^{n_d}$ is an exogenous disturbance vector belonging to $D = \{ d \in \mathbb{R}^{n_d} : Ud \leq \overline{H} \}$, a closed convex and compact set, with $U \in \mathbb{R}^{n_u \times n_d}$, $n_u \geq n_d$, a full column rank matrix, and $\overline{H} = [\overline{h}_1 \overline{h}_2 \ldots \overline{h}_n]^T \in \mathbb{R}^{n_u}$, a vector of nonnegative constraints ($\overline{h}_p \geq 0$, $p = 1,\ldots,n_u$); $y(t_k) \in \mathbb{R}^{n_y}$ is the output vector which is required to track $r(t_k)$; $c(t_k) \in \mathbb{R}^{n_c}$ is the vector to be constrained, viz. $c(t_k) \in C \subseteq \mathbb{R}^{n_c}$; $\delta(t_k)$ being a closed and convex set: $C = \{ c \in \mathbb{R}^{n_c} : Tc \leq f \}$, with $T \in \mathbb{R}^{n_c \times n_x}$, $n_c \geq n_x$, a full column rank matrix, and $f \in \mathbb{R}^{n_c}$ a vector of constraints.

Under the assumptions that system (4) is asymptotically stable and offset-free (i.e. $H_c(I_{n_c} - \Phi^{-1}G) = 0$), the CG design problem consists of finding, at each time $t_k$, a command $\delta(t_k) = g(x(t_k), r(t_k))$ as a memoryless function of the current state and the reference signal, in such a way that, under all possible disturbance sequences within $D$, and compatibly with the constraints set $C$ (i.e. $d(t_{k+h}) \in D$, $c(t_{k+h}) \in C$, $\forall h \geq 0$), $\delta(t_k)$ is the best approximation of $r(t_k)$ at time $t_k$. In order to propose a workable numerical procedure, the role of external disturbances and commands w.r.t. the prescribed constraint set must be clarified.

The disturbance effect is taken into account using a $P$-difference argument. Starting from the constraints set $C$ we have the recursion:

$$
c_0 := C \sim L_d D; \quad c_h := c_{h-1} \sim H_c \Phi^{h-1}G_d D; \quad c_\infty := \bigcup_{i=0}^{\infty} c_i
$$

(5)

where the symbol $\sim$ indicates the following operation between two sets $A$ and $B$:

$$
A \sim B = \{ a \in \mathbb{R}^{n_r} : a + b \in A, \forall b \in B \}
$$

(6)

The set $C_h$ turns out to be a suitable restriction of $C$ such that, if the “disturbance free” component of $c(t_k)$, depending on the initial state and the input time sequence, belongs to $C_h$, $c(t_k) \in C \forall k \leq h$ in the presence of disturbances.

The commands are instead considered by defining the convex and closed set $\mathcal{W}^{\xi}$ (assumed nonempty) which characterizes all constant inputs $\omega \in \mathbb{R}^{n_c}$ whose corresponding disturbance-free steady-state solutions of Eqs. (4), $\overline{c}_n = H_c(I_{n_c} - \Phi^{-1}G)\omega + L_0\omega$ satisfy the constraints with a prescribed tolerance $\xi$.

Once the role of disturbances and commands is clarified, the CG strategy consists in choosing, at each time step $t_k$, a constant virtual command $\omega \in \mathcal{W}^{\xi}$ such that the corresponding disturbance-free evolution from the measured state $x(t_k)$ fulfils the restricted constraint sets $C_h$, $\forall h > k$ (5), accounting for disturbance effects, and its distance from the reference $r(t_k)$ is minimal. Such a command is applied to the plant in the time interval $[t_k, t_{k+1}]$, and the procedure is repeated at the next time $t_{k+1}$ on the basis of the new
measured state $x(t_{k+1})$.

Consequently, if we denote with $\mathcal{V}(x(t_k)) \in \mathcal{W}^\mathcal{F}$ the set of all constant commands $\omega \in \mathcal{W}^\mathcal{F}$, whose corresponding $c$-evolutions starting from an initial condition $x(t_k)$, at time $t_k$, satisfy the constraints also during transients (i.e. $\mathcal{V}(x(t_k)) := \{ \omega \in \mathcal{W}^\mathcal{F} : c(t_{k+1}, x(t_k), \omega) \in \mathcal{C}^\mathcal{V} \cap \mathcal{C}^\mathcal{W}, \forall \ h > 0 \}$, and provided that $\mathcal{V}(x(t_k))$ is nonempty, closed and convex for all $t_k$, the CG command is the solution of the following constrained optimization problem:

$$\vartheta(t_k) = \arg \min_{\omega \in \mathcal{V}(x(t_k))} J(r(t_k), \omega)$$

where

$$J(r(t_k), \omega) := \| \omega - r(t_k) \|_{\Psi}^\mathcal{W}$$

$\| \chi \|_{\Psi} := \chi^T \Psi \chi$ being a weighted norm with $\Psi$ a positive definite symmetric matrix.

