Plasma Position and Current Control Management at JET
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ABSTRACT
PPCC is hybrid group of interacting controllers managed through a decision-making logic. After nine years of successfully controlling the plasma in all JET experiments, is being overhauled to integrate the new full boundary controller “Extreme Shape Controller”. The difficult integration issues have spawn a re-evaluation of the overall management strategy of the many control abilities provided by PPCC. The aim of this paper is to describe the complex real-time decision logic implemented in PPCC and to explain how it has been shaped by the needs of JET plant. It will then describe the changes necessary to integrate the new component and finally will try to propose a different approach to the management problem.

1. INTRODUCTION
One of the most demanding aspects of operating a large tokamak like JET is the simultaneous plasma shaping and stabilisation while remaining within the physical limits of the plant. During routine operations, power systems capable of supplying powers of several MW and currents of tens of kA, are used to drive magnetic coils to produce magnetic fields in the range of some Tesla. These are used to create and confine the plasma within a doughnut shaped vacuum chamber filled with ultra low-pressure low impurity deuterium.

An accurate control of the aforementioned macroscopic characteristics deeply influences the plasma behaviour, like its interaction with the facing components, its coupling to the additional heating systems, its macroscopic internal stability, and its performance. On the other hand, a failure in taking into account any of the very complex plant and plasma limits may lead to serious damages to the device. Given the overall complexity of the machine it is wrong to consider tokamak control simply as a mere collection of elementary feedback systems, each acting on different aspects of the plasma. In fact more than the single control laws, it is their synergy and their ability to respond to the requirements of the whole plant that is the key issue in designing the controller. In this perspective, the term “Control Management” will be used in the following to describe the strategy to integrate the various control systems, and to program their response to variations in the plant state, such as pre-programmed events, failure or limits of the actuators, major changes in the plasma behaviour.

At JET, the main system that performs this task is the “Plasma Position and Current Control” (PPCC) with its three subsystems: plasma Shape Controller (SC) [1][2][3], Vertical Stabilisation (VS) [4][5] and internal walls protection system (WALLS) [6].

Because of the increasingly varying experimental needs the JET operative space has been continuously widening, generating the necessity for more and more flexibility in the control systems. The latest addition is the newly designed “Extreme Shape Controller” (XSC) [7][8] subsystem, a control module especially aimed at improving the machine performances with highly shaped plasmas. While the design of PPCC has been validated by its ability to cope with the continuous changing in the experiments, the need to avoid repeating certain potentially dangerous combination of events has made the controller complexity grow excessively. When it was originally constructed the control
management problem was approached from an inductive point of view: the JET operational space was analysed and the right strategy of control for each event was programmed in the controller, using a bottom-up process. The broadening of the experimental needs has made the extension to this approach difficult to manage, calling for a more general deductive approach.

2. THE STRUCTURE OF A JET PULSE

JET is a pulsed machine, with a typical period time of about half an hour. In this interval, the settings for an experiment are loaded on the plant, then follows a 30 to 60 second plasma discharge of which 10 to 30 of scientific interest, and finally the collected data is stored in the JET databases for further analysis.

After the pulse parameter preparation, the count down and the pre-pulse checks, the “Central Timing and Triggering System” (CTTS) gives the start signal to PPCC, which immediately takes the control over the power supplies and starts the experiment.

In the first 40 seconds of the plasma discharge, first the primary coil P1 is pre-charged with a fraction of its maximum current, then the power supply is disconnected leaving just a resistor bank in parallel to the inductor. The voltage on P1 will increase immediately causing the gas in the chamber to start ionising and eventually to become plasma. In this short period of time, PPCC controls the P1 voltage and consequently the plasma evolutions by activating thyristors so that to insert more resistors banks in parallel to the P1 (Fig.1). When P1 voltage has finally decreased below a threshold the power supply can be reconnected with opposite polarity.

2.1. THE MAIN EXPERIMENT PHASE

The evolution of the plasma from now on is driven according to the experiment aims. The plasma shape can be modified in order to assume a particular geometry; it may be heated using beams of high-speed deuterium atoms, or by coupling it to various radio frequency sources. Density may be changed using different gas fuelling schemes and several gas species may be injected.

