First Operational Experience with the new Plasma Position and Current Control System of JET

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1. Abstract

The Pumped Divertor phase of JET involves the use of plasma configurations with complex control requirements. Therefore a new Plasma Position and Current Control system (PPCC) has been developed. It consists of two separate subsystems: Vertical Stabilisation (VS) and plasma Shape and Current Control (SC). SC performs a real time calculation of the plasma boundary using the Xloc algorithm [1]. It uses a full multivariable decoupling control algorithm which is applied to a combination of plasma wall-gaps and currents directly controlled [2]. SC and VS were brought into operation during the past months. The paper describes the operation of the system and reports on the performances achieved during the 1994 campaign.

2. Hardware Construction

Both SC and VS are VME digital systems using two floating point Digital Signal Processors (DSP) TMS320C40 running at 40MHz.

The Poloidal Field (PF) circuit currents and other few measurements are digitised by SC. The plasma-wall gaps and the X-point position are measured in real time using the Xloc algorithm [1] running on 91 magnetic signals sent through a fast optical link running at 16Mbyte/s (Figure 1).

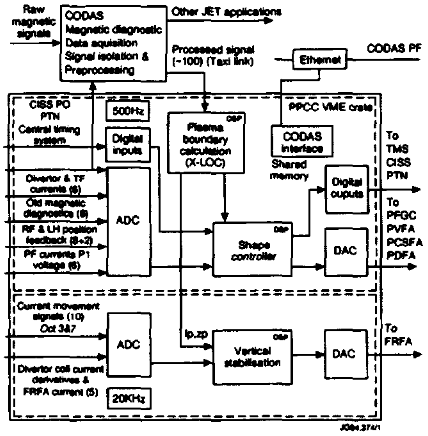

Figure 1. Hardware block diagram

VS is based on the measurement of the plasma current moment derivative. This is achieved by summing thirty-two magnetic signals in a passive summation stage and grouped to provide ten inputs to the ADC. Signals from opposite toroidal locations in the machine are used to minimise the influence of plasma n = 1 modes on the measurement. In addition the divertor coil current derivatives are digitised because they are included in the measurement path and their contribution has to be subtracted to obtain the plasma vertical current moment alone. The analogue to digital conversion is carried out on standard ADCs on the VME bus. This produces a delay in the order of 20μs from when the signals are digitised to the moment they are available for processing in the DSPs. VS is implemented on two DSPs with a 20kHz sampling time.

Both systems are interfaced with the Control and Data Acquisition System (CODAS) of JET through an Ethernet link running on a dedicated Motorola 68040 processor. This processor is used only for off line activities.

3. Plasma Shape and Current Control

The block diagram of the SC system is shown in Figure 2. It decouples nine loops simultaneously either in current control, or controlling the plasma shape through a plasma-wall gap control. The control algorithm and the model of the PF circuit and the plasma used to derive it are described in [2]. It is worth noting that the control matrix varies during the pulse and is recalculated in real time according to preprogrammed changes in the control mode or due to circuits currents that reach saturation in the attempt of fulfilling a gap request.

In case of current saturation the controller abandons the control of the gap which is more closely related to that current and resumes the gap control only when the demand waveform asks it to go back in the linear regime. The SC drives eight thyristor bridges and one flywheel generator used for the plasma current control [3].

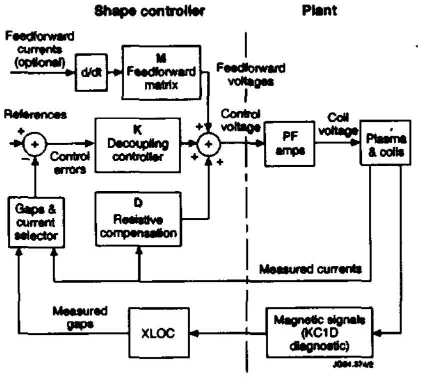

Figure 2. SC block diagram

Figure 3 shows the plasma boundary as reconstructed by the shape controller during pulse 30693 at the times 14.5s and 17.5s. This is a 2MA X-point plasma with an Ohmic phase (14.5s βp = 0.16) and an H-mode phase (17.5s βp = 0.65). The figure clearly shows that the location of the control points is not affected by the change in βp.

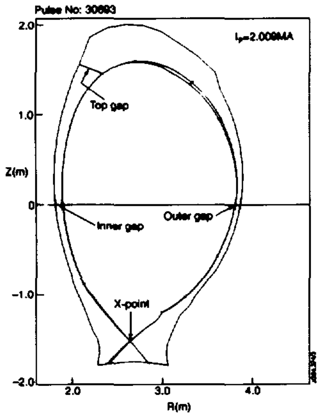

Figure 3. Plasma boundary from SC

Figure 4 shows a typical pulse during the Gap control phase.

