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ABSTRACT

The Current Limit Avoidance System (CLA) has been recently deployed at the JET tokamak to avoid current saturations in the Poloidal Field (PF) coils when the eXtreme Shape Controller is used to control the plasma shape. In order to cope with the current saturation limits, the CLA exploits the redundancy of the PF coils system to automatically obtain almost the same plasma shape using a different combination of currents in the PF coils. In the presence of disturbances it tries to avoid the current saturations by relaxing the plasma shape constraints. The CLA system has been successfully implemented on the JET tokamak and fully commissioned in 2011. This paper reports on the first experimental results achieved in 2012 during the restart and the ITER-like wall campaigns at JET.

1. INTRODUCTION

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 at the JET tokamak. The XSC 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 [1]. Thanks to the XSC, the session leaders can directly specify the target shape, without specifying the PF current waveforms, since these waveforms are automatically computed by the XSC's model-based control algorithm. However, the XSC algorithm does not take into account the current limits in the PF coils, hence it may happen that the requested PF currents are outside the permitted ranges. This behavior could trigger a pulse stop due to current saturations.

The CLA has been implemented to solve this problem, giving the possibility to use the XSC when the PF currents are close to their saturation values. The idea is to keep the PF currents within their limits without degrading too much the plasma shape, by finding an optimal trade-off between these two objectives (more details can be found in [2]). The use of CLA permits to enlarge the operational space of the XSC [3] either when the equilibrium currents in the PF coils are close to their limits and there is no margin for plasma shape control (e.g. running a discharge at higher plasma currents), or when large variations of poloidal beta p and/or internal inductance li push the currents requested by the XSC close to their limits (e.g. during the main heating phase). The CLA algorithm is based on the dy namic allocator originally proposed in [4].

In this work we briefly report on the first experimental results with the CLA at the JET tokamak during the ITER-like wall campaigns (2011-12). In particular, we show an experiment where the CLA has proved to be able to manage a severe limitation for the plasma shape control, i.e. the saturation of the current in the four JET's divertor coils. The paper is structured as follows: the next section briefly introduces the CLA system deployed at JET. In Section 3 the experimental results are discussed. Eventually some conclusive remarks are given.

2. THE CLA SYSTEM AT JET

This section briefly describes the CLA system deployed at the JET tokamak. The readers interested in more implementation details are referred to [5].

The CLA is a dynamical system implements the current allocation algorithm described in [2]. In particular, The CLA modifies the PF current requests computed by the XSC before sending them to the PF current controller. Fig. 1 shows a block diagram of the JET shape controller as it has been modified in order to deploy the CLA system. In particular, the CLA system receives as inputs:

1. the PF current requests computed by the XSC;
2. the reference shape for the XSC (gaps, strikepoints and x-point position);
3. the shape measurements (gaps, strike-points and x-point position).

and gives as outputs:

1. the modified PF currents requests to be sent to the PF currents controller;
2. the additional references (gaps, strike-points, and x-point position) to be sent back to the XSC.

The CLA block reported in Fig. 1 has been implemented as an independent and isolated plug-in by using JETRT [6], which is the first version of the MARTe framework [7], and which was adopted to originally develop the XSC in 2003.

3. EXPERIMENTAL RESULTS

This section reports on the experiment carried out in January 2012, aimed to producing a severe limitation for the plasma shape control, and hence to prove the effectiveness of the CLA system. In order to do that, up to four out of the eight PF currents available for plasma shape control have been limited.

The following strategy has been adopted to carry out the experiment; first the reference pulse was run (Pulse No: 81710), where the XSC without CLA has successfully controlled the plasma shape between 20s and 23s.