Most experiments are executed using an X point plasma configuration: the plasma cross-section shows a drop-like shape and is completely detached from the walls. This allows reducing the impurity influx from the plasma facing components thus improving performance.

2.2. THE PROTECTION SYSTEMS

During the experiment, some component of the plant may develop a fault or be driven to one of their limit, an additional heating system may fail or the plasma itself may develop an internal problem. In these cases one of the JET protection systems (Real Time Plasma Protection RTPP, Coil Protection System CPS, Direct Magnet Safety System DMSS […]), or PPCC itself, will attempt to avoid damages to the machine by triggering events on one of the two main protection networks: Central Interlock and Safety System (CISS) and Pulse Termination Network (PTN).
3. THE PPCC INTERNAL STRUCTURE
To describe in detail the design of the components of PPCC control systems is beyond the scope of this paper. It is anyway necessary to highlight their leading ideas and main features, so as to understand the motivation and the development of the new implementation.

3.1. VERTICAL STABILIZATION
PPCC operates a frequency-decoupled multivariable control, where the vertical position is stabilised on a much shorter time scale than that of the shaping. This choice has a physical reason, since elongated plasmas are naturally unstable for the vertical position with growth times in the range of some milliseconds. Active control is needed to complement the passive stabilisation effects of the eddy currents, which promptly decay with the facing structure resistive time constant (~3ms). This is reflected into the design choice of the vertical speed regulator: the non-linear FRFA amplifier [9] driven by a powerful DSP based controller.

The VS main component is the plasma velocity loop, a simple bang-bang controller that acts by switching the 9 level FRFA amplifier voltage output to a value proportional to the plasma speed. This alone would be sufficient to dump any plasma vertical movement if not for an uncontrollable drift in the actuator current. Introducing a weaker feedback loop on the current, which biases the switching thresholds, solves the problem.

Since the plasma position is unstable, the overall control action is that of a limit cycle, whose frequency is proportional to the controller gain and the, shape related, vertical instability growth rate. If the variation of this last parameter was not taken in account, in one case the FRFA amplifier would overheat, in the other the actuator current would develop a slow oscillatory behaviour. This is avoided by tuning the velocity loop proportional gain, using a simple frequency adaptive controller.

3.2. SHAPE CONTROLLER
SC performs its task of plasma boundary shaping using a combination of three different types of control actions: current, flux and gap control. While the plasma shape is fundamentally determined by the relation between plasma current and the poloidal circuit currents, simply pre-programming the current evolution in the actuators is not sufficient. The plasma current distribution significantly contributes to the final shape together with the very sensitive machine iron core saturation state.

A simple solution is flux (space integral of the magnetic field) control. Since the plasma column position affects the magnetic field map, the measurement of the difference in the magnetic flux taken from two points can be used to roughly centre the plasma between them. All the feedback quantities broadly based on this concept manifest an almost linear relation to the poloidal circuit currents.

However, in order to obtain good heating and confining performances, it is important to know not just the plasma centroid but also its size and its distance from the vessel walls (gaps). Using a sophisticated reconstruction algorithm (XLOC [10,11]) it is possible to obtain the real-time
measurement of the gaps with a sufficient accuracy. Unfortunately, their relation with the actuators becomes strongly non-linear if the plasma touches the vessel wall anywhere. The definition itself of plasma boundary as the last closed flux surface inside the vacuum chamber inherently introduces a non-linear effect.

Within this framework, PPCC performs its Control Management tasks: an accurate as well as robust control action is provided, routinely switching between different sets of control quantities and control techniques, both as pre-programmed (feedforward) evolution and as a response to variations in the plasma and the plant needs (feedback component).

Shape Controller is logically and algorithmically subdivided into different interacting modules. In particular, the decision on which control action or what protective measure to take is made in the “Control Mode Selector”, on the basis of computation performed by the other units, which are briefly summarised in the following.