At 14.5 seconds into the discharge the Gap control is switched on and the desired X-point configuration is formed. A step of 4cm is applied to the X-point vertical position to verify the effectiveness of the decoupling action. The plasma centroid vertical position (not controlled) is shown together with the response to the step of the Top Gap which is the most closely coupled quantity with the X-point height.

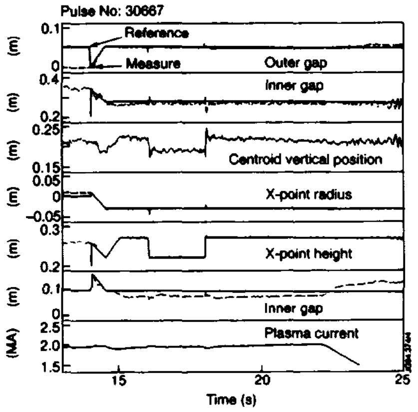

Figure 4. Typical Gap control discharge

Figure 5 shows a pulse with the X-point sweeping activated. The sweeping is performed applying to the X-point radius a 4Hz triangular demand waveform.

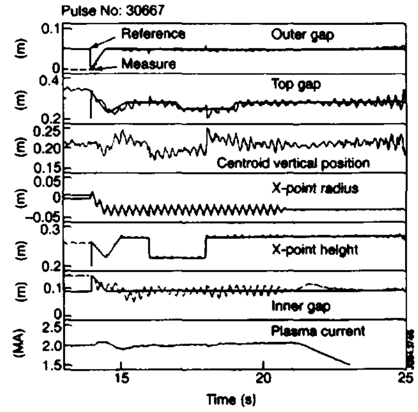

Figure 5. Sweeping of X-point in Gap Control

During the sweeping steps were applied both in the Top Gap and in the X-point Height demands to check that no degradation of the time responses or the decoupling take place.

The Inner Gap is coupled to the sweeping and shows a deviation from its reference by ±1cm. This is due to the choice of the time response of 100ms on this gap, selected in order to avoid huge voltage swings on the power supplies.

An integral term was added on the Inner Gap control to correct the static error of 2cm visible in Figure 4. The transition phase from current control to gap control at 14.5s during the pulse is visible in both Figures 4 and 5. It should be noted that, in order to avoid voltage saturation, the demand waveforms are matched to the measured gaps at the transition time and then are linearly interpolated to reach their pre-programmed value.

It is important to point out that the gap control cannot be applied throughout the pulse. The plasma boundary reconstruction codes do not give reliable results for plasma currents below 100kA and therefore cannot be used during breakdown. However the plasma radial position control is very critical during the breakdown phase which is carried out using the flux extrapolation method historically used at JET [3].

SC carries out internal checks which demand a premature pulse termination in case of faults. Watchdogs are applied on the control errors. If the control error exceeds consistently a threshold for too much time the pulse is terminated. Checks on data consistency from the ADCs and maximum delays of transmission on the optical links are applied.

SC is interfaced to the Plasma Protection System (PTN) of JET to which it sends a termination message whenever it decides to initiate a controlled shutdown. From PTN it can receive two requests. A *Slow* and a *Fast* termination can be requested depending on the level of the fault detected.

Termination scenarios are implemented using waveforms which are relative to the termination time and are rescaled with the actual values of the gaps or the currents which are controlled.

4. ICRH Coupling Resistance Feedback

Included in the decoupling scheme is the control of the plasma ICRH antenna coupling resistance. This control mode is preferred to the Outer Gap control when radio frequency heating is applied.

The Outer Gap control is replaced by the translation of the ICRH coupling resistance error into a gap error by means of an appropriate gain and can therefore compensate for changes in the RF coupling at critical times like during an L to H mode transition.

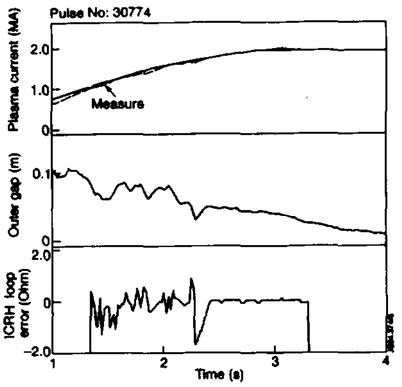

Figure 6. ICRH Coupling Resistance Control

This technique allows a very easy integration of this mode of control in the general decoupling scheme without any further modification.

It is important to note that this feedback is used in a limited range defined by a maximum and minimum distance from the outside wall. The outer gap control is resumed in case of transient tripping of the RF generators.

Figure 6 shows an example of this feedback. The different behaviour during the plasma rise and the flattop phase should be noted.

5. Vertical Stabilisation

The new system is designed to stabilise plasma growth rates of up to $1000s^{-1}$, however the growth rates measured so far do not exceed $160s^{-1}$.

