SHAPE CONTROLLER UPGRADES FOR THE JET ITER-LIKE WALL

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Abstract

The upgrade of JET to a new all-metal wall will pose a set of new challenges regarding machine operation and protection. One of the key problems is that the present way of terminating a pulse, upon the detection of a problem, is limited to a predefined set of global responses, tailored to maximise the likelihood of a safe plasma landing. With the new wall, these might conflict with the requirement of avoiding localised heat fluxes in the wall components. As a consequence, the new system will be capable of dynamically adapting its response behaviour, according to the experimental conditions at the time of the stop request and during the termination itself. Also in the context of the new ITER-like wall, two further upgrades were designed to be implemented in the shape controller architecture. The first will allow safer operation of the machine and consists of a power-supply current limit avoidance scheme, which provides a trade-off between the desired plasma shape and the current distribution between the relevant actuators. The second is aimed at an optimised operation of the machine, enabling an earlier formation of a special magnetic configuration where the last plasma closed flux surface is not defined by a physical limiter. The upgraded shape controller system, besides providing the new functionality, is expected to continue to provide the first line of defence against erroneous plasma position and current requests. This paper presents the required architectural changes to the JET plasma shape controller system.

INTRODUCTION

The JET [1] plasma position and current controller (PPCC) [2] is a real-time system responsible for the control of the currents in poloidal fields (PF) circuits, the plasma current and the plasma shape [3]. Its two main components are the shape controller (SC) and the vertical stabilisation (VS) systems. PPCC receives its input data from the magnetics systems, poloidal field (PF) circuits, central interlock and safety system (CISS), pulse termination network (PTN), radio-frequency (RF) and lower-hybrid (LH) systems, central timing and triggering system (CTTS) and Level-1, the high-level plant configuration interface. The latter is used for the configuration of the system, both with parameters from the session leader (SL) user-interface and from the PPCC expert settings. Magnetic signals arrive from the ATM real-time network systems [4] and are used to calculate the plasma current, radial and vertical moments, perform the reconstruction of the plasma boundary [5] and to provide flux measurements. Some of these are used later as control variables in the form of plasma current, gaps and flux. The PTN connection enables the shape controller system to change its execution configuration, as part of a global response to an external event.

The main output of SC is the voltage reference to all the PF amplifiers. It can also trigger the stop of a JET pulse through PTN, or CISS, in the case of internal problems, control errors and violation of amplifier limits. The boundary reconstruction coefficients and the circuit currents are sent to other JET plant using the ATM real-time network.

Each circuit can be controlled either in absolute current, proportional (to the plasma current) current or against a geometrical parameter, defined as a vector, named gap. Examples of gaps are the radial outer gap (ROG), which defines the distance between the outer limiter and the plasma, and the radial inner gap (RIG). The amplifier can also be set in a blocked state, where minimum negative voltage is applied, and no induced current is allowed to flow in the circuit (due to the presence of a diode); or in the free-wheeling state where 0 V are applied across the circuit.

The SC system is based on time windows, so that each circuit can change its control mode during the experiment. Indeed, most of the amplifiers start the experiment either blocked or in absolute current control, as no plasma exists at that time. As soon as a sustained plasma breakdown is achieved, most circuits are either set in proportional current or gap control. The shape controller hardware is based on

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[*] See the Appendix of F. Romanelli et al., Proceedings of the 23rd IAEA Fusion Energy Conference 2010, Daejeon, Korea

VME®, PowerPC® and custom built I/O and data acquisition cards. The system control cycle is 2 ms.

eXtreme Shape Controller

A module named eXtreme Shape Controller (XSC) [6] allows a full boundary control. The main idea behind the XSC algorithm is to control the full plasma boundary, while minimising the error over a large set of geometrical shape descriptors, so that the system is no longer limited to the accurate control of only a few gaps, further constrained by the circuit control mode selections. When the XSC is used, all the circuits in shape controller are set to proportional current control, with the appropriate current references provided by the XSC algorithm.

The XSC operational scenarios are implemented around a given plasma shape and equilibrium (in terms of plasma current, internal inductance and the ratio of the poloidal kinetic to magnetic pressure). Using linearised plasma models, the predicted PF currents for a given plasma shape and configuration are evaluated. If these are within power supply saturation limits, the XSC is finally designed by carefully tuning the weighting matrices related to the minimisation function [7] and the system stability is assessed in closed-loop simulations. As the algorithm is valid only around a given equilibrium, the plasma must be driven into the reference conditions using shape controller, before enabling XSC.