In other words, the minimiser (8) represents the best approximation of the reference signal $r(t_k)$ which, if constantly applied from $t_k$ onwards to system (4), would never produce constraints violation.

The implementation of the CG strategy requires a finite-time computable way to solve the optimization problem (8). To overcome the difficulties due to the infinite number of steps/constraints in the definition of $\mathcal{V}(x(t_k))$, it has been shown that $\mathcal{V}(x(t_k))$ can be finitely determined. In facts there exists an integer $k^*$ such that, if $c(t_{k+1}, x(t_k), \omega) \in \mathcal{C}^\mathcal{V} \cap \mathcal{C}^\mathcal{W}$, $h \in \{0, 1, \ldots, k^*\}$, then $\forall h \geq 0 \ c(t_{h+1}, x(t_k), \omega) \in \mathcal{C}^\mathcal{V} \cap \mathcal{C}^\mathcal{W}$. The horizon length value $k^*$ can be obtained according to an algorithm which is based on the solution of the following optimization problem:

$$G_k(j) = \max_{\omega \in \mathcal{W}^\mathcal{F}} T_j c(t_k, x, \omega) - f_j^k$$

subject to

$$T_j c(t_i, x, \omega) \leq f_j^i, \ i = 0, \ldots, k-1$$

where $T_j$, $j = 1, \ldots, n_t$ denotes the $j$-th row of matrix $T$ and $f_j^i$, $i = 0, \ldots, k-1$ have the following expression:

$$f_j^0 = f_j - \sup_{d \in \mathcal{D}} T_j L_d d$$

$$f_j^i = f_j^0 - \sup_{d \in \mathcal{D}} T_j H_c G_d d$$

$$f_j^{k-1} = f_j^{k-2} - \sup_{d \in \mathcal{D}} T_j H_c \Phi^{k-1-j} G_d d$$

Eqs. (12) represent a correction to the vector of constraints based on the $P$-difference operator between sets defined in (6) which allow to take into account the presence of disturbances. The algorithm to derive the constraint horizon is the following:

Step 1. $k = 1$ ;

Step 2. Find $G_k(j)$ solving Problem (10), for $j = 1, \ldots, n_t$ ;

Step 3. If $G_k(j) \leq 0, \forall \ j = 1, \ldots, n_t$; then, set $k^* = k$, and stop; else, $k = k + 1$, go to Step 2; end.

With the application of the above algorithm that can be performed off-line, the optimization problem (10) is converted into a Quadratic Programming (QP) problem with a finite number of linear constraints to be solved on-line, that is:

$$\vartheta(t_k) = \arg \min_{\omega \in \mathcal{W}^\mathcal{F}} J(r(t_k), \omega)$$

subject to

$$TH_c \Phi^h x(t_k) + \gamma \sum_{i=0}^{h-1} \Phi^{h-i} G_d + TL_d \omega \leq f^h, \ h = 0, \ldots, k^*$$

In the case that system (4) satisfies the offset-free and asymptotic stability assumptions and that $\mathcal{V}(x(t_k))$ is nonempty, the minimiser in (13) uniquely exists at each time. Moreover $\mathcal{V}(x(t_k))$ nonempty implies $\mathcal{V}(x(t_{k+1}))$ nonempty for all $h$ along the trajectories generated by the CG command (viability property). Finally the constraints are always fulfilled and the overall closed loop system is asymptotically stable. In particular, whenever $r(t_k) \equiv r$, $\vartheta(t_k)$ monotonically converges in finite time to either $r$, or its best admissible approximation compatible with constraints $\tilde{r} = \arg \min_{\omega \in \mathcal{W}^\mathcal{F}} J(r, \omega)$. Consequently, by the offset-free condition $\lim_{t_k \to \infty} \mathcal{V}(x(t_k)) = \tilde{r}$, $\mathcal{V}(t_k)$ denoting the disturbance free component of the plant output.

As for the computational aspects of the proposed technique, it is worth pointing out that the off-line problem (10) represents a Linear Programming (LP) problem, which can be solved using standard Simplex algorithms, whereas problem (13), which has to be solved on-line, is a convex Quadratic Programming (QP) problem that can be solved through any common solver embedded in the main commercial optimization and control software packages.

As it will be shown in the next section QP solvers provide a solution fast enough to be implemented on-line for our application studies. However we cannot theoretically assure that a solution is given within a sampling time interval. In the event that, at a given time instant the CG computation time of the command $\vartheta(t_k)$ exceeds the sampling interval, it is possible to resort to a non-optimal though feasible, and compatible with the constraints, strategy $\vartheta(t_k) \leftarrow \vartheta(t_k - 1)$, $\vartheta(t_k - 1)$ denoting the CG command computed at the previous time instant. This strategy is justified from a theoretical point of view by the viability property mentioned in the previous subsection and discussed in [12]-[13].

