Design and Development of the Current Limit Avoidance System for the JET tokamak

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Outline

Introduction

The Current Allocation Algorithm

CLA implementation at JET tokamak

CLA commissioning

(Very preliminary) Experimental results
The Current Limit Avoidance System (CLA) has been recently designed and implemented to avoid current saturations in the poloidal field (PF) coils when the eXtreme Shape Controller (XSC) is used to control the plasma shape.

PF currents saturations may lead to:
- loss of plasma shape control
- pulse stop
- high probability of disruption
The CLA uses the redundancy of the PF coils system to automatically obtain almost the same plasma shape with a different combination of currents in the PF coils.

In the presence of disturbances (e.g., variations of the internal inductance $l_i$ and of the poloidal beta $\beta_p$), it tries to avoid the current saturations by “relaxing” the plasma shape constraints.
The XSC control algorithm minimizes a quadratic cost function of the plasma shape error in order to obtain at the steady state the output that best approximates the desired shape.

The XSC algorithm does not take into account the current limits of the actuators \(\Rightarrow\) It may happen that the requested current combination is not feasible.

The current allocation algorithm has been designed to keep the currents within their limits without degrading too much the plasma shape by finding an optimal trade-off between these two objectives.
The plant model (plasma and PF current controller)

The plant behavior around a given equilibrium is described by means of a linearized model

\[
\begin{align*}
\dot{x} &= Ax + Bu + B_d d, \\
y &= Cx + Du + D_d d,
\end{align*}
\]

- \( u \in \mathbb{R}^{n_{PF}} \) is the control input vector which holds the \( n_{PF} = 8 \) currents flowing in the PF coils devoted to the plasma shape control
- \( y \in \mathbb{R}^{n_{SH}} \) is the controlled outputs vector which holds the \( n_{SH} \) plasma shape descriptors controlled by the XSC (typically, at JET, it is \( n_{SH} = 32 \))
The controller model (XSC controller)

The XSC can also be modeled as a linear time-invariant system

\[
\dot{x}_c = A_c x_c + B_c u_c + B_r r, \quad (2a)
\]
\[
y_c = C_c x_c + D_c u_c + D_r r, \quad (2b)
\]

under the interconnection conditions:

\[
u_c = y, \quad (3a)
\]
\[
u = y_c. \quad (3b)
\]
Where

\[ P(s) = C(sI - A)^{-1}B + D, \]

is the transfer matrix from \( u \) to \( y \) of (1), and

\[ P^* := \lim_{s \to 0} P(s), \]

denotes the steady-state gain.
The current allocator block

The current allocator

The allocator equations are given by

\[
\begin{align*}
\dot{x}_a &= -KB_0^T \left[ \begin{array}{c} I \\ P^* \end{array} \right] (\nabla J)^T \bigg|_{(u, \delta y)}, \\
\delta u &= B_0 x_a, \\
\delta y &= P^* B_0 x_a.
\end{align*}
\]

(4a)  
(4b)  
(4c)

- \( K \in \mathbb{R}^{n_a \times n_a} \) is a symmetric positive definite matrix used to specify the allocator convergence speed, and to distribute the allocation effort in the different directions.

- \( J(u^*, \delta y^*) \) is a continuously differentiable cost function that measures the trade-off between the current saturations and the control error (on the plasma shape).

- \( B_0 \in \mathbb{R}^{n_{PF} \times n_a} \) is a suitable full column rank matrix.
When designing the current allocator, a large number of parameters must be specified by the user once the reference plasma equilibrium has been chosen:

- the two matrices $P^*$ and $B_0$, which are strictly related to the linearized plasma model (1)
- the $K$ matrix
- the gradient of the cost function $J$ must be specified by the user. In particular, the gradient of $J$ on each channel is assumed to be piecewise linear.

**Figure:** Piecewise linear function used to specify the gradient of the cost function $J$ for each allocated channel. For each channel 7 parameters must be specified.
The CLA block is inserted between the XSC and the Shape Controller set in *Current Control Mode*
The Current Limit Avoidance

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The CLA block diagram
The CLA modifies the PF current requests computed by the XSC before sending them to the PF current controller.

The CLA block has been implemented as an independent and isolated plug-in within the JETRT framework (the MARTe ancestor).
The CLA Tools

- The CLA Tools are a set of Matlab/Simulink graphic applications developed to ease the design and validation of a CLA scenario
- The CLA Tools extend the capabilities of the XSC Tools that were developed to assist the development cycle of the XSC at JET
- The CLA scenario is stored as a configuration file (text file), and can be used
  - to perform validation via closed-loop simulations
  - to setup the real-time C++ code running on the plant system
Workflow of the CLA tools

CLA Generator

XSC configuration file

XSC + CLA configuration file

XSC Simulator

JETRT Framework

Real-time Thread

XSC

CLA
Offline validation of the CLA

- The coding of the CLA GAM was performed *by-hand*
- Different tests have been carried out to validate the implementation
- In particular:
  - the CLA GAM outputs have been compared with the outputs of the CLA Simulink block feeding both with the same inputs
  - closed-loop simulations using the CLA GAM and the CREATE plasma model have been performed.