P1 Logic

Plasma current is induced by changing the flux across a central solenoid. At JET this circuit is named P1E and is responsible for generating the current in the ten stacked central solenoid coils. The current is produced by a flywheel generator, named PFGC, capable of delivering a maximum of 400 MW of power. As shown in Fig. 1, at the same time, a second circuit, named PFX is also capable of driving current, in different windings, of the six central pancakes. The main role of this circuit is to reduce the stray fields, increasing the inboard vertical field and allowing for a more *D* shaped plasma.

The PFGC is a single quadrant amplifier, producing single direction current and voltage. A special circuit with hardware switches, named *s1* and *s4* in Fig. 1, allows for the current to flow in opposite directions during the same plasma pulse. When required, this scheme is used to provide a pre-magnetisation of the iron core, by forcing current through the solenoid in the opposite direction (*s1* closed and *s4* opened) in respect to the one using during the experiment (*s1* open and *s4* closed). The result is a larger amount of flux available to induce plasma current and consequently a greater pulse length.

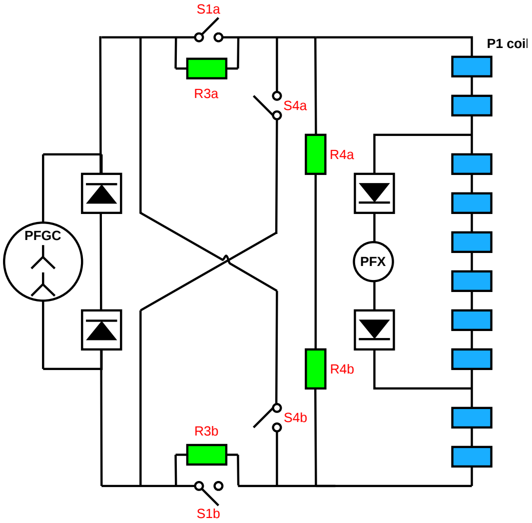


Figure 1: Simplified version of the JET ohmic circuit layout. By commutating the different switches, current from the flywheel generator will flow in opposite direction.

Since having currents in opposite directions in the PFGC and PFX circuits will lead to high repulsion forces, up until recently, the current in the PFX circuit was only allowed to flow when the current in the PFGC circuit was greater than a positive value (with the convention that a positive PFGC current is the one to be used during the plasma pulse).

Justification for the Upgrades

The upgrade of JET to a new all-metal wall poses a set of new challenges regarding machine operation and protection. These will be handled by a major project named Protection of the ITER-like Wall (PIW), responsible for the coordination amongst all the infrastructure that provides the diagnostic data (e.g. infra-red cameras and pyrometers) and the systems required to take control actions (e.g. PPCC and additional heating systems). The major problem is that the current strategy to stop a plasma pulse might conflict with the requirement of avoiding localised heat fluxes in the inner wall components. The greatest limitation in PPCC was that the stop strategies are global during the pulse and could not be adapted for the pulse phase and plant conditions.

A second improvement, aimed at an optimised operation of the machine, was designed in order to enable a limited amount of PFX current to flow before a positive value of P1E current is achieved, without putting the machine integrity and safety in jeopardy. The enlarged operational space will allow the earlier formation and exploitation of the X-point configuration.

Finally, a current limit avoidance (CLA) [8] system was designed in order to avoid PF current saturations when the XSC is used to control the plasma shape. It uses the redundancy of the PF coil system to automatically obtain almost the same plasma reference shape with a different combination of currents in the PF coils. In particular, in the presence of severe disturbances, it tries to avoid the current saturations by *relaxing* the plasma shape constraints. Its feedback scheme asymptotically guarantees an optimal trade-off between shape error and distance of the coil currents from their limits.