The CLA has been then enabled starting from 21s, in order to limit the currents in the four divertor coils D1–D4 within a range smaller than the one actually available. In particular the following steps have been considered:

- in Pulse No: 81712 both the currents in D2 and D3 have been limited between [–31.5,–10] kA and [–11,–2] kA, respectively;
- in Pulse No: 81713 the limit on the current on D1 has been added; the considered allowable range was [–16.5;–4] kA;
- finally in Pulse No: 81715 the limit on D4 has been added, by limiting this current within [0, 6] kA.

When a PF current is outside its saturation limits, the CLA tries to bring it back in the permitted range, by using the redundancy of the JET's coils system to obtain almost the same plasma shape (see Fig.2).

In Pulse No: 81712, when the currents in D2 and D3 are limited, the CLA changes also the current in D1 in order to minimize the shape control error, as shown in Fig.3. The new equilibrium currents computed by the CLA are such that the shape control error is negligible, as shown in Fig.2(a), where the shapes at 22.5s for the two Pulse No's: 81710 and 81712 are compared.

Let now consider the two Pulse No's: 81713 and 81715. In these cases three and four control currents are limited, respectively, and the shape error increases, as expected (see Figs. 2(b) and 2(c)). Figure 4 shows a comparison between the divertor currents for Pulse No's: 81710 and 81715. Taking into account that the limitation of more than two control currents represents already a challenging scenario for the CLA, the performance is satisfactory for both Pulse No's: 81713 and 81715.

Furthermore, it is important to note that the CLA parameters used in the considered experiment included a hard constraint on the x-point position. Indeed, when computing the new equilibrium currents, the CLA prefers to increase the shape error on the top-outer region of the plasma, rather than to change the position of the x-point, as shown in Figs. 2(b) and 2(c). The CLA behavior can be tuned by choosing different parameters. This task can be performed also by non-expert users by means of a set of dedicated design tools (more details can be found in [5])

CONCLUSIONS

The CLA system has been recently deployed and commissioned at JET. This system permits to achieve safe operations when using the XSC to control, since it prevents the plasma shape control algorithm to require currents in the PF coils that are outside the permitted range. This paper describes an experiment carried out at JET, aimed to showing the capability of the CLA to manage a severe limitation for the plasma shape control.

As a final comment, it is important to remark that in 2012 the XSC has been used for more than 200 pulses during the ITER-like wall campaigns. This has been possible thanks to the CLA, which acts as a safety system and hence gives more confidence to the session leaders when using the XSC. Furthermore, having proved to be beneficial for the control of plasma shape during both the plasma current ramp-up and ramp-down, the XSC with CLA has controlled the shape during the ramp-down of the last 151 pulses.

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REFERENCES

[1]. M. Ariola, A. Pironti, The design of the eXtreme Shape Controller for the JET tokamak, IEEE Control Systems Magazine **25** (5) (2005) 65–75.

[2]. G. De Tommasi, S. Galeani, A. Pironti, G. Varano, L. Zaccarian, Nonlinear dynamic allocator for optimal input/output performance trade-off: application to the JET Tokamak shape controller, Automatica **47** (5) (2011) 981–987.

[3]. G. Varano, et al., Performance assessment of a dynamic current allocator for the JET eXtreme

Shape Controller, Fusion Engineering and Design **86** (6–8) (2011) 1057–1060.

[4]. L. Zaccarian, Dynamic allocation for input-redundant control systems, Automatica **45** (6) (2009) 1431–1438.

[5]. G. De Tommasi, et al., A Software Tool for the Design of the Current Limit Avoidance System at the JET Tokamak, IEEE Transactions on Plasma Science **40** (8) (2012) 2056–2064.

[6]. G. De Tommasi, F. Piccolo, A. Pironti, F. Sartori, A flexible software for real-time control in nuclear fusion experiments, Control Engineering Practice **14** (11) (2006) 1387–1393.

[7]. A. Neto, et al., MARTe: a Multi-platfrom Real-time Framework, IIEEE Transactions on Nuclear Science **57** (2) (2010) 479–486.