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A MARTe based simulator for the JET Vertical Stabilization system


- **All the tests listed above have been done in the office, but NOT on the plant hardware!**
- The message exchange (CLA scenario) between the JET pulse scheduling system (*Level 1*) and the CLA plant system has been tested
Perform closed loop simulations with the CLA plant system

- A lot of tests were done before testing the CLA on the real plant during an experiment
- 99% of the bugs/problems were found and fixed/solved...
- ...but there is still the 1%!
- To fix this remaining 1% it would be very useful to run closed loop simulations using the real plant system
What is the problem at JET?

Why we do not run closed loop simulations with the plant systems

- **First**: the JET tokamak is a 30 years old machine!
- A plant system (e.g., the CLA) interacts with a large number of other (usually very different) systems, which “runs” different (and sometimes very old) technologies!
- Moreover, your project may be not “on top of the list” (usually there are priorities)
- In practice, running closed loop simulations with the real plant system may be almost impossible (in terms of time, effort, resources, etc.)
- Nevermind... there is the commissioning :-)!
During the CLA commissioning the remaining 1% caused a problem.

This problem was not found during the offline tests because it was related to the interaction between the JET pulse scheduling system (Level 1) and the CLA.

In particular, the problem was related to the routine that processes the Level 1 message and sets up all the CLA parameters.

During the offline tests we had simply bypassed this ancillary routine, since the external systems were not available.
Lesson learned (for ITER)

Lesson learned

- It is important to have a test facility that allows the developers to validate the real system (ITER PCS?) against a plant model.
- This test facility should include (almost) all the interactions with other external systems (pulse scheduling system, data collection system, etc.)
The commissioning of the CLA has been carried out in from September to November 2011 during the restart phase of the JET tokamak.

A number of experiments have been carried out to check the correctness of the implementation.

In each experiment the allowed range for the current in each PF coil was modified in such a way that at least one current would hit a limit.
During the commissioning a simulation has been performed before running each experiment.

But soon after the first tests:

- the simulations results were substantially different from the simulations
- we were not able to reproduce the experiment in simulation, using both the CLA Tools and running closed loop simulations with the real C++ code
- The remaining 1% problem was not a simple coding problem
Once the experimental data are available it is possible to playback a JET pulse in the office.

This feature is very useful and allows us to use the debugger!

By using this feature we fixed the problem!
The CREATE-L model of the JET reference pulse (Pulse #81076 at $t = 24.9\ s$) for the CLA commissioning was used to carry out the simulations.

Given the reference scenario, the planned test was to limit the maximum absolute value of the current in the $D3$ coil to $10.5\ kA$ by using the CLA system.

The simulation results have been confirmed during the JET pulse #81080, when the CLA has been enabled between 25 and 27 seconds.
**Example - 2**

**Figure:** Comparison between the reference shape (red curve) and the shape obtained in simulation (green curve) when the limit $|I_{D3}|_{\text{max}} \leq 10.5 \text{ kA}$ is imposed.
Example - 3

**Figure:** Comparison between the experimental shape of JET pulse #81080 at $t = 27$ s (blue curve) and the shape obtained in simulation (green curve) when the limit $|I_{D3}|_{\text{max}} \leq 10.5$ kA is imposed.
The first proposed experiment - January 2012

- The *Experiment #1* of the JET parasitic experiment Px-2.1.7 was carried out on January the 9th 2012
- During commissioning pulse #81078 the four divertor currents were limited and **a soft stop was triggered due to the error on plasma shape**
- The XSC and CLA behavior were reproduced in simulation and it was shown that the problem was due to non-optimal weights of the CLA cost function
- A new CLA scenario was designed to solve this problem, by tuning the parameters of the cost function
- This optimized scenario was commissioned in November 2011, but it was not been possible to re-run pulse #81078
- The limitation of the four divertor coils represents a severe constraint for plasma shape control
- Experiment #1 was aimed to repeat pulse #81078
The currents in the divertor coils

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- Experiments

The Current Limit Avoidance
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The plasma shape @62s
The plasma shape @63s
The Current Limit
Avoidance

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Comparison between #81078 and #81715

![Graph showing comparison between #81078 and #81715](image)

- **#81078/JETPF/EFIT/0**: t=66.086601
- **#81715/JETPF/EFIT/0**: t=61.982601
References

**The current allocation at JET**

- **L. Zaccarian**
  Dynamic allocation for input redundant control systems

- **G. De Tommasi et al.**
  Nonlinear dynamic allocator for optimal input/output performance trade-off: Application to the JET tokamak shape controller

- **G. Varano et al.**
  Performance assessment of a dynamic current allocator for the JET eXtreme Shape Controller