The control algorithm is based on a proportional controller for the current moment derivative feedback and a slower proportional-integral control of the amplifier current.

The proportional gain is time dependent. The value of the gain is decreased by typically 60% after the first second during the plasma pulse. This technique allowed a substantial reduction of the limit cycle present due to the non linear amplifier characteristic. The plasma breakdown in fact is not successful unless the gain of the fast loop is in a very narrow window (±20% of the nominal value).

Figure 7 block diagram shows the control scheme used. The fast velocity loop is based on a proportional control of the plasma vertical speed. At present the measurement does not yield the vertical speed of the centroid but is based on the derivative of the radial flux. This is due to the high noise

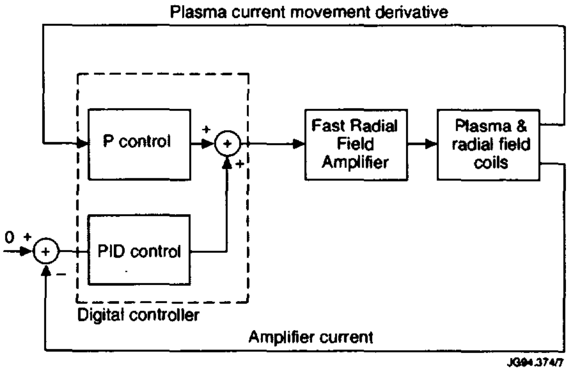

Figure 7. VS block diagram

generated by the divertor power supplies at the 600Hz (and higher harmonics) being amplified by the thin coil casing.

A digital filtering technique for restoring the full current moment measurement has been developed. However these filters are not compatible with the 20kHz sampling rate. The introduction of a third DSP will allow the use of the filters. Operation of the machine was permitted by using of the Mirnov coils located on the top of the vessel only by doubling their contribution in the control signal.

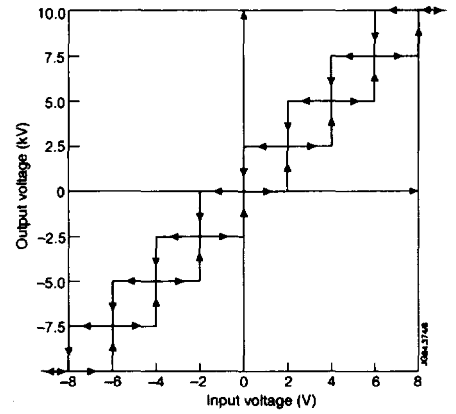

Figure 8. FRFA I/O Characteristic

The amplifier driven for the plasma stabilisation (Fast Radial Field Amplifier) is a ±10kV/±2.5kA GTO DC/DC converter with an input output characteristic given in Figure 8. FRFA shows a maximum input to output delay of 200μs [4].

Figure 9 shows a pulse during which the feedback was suppressed for 20ms. The plasma (1MA) drifted upwards by 10cm and then was recaptured by the stabilisation. A current swing of about 1.5kA and a voltage up to 5kV was needed by the control system.

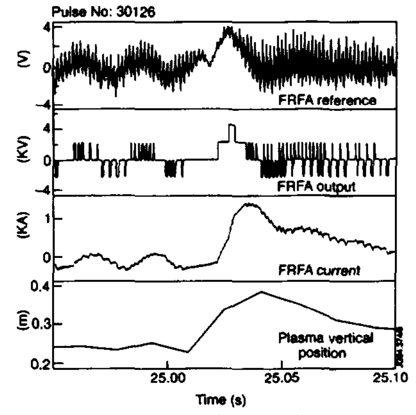

Figure 9. Temporary Switch Off of VS

6. Conclusions

The new PPCC system has been brought in operation and has performed up to the design specifications being capable of handling both the traditional current control of coils and the new concept of gap control using a decoupling controller. The application of the gap control allows a precise positioning of the plasma separatrix at chosen positions. This demonstrates the feasibility of such control systems for ITER.

The Vertical Stabilisation system is also implemented as a digital system. This choice has simplified operation in the view of the unexpected high noise input from the divertor amplifiers. The machine operation is not affected by the non-linear behaviour of the power amplifier.

References

[1] D. O'Brien et al., Local Expansion Method for Fast Plasma Boundary Identification in JET, Nuclear Fusion, Vol. 33, No. 3, 1993

[2] M. Garribba et al., The New Control Scheme for the JET Plasma Position and Current Control Scheme, XV SOFE, Hyannis, Massachusetts, 11-15 October 1993.

[3] E. Bertolini et. al., The JET Magnet Power Supplies and Plasma Control Systems, Fusion Technology, January 1987, Vol 11, No 1

[4] T. Bonicelli et al., Analysis and Specification of the Performances of the New JET Amplifier for the Vertical Stabilisation, XV SOFE, 1993