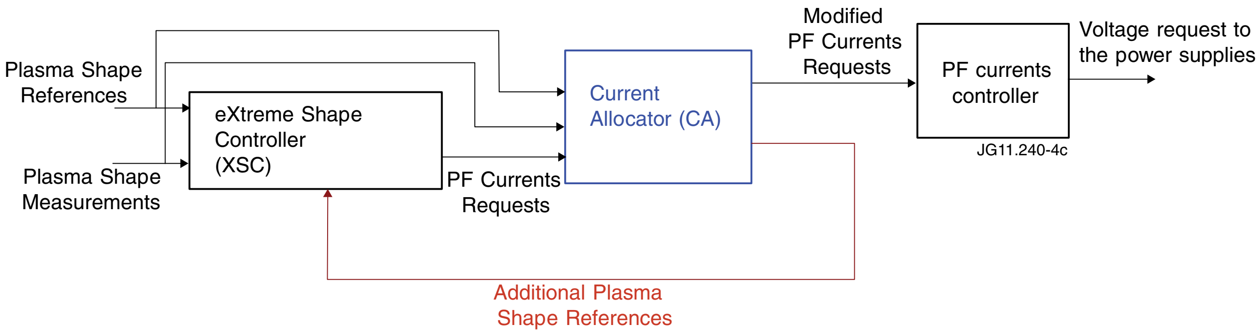
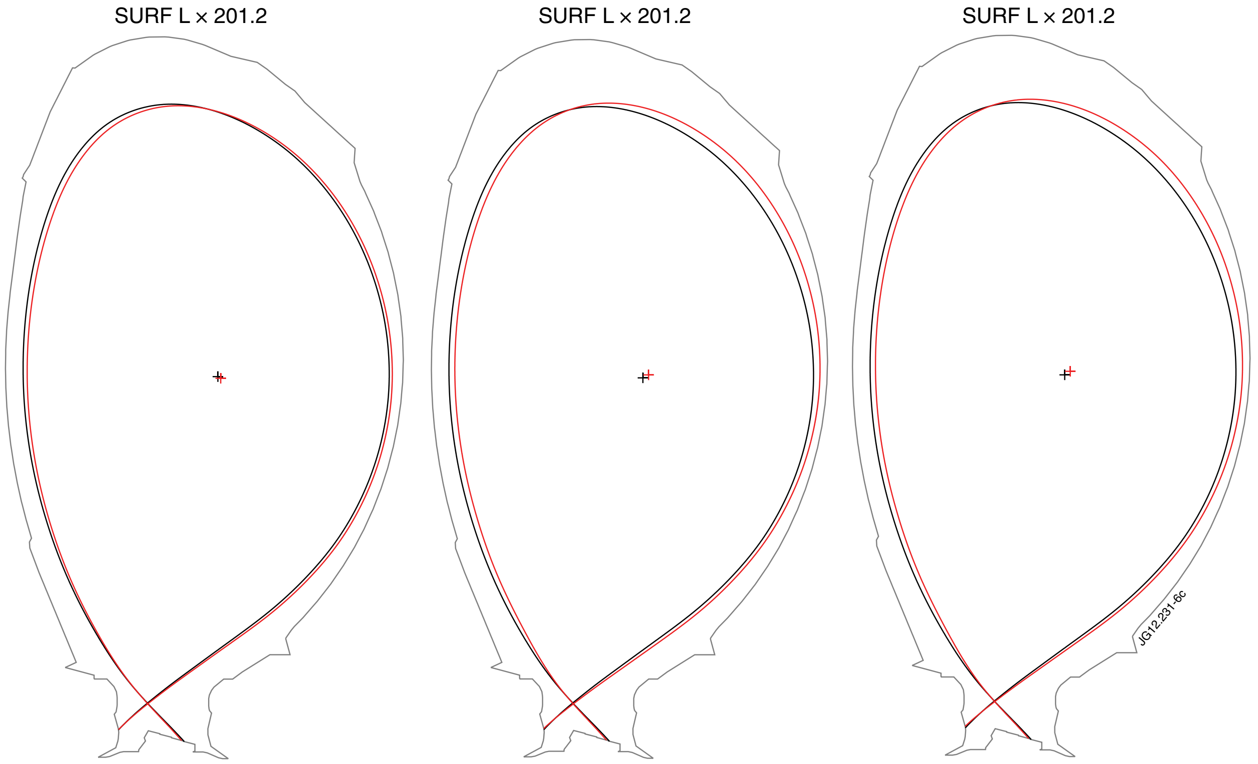


