CENTRALISED COORDINATED CONTROL TO PROTECT THE JET ITER-LIKE WALL*

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Abstract

The JET ITER-like wall project (ILW) replaces the first wall carbon fibre composite tiles with beryllium and tungsten tiles which should have improved fuel retention characteristics but are less thermally robust. An enhanced protection system using new control and diagnostic systems has been designed which can modify the pre-planned experimental control to protect the new wall. Key design challenges were to extend the Level-1 supervisory control system to allow configurable responses to thermal problems to be defined without introducing excessive complexity, and to integrate the new functionality with existing control and protection systems efficiently and reliably. Alarms are generated by the vessel thermal map (VTM) system if infra-red camera measurements of tile temperatures are too high and by the plasma wall load system (WALLS) if component power limits are exceeded. The design introduces two new concepts: local protection, which inhibits individual heating components but allows the discharge to proceed, and stop responses, which allow highly configurable early termination of the pulse in the safest way for the plasma conditions and type of alarm. These are implemented via the new real-time protection system (RTPS), a centralised controller which responds to the VTM and WALLS alarms by providing override commands to the plasma shape, current, density and heating controllers. This paper describes the design and implementation of the RTPS system which is built with the Multithreaded Application Real-Time executor (MARTe) and will present results from initial operations.

INTRODUCTION

The main experimental control of the JET[1] machine is provided by five real-time control systems, or actuators, which govern : plasma position and current control (PPCC [2]), fuelling, via the plasma density local manager (PDLM) and additional heating, via the local manager systems for neutral-beam heating (NBLM), radio frequency heating (RFLM) and lower-hybrid current drive (LHLM).

JET machine protection has been provided historically by three systems. The Central Interlock and Safety System (CISS) provides basic hardwired plant protection. Higher level protection with limited configurability is provided by the Pulse Termination Network (PTN[3]). This is triggered if key systems fail, or if protection signals move outside of predefined limits. The PTN output is a latched stop signal to each of the control systems, which execute a fixed shutdown sequence in response. Finally, additional heating systems require enable signals from the Plant Enable Window System (PEWS) which are conditioned by real-time protection signal validation algorithms.

The design of these systems is characterised by a high degree of configurability in respect of detecting machine fault conditions, but extremely limited control over stop strategies which are constrained to be fixed throughout the duration of an experiment. The stops are designed to minimise the global damage to the machine but are unable to take account of any localised heat flux limits on plasma facing components (PFCs).

The ILW project[4] has rebuilt the plasma facing surfaces of the machine with all-metal tiles which should have improved fuel retention properties. However, their temperature needs to be carefully controlled to avoid damage. The Protection of the ITER-like Wall (PIW) project was launched in late 2009 to upgrade the protection systems to address this need.

CONCEPTUAL DESIGN

The PIW system design aimed to augment the diagnostic monitoring of wall component temperatures and to provide a new protection system which could intervene to keep these temperatures within limits. The new system should act early, to prevent PTN or CISS from following a global stop strategy that might cause excessive energy loads on the walls. However, the basic machine protection provided by PTN and CISS had to be retained. The structural archi-