- **Signal Processing** module. It performs the complex mathematics necessary to transform raw measurements into control variables.
- **Diagnostic** module. Having access to all the measurements, waveforms, external events and programmed limits, detects any of the fault conditions, producing a set of warnings and alarms.
- **Control** module. It calculates the voltage references to the actuators, using the selected waveforms and feedback quantities together with a set of control matrices. Every time the “Control Management” changes the set of control variables, these matrixes are recalculated.
- **Waveform** module. The unit calculates the necessary references to the controller as a function of the control mode selection.

A set of plant states is then produced, which includes the overall pulse state (online, offline, termination…), each circuit state (controlled, shorted, open circuit), the associated control variables, and eventual saturation condition. This dataset is used in all the code to affect the behaviour of all the controller components.

### 3.3. WALLS

A very energetic particle flow is discharged to the vessel either where the plasma touches the walls or on the strike points, if in X-point configuration. Since the plasma facing structures will be damaged if their temperature becomes excessive, it is necessary to monitor the energy deposition on each section of the walls.

Using data from the magnetic field structure reconstruction code XLOC, WALLS continuously tracks the interaction between plasma and vessel in terms of distances from the wall, angle of the magnetic field lines and estimated temperature state of the wall locations. In addition the code monitors if the position of the strike points are clear of unprotected areas at the machine bottom.

### 3.4. USER INTERFACE

In order to simplify the real-time PPCC code, some control management decisions are taken even
before the commencing of the pulse: the checks on the programming of the pulse are delegated to “Pulse Schedule Editor” user interface. This solution was also chosen because this is the area where changes are required more frequently, and a continuous re-commissioning of the real-time part of PPCC would have proven too expensive.

Shape Controller provides the user with a sequence of programmable control states called “Time Windows”, describing the evolution of the experiment in terms of desired combination of control laws. With the introduction of “Scenarios”, instead of having to program waveforms and control actions for each window, the user simply selects among a set of pre-programmed combinations. In addition the concept of “Breakdown Scenario” was added to standardise the plasma formation part of the pulse, and the “Expert Scenario” to hide from the user the most delicate configurations, like limits, gains, and control matrices.

4. THE CONTROL MANAGEMENT STRATEGIES

4.1. TRANSITIONS

When a “Time Window” starts, the controller logic assigns the selected feedback quantities and reference waveforms to the actuators, and prepares a new set of control matrices. If the feedback variables are changed, it is very probable that pre-programmed reference values are far from the feedback measurements. This could make the controller request high voltage levels to the actuators. While this situation does not create problems to the controller or the actuators, the evolution it implies is most often not what the user was expecting, and in addition undesired effects may be induced on the plasma.

The control management logic introduces an additional “Smoothing Window” allowing SC to use a different reference waveform ramping from the measurement to the user request. The length of the smoothing time is set to be the same for all circuits, being the longest that satisfies each rate requirement.

4.2. ASYNCHRONOUS EVENTS

Asynchronous triggers differ from the Time Windows events because their occurrence or timing cannot be predicted. In PPCC these events are extended to embrace all the triggers resulting from external signals or their elaboration. Depending from the context and the gravity of the occurrence the control management will decide whether to introduce a temporary change in the sequence of “Time Windows” or to branch into a completely different path.

A new path is constructed by immediately terminating the present control actions and by replacing all the remaining “Time Windows” with a single “Termination Window”. Depending on the chosen termination path, the SC adopts a set of control laws and termination waveforms without producing any “Smoothing Window”: the reference is instead scaled to match the relative measurement. This is because the typical termination request is either to keep the variable constant or to bring it to zero with a given law.
4.3. **“TERMINATION WINDOW” STRATEGIES**

SC will react to several types of external or internal triggers by immediately taking the relative pre-programmed “Termination Window”. Depending on the relative priority of the commands SC may only branch from one “Termination Window” to a higher priority one.

**SOFT STOP** is the lowest priority and the most common of the termination requests. Plasma current is slowly brought to 0 while the plasma shape is unchanged.

**FAST STOP** brings all the shaping currents promptly to 0, plasma current is let to decay at maximum natural speed.

**P1 STOP** is similar to SOFT STOP but the P1 current generator excitation current is blocked.

All the next stop strategies do not allow branching out.