PIW STOPS

As illustrated in Fig. 3 the PPCC code was updated to react to ten different stop sources for each available time window. Examples of stop sources are localised hot spots in the main chamber, magnetohydrodynamic modes and unavailability of a crucial resource for the experiment (e.g. additional neutral beam power heating). A stop response is configured with a control mode and a control value for each of the 9 PF circuits. The only exceptions are the P1 circuit, for plasma current control, and the P4 circuit, for radial wall distance control, which are programmed using an hold-and-ramp waveform. These waveforms consist of four distinct segments where an hold value time is specified, together with a ramp-rate to the following value. Moreover, the values and times of an hold-and-ramp waveform can be synchronised to the plasma current waveform values, being dynamically adjusted to its values at the time of the stop.

A special type of stop, named jump to termination, enables the system to react to a stop request by fast forwarding the execution to the time window corresponding to the pre-programmed termination time, ignoring any time windows in between.

The request for a stop is driven by the real-time protection sequencer (RTPS) [9], connected to PPCC using the real-time network. RTPS is responsible for the central coordination of all the JET actuators and reacts to alarm requests from the vessel thermal map (VTM) [10] system.

An alternative sequence facility is also available in the PIW PPCC version. The idea is to switch to a different experimental program if a given resource is not available during the execution of the experiment, allowing to maximise the optimisation of resources and machine time.

It should be noticed that the old, pre-PIW, stops are still available to be used when required and can be programmed together with the PIW stops.

POET

In order to study the implications of enabling current on the PFX circuit, while there is still current from P1E flowing in the opposite direction, a project named PFX-on-early-task (POET) was started. The major problems addressed concerned the modelling of the maximum forces in the P1 stack, taking into account the machine mechanical structure, and the effects of external faults in the machine integrity if these were to happen while taking advantage of the new operational space.

At the same time a study regarding the implementation of a new control logic for PPCC was also performed, mostly based on the value of the current across the central pancakes, given by: $P1C = P1E + PFX$. As depicted in Fig. 2, it was decided to set three operational regions: one where no PFX is allowed to flow, so that $P1C = P1E$; a second where the value of PFX is limited; and finally a region where the PFX value is only limited by the amplifier. Even if the control system is not used as a protection system, it makes every effort to avoid triggering the interlock protection systems, and consequently a state machine with the previously described logic was implemented in PPCC. All the possible current combinations, simulation of possible faults, and the performance of the controller itself were asserted using a simulator of the controller, connected to linearised plasma models provided by the CREATE [11] tools. The results of these simulations have also allowed to select the first set of values for the limits, even if these are then expected to be tuned during the experimental campaigns.

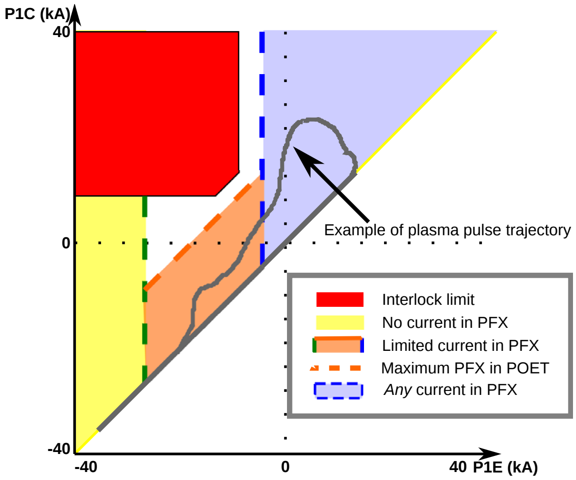
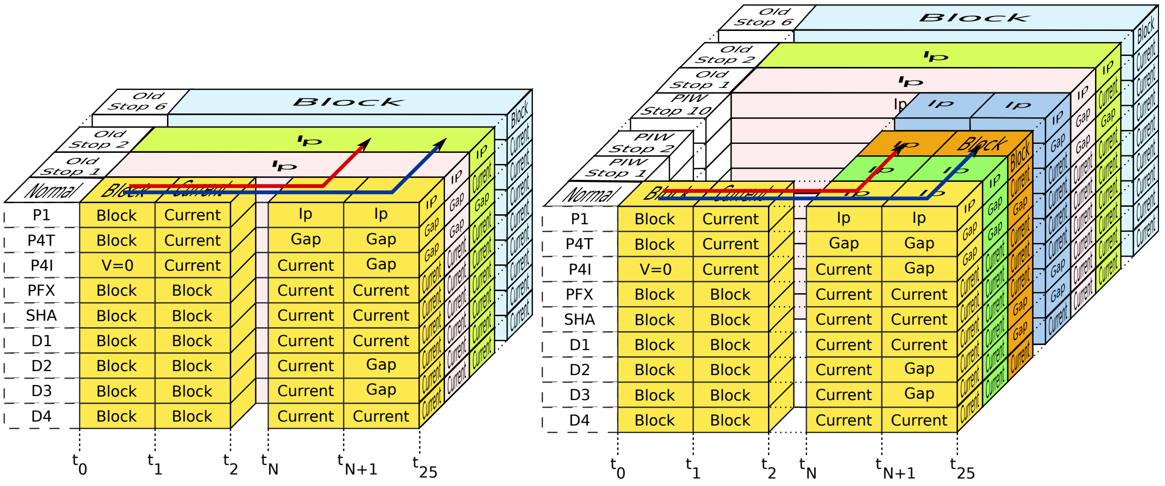