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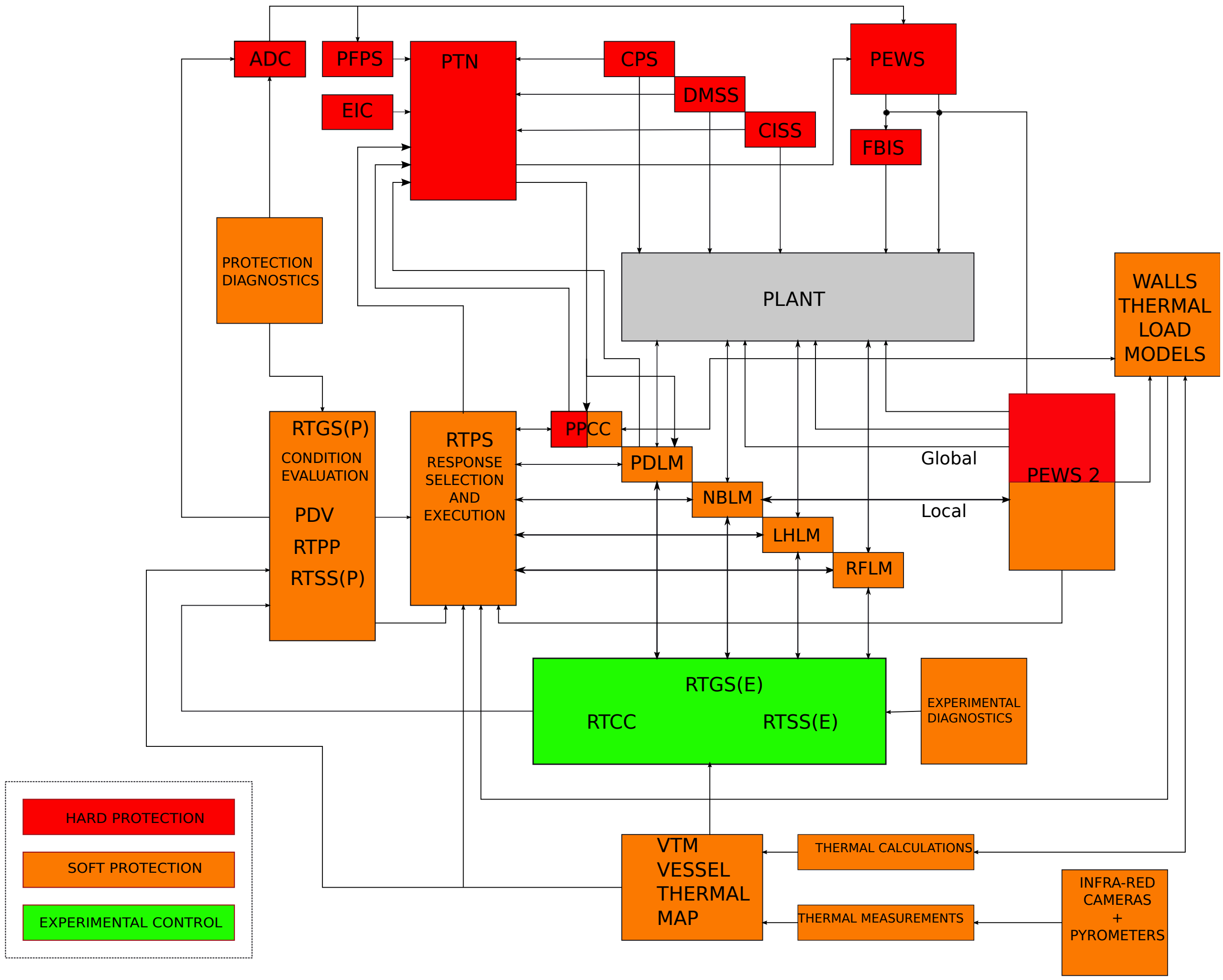

Figure 1: JET protection of the ITER-like wall system architecture. The experimental real-time control links to the density and heating local managers (PDLM, NBLM, RFLM and LHLM) is expanded to allow protection overrides from the new RTPS system which receives alarms from VTM, WALLS and also from the real-time plasma protection (RTPP) and real-time central controller (RTCC) systems. The original higher level protection systems of CISS, PTN and PEWS are retained.

tecture was clear and is outlined in figure 1. The density and additional heating real-time controllers already had interfaces which allowed for real-time modification of plant control. PPCC would be similarly updated. A new system, called the Real-Time Protection Sequencer (RTPS) would provide protection override commands to adapt the experimental control as required to keep temperatures under control, or to achieve a safe termination when necessary.

Temperature monitoring is provided based on real-time measurements from new infra-red camera and pyrometer diagnostics[5] which are analysed by a new system called the Vessel Thermal Map (VTM[6]) in order to generate alarms where limits are reached. The plasma wall load system (WALLS) may also generate alarms if modelled predictions of temperature or energy load become excessive. WALLS required to be updated to take account of the new component geometry and materials.