Figure 1: Block diagram of the JET shape controller, including the XSC and the CLA system.



(a) Pulse No: 81712 (b) Pulse No: 81713 (c) Pulse No: 81715

Figure 2: Shape comparison at 22.5s. The black shape is the one obtained in pulse 81710 when the CLA is disabled, while the red shape is the one obtained when the CLA is enabled.

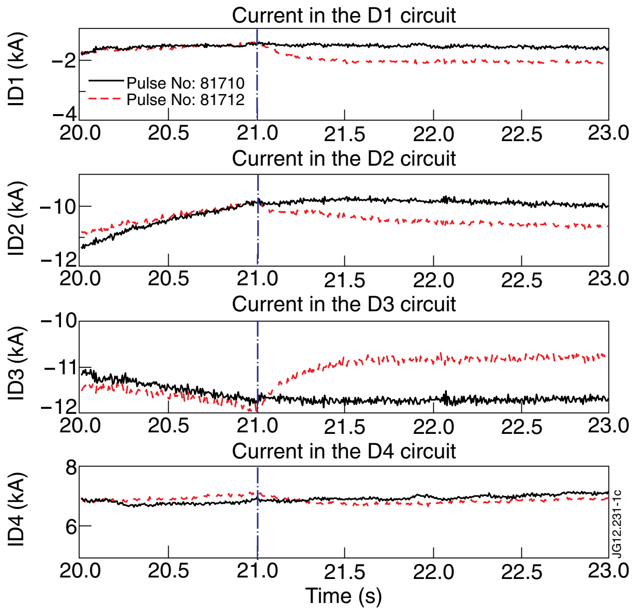


Figure 3: Currents in the divertor circuits. Comparison between Pulse No's: 81710 (reference pulse) and 81712. The shared areas correspond to regions beyond the current limits enforced by the CLA parameters.

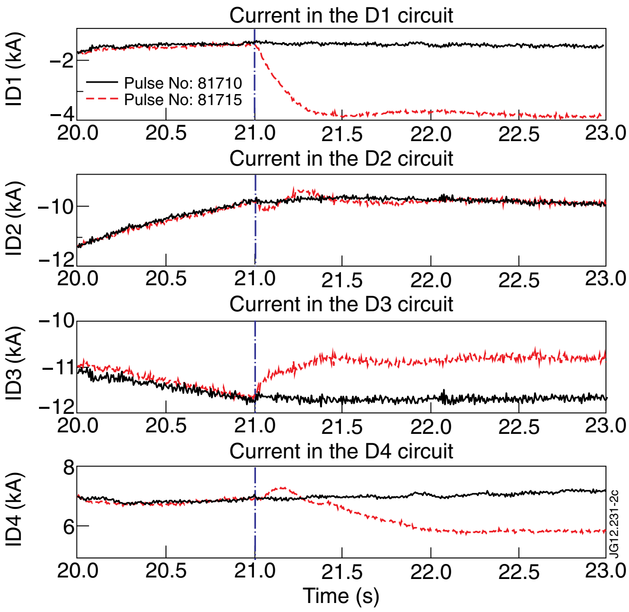


Figure 4: Currents in the divertor circuits. Comparison between Pulse No's: 81710 (reference pulse) and 81715. The shared areas correspond to regions beyond the current limits enforced by the CLA parameters.