Figure 2: The new POET region will enable the use of PFX early in the plasma discharge. A possible plasma pulse trajectory is represented in grey. PPCC ensure that none of the limits are violated due to an erroneous request.

CURRENT LIMIT AVOIDANCE

The previously introduced current limit avoidance (CLA) was implemented as an additional feature of the eXtreme Shape Controller, being completely transparent to the existing SC code. As depicted in Fig. 4, the CLA modifies the PF current requests computed by the XSC before sending them to the SC, which is set in proportional current control mode with the only exception of the P1E circuit, as this is usually controlling the plasma current. Even when away from the saturation limits the CLA can be used to automatically equalise the best distribution of currents for a given shape, a process that is usually manually performed while developing the XSC controller settings for a given experiment.

Any changes performed by the CLA to the actual plasma shape are hidden from the XSC controller in order to inhibit its reaction. More details regarding the actual algorithm can be found in [8].



P1	Block	Current	Ip	Ip
P4T	Block	Current	Gap	Gap
P4I	V=0	Current	Current	Gap
PFX	Block	Block	Current	Current
SHA	Block	Block	Current	Current
D1	Block	Block	Current	Current
D2	Block	Block	Current	Gap
D3	Block	Block	Current	Gap
D4	Block	Block	Current	Current

Before PIW

P1	Block	Current	Ip	Ip
P4T	Block	Current	Gap	Gap
P4I	V=0	Current	Current	Gap
PFX	Block	Block	Current	Current
SHA	Block	Block	Current	Current
D1	Block	Block	Current	Current
D2	Block	Block	Current	Gap
D3	Block	Block	Current	Gap
D4	Block	Block	Current	Current

After PIW

Figure 3: The previous version of shape controller had the same reaction to the same stop trigger, independently of the pulse phase and plant conditions. With the new all metal wall this could lead to highly localised hot spots and it was decided to allow for up to ten different stop responses for each experimental time window. The first column labels the 9 PF circuits controller by SC. In this example, for the same stop trigger (PIW stop 2), depending on the stop time, different control modes will be set.

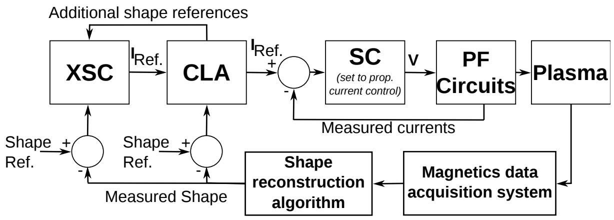


Figure 4: The XSC and CLA are implemented as additional modules of shape controller. XSC provides the current references to be controlled by SC which then sends voltage commands to the PF amplifiers. The additional shape references have the purpose of hiding from the XSC controller any changes to the plasma shape due to the CLA algorithm.

CONCLUSIONS

The JET shape controller was upgraded in order to cope with the operational requirement of the new ITER-like-wall. A new stopping architecture enables a greater control over the experiment and enhances the first line of defence for the machine protection. A new operational mode, named POET, enables an earlier exploitation of the X-point configuration, optimising experimental resources and time. Finally, it is expected that with the introduction of a current limit avoidance module it will be possible to demonstrate a safer operation of the machine, while using XSC, even in the presence of disturbances and when working near the power supply limits.

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