The design distinguishes between *local* and *global* events. Local alarms are limited in location or time, or may be set at lower thresholds and trigger a protection response which allows continued operation with dynamically controlled limits on further injection of heating with fine granularity. If this fails to bring checks back into tolerance, global alarms are raised which result in control overrides which truncate the experiment and land the plasma safely.

The significant design challenge was to make the new system practical to configure. The best control to provide a soft landing in the event of a fault condition depends on the state of the plasma. This is a function of the experiment design, the phase within a particular discharge, and the type of fault detected. Potentially, this represents a large number of possible paths. This was addressed with a fault and response classification scheme which confines the complexity to a manageable level, and by providing a way to define response actions generically, such that a library of reusable stop responses may be applied to many similar experimental scenarios.

RTPS IMPLEMENTATION

Local Protection

Local alarms and local protection are defined in relation to the additional heating systems. Each heating system comprises several individual units, and under certain conditions, particular heating units may directly heat a specific plasma facing component. For example, the neutral-beam heating system has 16 positive ion neutral injectors (PINIs). Depending on the plasma density, a proportion of beam particles pass through the plasma and strike the surface of the machine, a condition known as shine-through. Each PINI has a shine-through footprint on a specific set of components. Therefore, when a local hotspot alarm occurs for such an element, the relevant PINI should be turned off to prevent further overheating. This should not preclude the neutral-beam system as a whole from continuing to deliver the total requested power to the plasma, as other PINIs can be turned on to compensate. Similar relationships and control rules can be determined for the RF antennae, and the LH klystrons.

Global Protection

If local protection is not adequate to keep the machine safe the experiment must be curtailed. To manage the potential complexity of the design, the key observation is that although there are many hundreds of individual fault conditions, most require similar reactions, and we introduce the term *stop trigger* to classify the types of threat.

Seven stop triggers have been identified. Three represent thermal problems. These are hot spots in the main chamber (inner and outer walls), in the divertor (the base region where particles are exhausted from the machine) or which occur in both regions. Two are associated with magneto-hydrodynamic (MHD) instabilities. Two more allow for generic conditions requiring either a slow or fast termination of the pulse.

Each stop trigger is associated with a corresponding *stop response*, which defines the required override control strategy to mitigate the effects of the related alarm. There are three kinds of stop response. If a fault occurs early in the discharge before main heating phase, it can be sufficient to trigger the PTN system. During the heating phase, the real-time controllers require overrides which are fully programmable, termed *RTPS* stops. In some cases, the best possible way to end a pulse is to execute the control waveforms that would have come into force had the experiment reached a natural conclusion. This is termed a *jump-to-termination* (JTT) stop. Table 1 illustrates the matrix that links stop triggers to stop responses, as a function of experimental phase. The full control matrix is a key part of the protection system configuration interface.

The system also takes account of the possibility that one class of fault (and corresponding stop response) might be followed soon after by another. For example, a magnetic instability followed by a hotspot, or vice versa. This is addressed, by allowing for two levels of stop response, *primary*, and *secondary*. Not all possible combinations of control are allowable, since in some cases, once a primary stop response has begun, the best outcome is achieved by allowing it to run to completion.

Table 1: The primary stops table configures the mapping between stop triggers and stop responses as a function of experimental phase. A subset of the possible stop triggers are shown, including mode lock (MHD), main chamber hotspot (MCHS) and divertor hotspot (DHS).

Phase	Slow	MHD	MCHS	DHS
Breakdown	PTN	None	None	PTN
Ip Rise	|	|	|	|
Limiter	PTN	|	|	|
X-point	PTN	|	|	|
Heating 1	RTPS	|	RTPS	PTN
Heating 2	RTPS	|	RTPS	JTT
Plasma Termination	PTN	|	PTN	PTN

Stop Responses

A particular stop response is defined by a set of override references for each of the five actuator systems, each of which has one or more control signals. For a given control signal, the override is specified as a waveform which is parameterised as a set of steps, where for each step, the reference value to achieve and the time in which to make the transition are defined.