Some guidelines on the computation of the set $\mathcal{W}^\mathcal{F}$ are also useful since this is a key ingredient in the numerical setup of the CG. The set $C_{\infty}$, which is mandatory to compute $\gamma \mathcal{V}^\mathcal{F}$, can be numerically approximated with a convenient $C_{\infty}^a(\varepsilon)$ such that $C_{\infty}^a(\varepsilon) \subset C_{\infty} \subset C_{\infty}^a(\varepsilon) + B_\varepsilon$, where $B_\varepsilon$ represents a ball of radius $\varepsilon$ (safety level) centred at the origin. Such a set is computable in a finite number of steps. In facts it can be shown that
\[ C_{\infty} = C_k \sim \left( \sum_{i=k}^{\infty} H_c \Phi^i G_d D \right) \] (14)

The stability of matrix \( \Phi \) and the boundedness of \( D \) imply the existence of two positive constants \( M \) and \( \lambda \in (0, 1) \) such that \( \| \Phi \|_2 \leq M \lambda^k \), and of \( d_{\text{max}} = \max \| d \|_2 \).

This assures that, for all positive \( \varepsilon \), there exists an index \( k_\varepsilon > 0 \) such that

\[ \sum_{i=k}^{\infty} H_c \Phi^i G_d D \subset B_{\varepsilon} \quad \text{for all } k > k_\varepsilon \] (15)

Once the prescribed tolerance is fixed and \( M \), \( \lambda \) and \( d_{\text{max}} \) are determined, due to the following inequality

\[ d_{\text{max}} \tilde{\sigma}(H_c \tilde{\sigma}(G_d) M \sum_{i=k_\varepsilon}^{\infty} \lambda^i) \leq \varepsilon \] (16)

the value of \( k_\varepsilon \) can be computed as

\[ k_\varepsilon = \frac{\ln(\varepsilon) + \ln(1 - \lambda) - \ln(\tilde{\sigma}(H_c \tilde{\sigma}(G_d) M d_{\text{max}}))}{\ln(\lambda)} \] (17)

Now if we also consider the tolerance margin on the constraints fulfilment \( \xi \), we have the following approximation of \( C_{\infty} : C_{\infty}^0(\varepsilon) = (C_{k_\varepsilon} \sim B_{\varepsilon}) \sim B_{\varepsilon} \) that can be used to compute \( \tilde{\psi} \xi \) by solving the problem of determining all commands \( \omega \in \mathbb{R}^{n_\Theta} \) such that \( \overline{\omega} \in C_{\infty}^0(\varepsilon) \) that brings finally to the following set

\[ \tilde{\psi}^0_\xi = \left\{ \omega \in \mathbb{R}^{n_\Theta} : T H_c (I_{n_\Theta} - \Phi)^{-1} G \omega + T L \omega \leq f_{k_\varepsilon}^0 - (\xi + \varepsilon) \sqrt{\sum_{j=1}^{n_\Theta} T_j^2 T_j} \right\} \] (18)

V. NUMERICAL SIMULATIONS

The proposed control strategy has been applied to an ITER 15 MA plasma with an internal inductance \( l_i = 0.85 \) and poloidal beta \( \beta_{\text{pol}} = 0.1 \). In particular, the reference Scenario 2 Start of Flat Top (SOF) configuration was considered. A number of 87 acting constraints are listed in Table 1.

As for the primal controller, the vertical stabilization loop was tuned to exhibit a 15 rad/s crossover frequency, the plasma current control loop and the plasma shape multivariable control loop were tuned to have time responses in the order of 10 s.

The CG procedure has been set in operation on a full nonlinear model of the plasma evolution [17]. Fig. 5 shows some typical desired changes in plasma shape hereinafter called plasma manoeuvres \( A \), \( B \), and \( C \). Among the available 36 gaps, the n. 9, 21, and 30 were chosen as controlled outputs together with the position of the left and right strike points (see Fig.4).

We will now show and discuss in more detail the results obtained when trying to achieve the plasma manoeuvre \( A \) in the presence of constraints.

<table>
<thead>
<tr>
<th>Constrained Outputs</th>
<th>Bounds</th>
</tr>
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<tbody>
<tr>
<td>Maximum coil currents:</td>
<td>[MA]:</td>
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Table 1. Overview of the 87 constraints considered in the design of the CG.

Fig. 6 shows how the reference governor mitigates the reference signals to the primal control loop to avoid constraint violation. Fig. 7 shows the corresponding inputs (voltages), states (currents), and outputs (gaps), whereas Fig. 8 depicts the time trend of some of the variables which are very closed to constraint violation. Finally in Fig. 9 the shape evolution of plasma at given time instants are represented.

It is worth to notice that in the absence of the CG action, plasma would have assumed a limiter configuration due to the saturation of some of the control variables.
Fig. 6. Command Governor action. \( g(t) \) is generated as a sort of best approximation of \( r(t) \) compatible with the acting constraint.

Fig. 7. Input, States and Outputs (Gaps) generated with a NL simulation

Fig. 8. Time history of some of the variables which are nearly violating constraint.

Fig. 9. Nonlinear plasma shape evolution

REFERENCES