**CISS-ES**, triggered externally by a power supply fault, acts like FAST STOP with the addition of removing decoupling terms in the control matrix.

**MAGNETIC STOP**, initiated whenever a fault is detected in the measurement of a current, terminates the plasma only using magnetic based control variables.

**BLIND STOP**, triggered by a fault in the communication with the main magnetic acquisition system, results in a termination using only basic plasma measurements and proportional current control.

4.4. **CTTS TRIGGERS**

SC uses the JET wide CTTS triggering system to synchronise its internal logic to the main tokamak status. In additions it verifies whether the timing and the sequence of these events are as expected from the user, in order to verify the coherence between plant settings and PPCC settings. In case of a serious mismatch the experiment sequence is branched into the SOFT STOP “Termination Window”.

4.5. **CONTROL ERROR EVENTS**

One of the major drawbacks of the decoupling algorithm is that if a large error is present on one of the controlled variables, this error requires strong actions from all power supplies, inducing large errors in all other controlled variables. For SC, a large control error could cause one or more power supplies to reach their current limits. When a current is saturated, the decoupling control algorithm would react trying to use the other circuits to minimise the error induced by the saturated circuit.

PPCC continuously checks the difference between each measurement and its relative control references. If it finds that one of these errors remains bigger than a threshold for more than a given minimum time, it then prompts the decision to terminate a pulse using a SOFT STOP.

4.6. **CURRENT LIMIT EVENTS**

While the reaching of a voltage limit on actuator is just a temporary event solely affecting the performance of the control action, a limitation on a current often requires the termination of the plasma discharge.
SC general strategy of managing a current saturation is to avoid it by keeping the current to a level just below the limit. If this circuit is not controlled in current, then the selection of control variables has to be changed: the absolute current control of the saturating current must substitute the control variable most coupled with it. This temporary branch outside the normal “Time Window” sequence will terminate once estimated that returning to the original control mode would cease requesting a current outside the limits.

The reaching of a current limit is equivalent to the loss of a degree of freedom in the system. If this was necessary for the safe operation of the machine, the Control Management will not just track the limit but at the same time branch to a SOFT STOP “Termination Window”: this happens for the poloidal circuits P1, P4, D1- D4.

4.7. CENTRAL SOLENOID CURRENT LIMITS
The P1 and the PFX circuit currents both circulate on the central solenoid (Fig 1)

The forces between the central part of the coil (P1C) and the upper and lower extremes (P1EXT) are proportional to the product of the 2 different currents flowing in solenoid. Since the mechanical structure of the coil was not designed to stand a negative force (it would separate the coil parts), the control system must avoid activating the PFX circuit when the P1EXT current is of different sign. In fact, since the two circuits are strongly coupled, any rapid increase of the current in P1C would result in a loss of current in the external parts. For this reason the SC will immediately stop increasing the PFX current if the current in the P1EXT circuit is below a threshold.

Compared to the fixed limit of the P1EXT, that of P1C is calculated as a function of the toroidal field coils current. This is because these coils are mechanically mounted in contact with the central solenoid. When a significant amount of current flows on them, they expand and compress the P1C, thus allowing more current on it.

Because of the strong coupling between the P1C and P1EXT it is assumed that any rapid change on any of the two circuits would conserve flux. Because of this, in case of a rapid reduction of PFX current the P1EXT might raise above its limits. This fact is taken in account by further limiting the central solenoid current to a value function of the external solenoid current.

4.8. PLASMA CONTACT EVENT
When controlling the outer gap ROG (or the inner gap RIG), SC measures the Plasma to Wall distance along a line on the equatorial plane. If the plasma centre is not aligned with the wall curvature centre, it is very probable that it will become limiter if a small ROG reference were used. Any further radial movement of the plasma centre will cause ROG to increase because the plasma will at the same time shrink.(Fig 2) To avoid the ROG control being unstable the “Control Management” decides to temporarily change the control variable to RIG (or to ROG if the plasma touches the internal wall).
4.9. SWEEPING
In order to spread the plasma heat and particles load evenly, SC can be programmed to sweep the “Strike Points” over the divertor (portion of the machine vessel designed to trap the plasma exhausts) modulating the D2 and D3 currents. To avoid producing a too high oscillating power consumption, the “Control Management” automatically forces D3 into current control and constructs a waveform so that the magnetic energy is conserved. This means that any user waveform trying to change the D2 and D3 independently will be disregarded.