There are many ways of specifying these parameters. Reference values can be defined in absolute terms, or relative to the control value at the beginning of the stop, or in proportion to any other control signal. e.g. If 10MW of neutral-beam total power were being delivered and a stop response was initiated, the new reference could be set to 6MW (absolute mode), 60% (relative mode) or proportional to plasma current, in which case the reference would be calculated dynamically. Step durations can be defined as an absolute time, as a ramp rate (where the duration will be computed from the difference between the reference values) or to be synchronised to another control signal.

Software and Hardware

To achieve the required degree of configurability and reliability, the software is constructed using a component based approach, based on the Multi-threaded Application Real-Time executor (MARTe[7]). A MARTe application is organised as a chain of processing objects instantiated from Generic Application Modules (GAMs) interconnected by a software bus called the dynamic data buffer (DDB). A supervisory level set of tasks implements a state machine distinguishing background operation, preparation for an experiment (pulse), pulse on, and post-pulse actions (including data collection). The set of GAMs and their attributes are data driven, which allows a powerful separation of source code and binary modules from experimental parameters. This allows the application to be comprehensively configured from the JET Level-1 system.

The standard MARTe library provided the key infrastructure, driver modules for the peripheral electronics and data collection modules. The RTPS software was completed by writing custom MARTe modules. These include the *Stop Selector* GAM which implements the state machine and alarm processing logic, and the *Stop Manager* GAM which defines and executes the stop responses. The application is executed on a PowerPC processor hosted in a VME rack, with digital IO modules providing links to the PTN system.

MARTe has been used with several operating systems and was ported to VxWorks 6.8 to develop the online real-time version of the RTPS application. A major benefit of using MARTe was the possibility of recompiling the application to run on Linux to allow development and offline testing with access to powerful debugging and checking software tools.

Communications with the alarm generator and control actuator systems is via the JET real-time data network (RTDN[8]) which provides low latency, high reliability exchange of fixed size datagrams over permanent virtual circuits. The processing rate is 500Hz, with inputs from the VTM at 100Hz.

Ensuring Reliability

Alarm systems such as the VTM define blind stop alarms to handle loss of critical signals during a shot. If RTPS detects communication or status faults with the alarm source systems, or real-time controllers, it can trigger the PTN system. A hardware watchdog signal to PTN ensures that RTPS is operational itself. Detection of PIW system failures needs to be reliable and appropriate. The Level-1 user interface provides intelligent conditioning of these checks so that features or subsystems which are not in use cannot cause problems.

The PIW system overall relies on distributed interaction between simpler, smaller systems. This reduces the cost of developing, commissioning and testing of each subsystem, but demands correct communications. To ensure this, all messages between systems are defined in a central database. Each message is allocated a unique identification number which is used to allow run-time verification that all systems on a virtual circuit are coherent and operating correctly.

OPERATIONS

JET recommenced operations with the ILW on 24 August 2011 and initial plasma performance has exceeded expectations. Unusually following a JET shutdown, the experimental and restart commissioning activities are interleaved. The restart programme has included sessions dedicated to the commissioning of the PIW systems.

The basic protection logic has been tested thoroughly, and the response of the PPCC and PDLM systems for a number of stop response types has been verified. End to end testing of alarm generation from camera systems through to RTPS response has been demonstrated. This was done initially without heating the wall, by using the cameras without infra-red filters. Calibration parameters and the visible plasma light intensity levels were tuned to simulate high temperature signals. Similar tests will be repeated using real temperature signals when the infra-red filters have been fitted, and the additional heating systems commissioned. RTPS has been used successfully to override a plasma discharge by requesting PPCC and PDLM to execute the jump-to-termination response in JET pulse number 80500.

CONCLUSIONS

The impact of plasma fault conditions which risk damage to the JET ITER-like wall will be mitigated by the action of a new, highly flexible protection system. This allows safer and more efficient exploitation of the new machine by expanding the operational space available, and by gently landing the plasma when necessary, without making the task of session preparation excessively onerous.

ACKNOWLEDGEMENTS

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