4.10. RF FEEDBACK
Instead of controlling the outer gap the P4 circuit can be used in feedback with the RF heating system plasma coupling resistance. During this phase, if the outer gap becomes too big or too small, SC limits the plasma excursion tracking the limit.

4.11. WALLS INITIATED TERMINATIONS
Walls communicates to SC the need to terminate the pulse by producing a SOFT STOP request input to PTN. To protect a weak divertor area from overheating, a new protection has recently been added. For this reason a different connection to PTN has been installed on WALLS, and a more appropriate “Termination Window” will be introduced in SC: instead of keeping the shape constant, the strike point position will be promptly moved to a better power loading area.

4.12. VERTICAL STABILIZATION CONTROL MANAGEMENT
VS has a much simpler controller logic. It can operate into two main control modes depending on the presence of measurable plasma current: FRFA current control or plasma speed control.

During plasma, the controller may also decide to switch to voltage control. This action may be triggered by different events: user programming, disturbances in the measurements, near saturation of the actuator current.

5. EXTREME SHAPE CONTROLLER
The new XSC controller differs from the SC design because it works by minimising the difference between the plasma boundary and a desired shape described as a set of co-ordinates. It is being implemented as a SC internal module, functionally interfaced to the controller as an additional waveform generator. To enable the new system the “Control Management” logic will activate the proportional current control for all the circuits used and select XSC outputs as references. This method allows the introduction of the new functionalities without major changes to SC structure and at the same time minimised the required commissioning time because the internal diagnostic and protection actions are untouched.

To describe a plasma shape, a big set of references is necessary. In order to avoid the need for an equal number of waveforms, XSC will be programmed directly using the “Scenario” concept. For
each “Time Window” the controller needs just the set of co-ordinates describing the desired shape and the allowed time to reach it. In addition it will have to be provided with the set of control matrices adequate with the specific plasma configuration.

While SC operates in the full space of the actuators current, XSC minimises currents by operating in the subspace of the “principal values”. This causes a problem in the transition between the two controllers, since the existing plant current might not belong to the XSC subspace. This problem will be solved by preloading the XSC integrators with the plant currents and introducing a filter that will cause the current component outside the subspace to decay at a fast rate.

If any limit is exceeded in any of the shaping errors or in any of the currents, the chosen strategy will be to immediately branch to a SOFT STOP termination strategy. It is also planned, in a future version, to let XSC deal with current saturations by recalculating its control matrices. At the moment this has been postponed, both because of the complexity it will introduce in the “Control Management” and because the heavy computational needs.

**DISCUSSION.**

PPCC “Control Management” follows a very complex set of rules derived from the operational experience of the machine, and allows the execution of most, if not all, of the user desires.

The difficult management of its implementation is its major shortcoming. Every new addition to the controller implies modifications to all the components of the software, which forces a major recommissioning exercise.

In addition several problems have been manifesting themselves over the years indicating defects in the logic: the state machine oscillating between two states, “Control Management” choosing a set of controls doing a termination incompatible with the machine status. In addition, too many exceptions are handled by terminating the discharge even if a different solution is available, as in the XSC controller case.

In fact it is conceptually possible to design a Control Management system capable of taking unprecedented actions as a result of unexpected events. The control selection would be based both on the base of the contingent plant constraint and on the user desires.

This system would be even more interesting, if in addition it was possible add new control modes in modular fashion. Any new control scheme would consist on a data set describing the control variable, the actuator and the limitations associated with it.

Its major problems are how to guarantee that it would always take a safe control decision and how to verify that it would not manifest an unstable behavior.

Nevertheless, even taking in account these difficulties and the complex design exercise, the target is still attractive, especially considering the difficulties encountered in working on the old logic.

**ACKNOWLEDGEMENT**

This work was performed under the European Fusion Development Agreement and partly funded by EURATOM and the UK Department of Trade and Industry
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