FAILURE MODE AND RECOVERY STRATEGIES FOR THE OPERATION OF THE TORE SUPRA TOKAMAK*

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Abstract

Plasma experiments in tokamaks are more and more demanding in terms of performance and discharge duration. In parallel the machine protection must be ensured. Handling any deviation from the reference plasma scenario and any failure of the tokamak subsystems without terminating the discharge is becoming a crucial point. On the Tore Supra tokamak, off-normal event detection procedures and mitigation strategies have been embedded in the real time Plasma Control System (PCS) and are now in frequent or routine operation. The present work provides a review of the existing Tore Supra exception handling system.

INTRODUCTION

The Tore Supra tokamak is the largest superconducting magnetic fusion facility in operation. It is devoted to long-duration high-performance discharge research. The operation of the tokamak requires the orchestration of more than 50 systems including several sub-plants (cryogenic plant, magnetic coils, water cooling loops, multi megawatt heating systems, etc.), as well as plasma diagnostics. To ensure both plasma performance and safe operation, it is crucial to optimise the way each plasma discharge is driven. This point is even more crucial considering that the duration of the plasma discharges will increase over the coming years: (Tore Supra present status > 360s, ITER > 1000s and continuous operation for a reactor). Setting up a system allowing the management of abnormal situations to recover the plasma performance in safe conditions instead of terminating the plasma discharge is a key issue overtaking the scope of the present fusion devices. Since a tokamak is a complex system, a default manifests itself in various ways and has various consequences:

- Actuator may degrade or switch off for self protection temporarily and/or partially.
- Diagnostics comprise a large set of channels or sensors amongst which only a small number can be unavailable. If needed, the plasma domain of operation could be subsequently reduced in accordance with the loss of accuracy of the diagnostic.
- PCS or related networks may crash, or real time (RT) evaluation and feedback processes may go wrong.
- Being a non linear media, the plasma can experience unexpected evolution or instability growth leading to a degraded performance plasma regime or to the abrupt termination of the plasma discharge in a disruption.

PCS hardware failure or uncontrolled plasma off-normal events may cause loss of plasma control and consequently seriously damage the in-vessel components. An automatic RT detection of such events is implemented on Tore Supra allowing operating time to be saved. This paper gives an overview of the failure mode detection and recovery strategy implementation. Section 1 is devoted to an overview of the PCS. In Section 2 the hardware and the network default detection system are discussed. Section 3 describes off-normal plasma events and sub-plant unavailability. Section 4 addresses the improvement of the failure and recovery system.

OVERVIEW OF TORE SUPRA PCS

The Tore Supra real time PCS is completely integrated into the data acquisition system [1] (Fig. 1). Since the first experiments in 1988, the acquisition system has evolved. At present, it is made of about 50 units: the original INTEL multibus units; VME bus units using PowerPC processors monitored by a RT operating system (OS) LynxOS™ and PCs using real time Linux or windows 2000 as OS. Two types of acquisition unit can be distinguished: real time diagnostics providing plasma measurements to the plasma controllers and a set of controller units which act on the corresponding subsystems. Five VME units are devoted to the plasma control. They are hard-wired to their corresponding actuators which consist of an external set of magnetic coils (poloidal system) to control the plasma position and shape; piezoelectric gas valves and pellet injector to control the fuelling and 3 multi-megawatt radio-frequency heating systems.

To ensure the plasma control and the data acquisition, 3 optical networks [1] are used for various purposes. During the pulse most of the data acquisition units stream the data through a 7 MB/s fast Ethernet network to the central archive computer. A shared memory ring (Scramnet® from SYSTRAN Corporation) working at 150MHz [1] is used to allow the sharing of information and processed data between diagnostics and controllers in real time. Each processor on the network has access to its own local copy of shared memory that is updated over a high-speed, serial-ring network. At present 20 nodes are active. The third optical network has 2 roles: it assures the synchroni-

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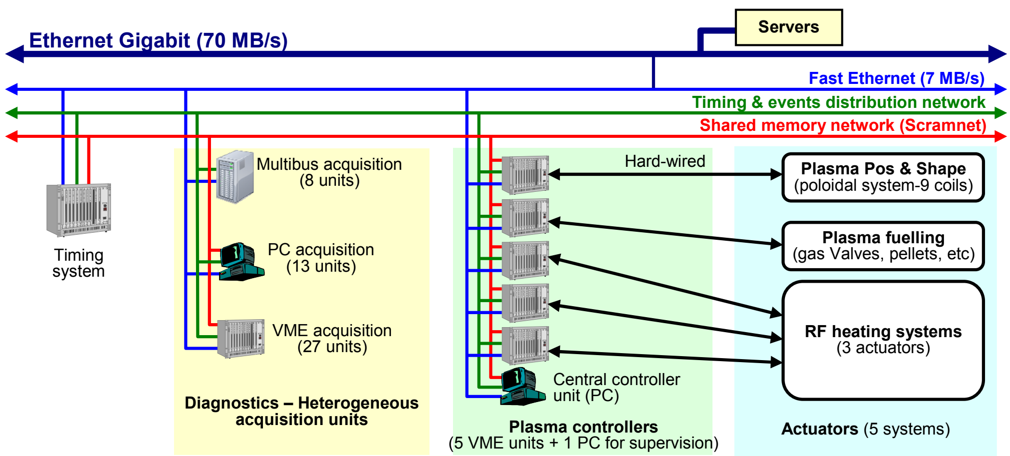

Figure 1: Schematic view of the Tore Supra Plasma Control System and actuators.

sation of all subsystems by providing a single clock at 1 MHz given by the centralised timing system and it is responsible for the plasma event distribution (a diagnostic can detect a plasma event and trigger other diagnostics through the timing system).

Additionally, a central controller unit explicitly developed to perform advanced feedback control has been recently implemented in a PC running Windows 2000 as OS. This PC is not directly connected to an actuator but acts through one of the 5 basic controllers by sending requests through the shared memory network.

HARDWARE FAILURE HANDLING

The real time detection of hardware failure is performed at both sub-plant system and inter-plant link levels (Table 1). It is done at any step of the data flow from the diagnostics to the actuators via the controller units. Most of the time a hardware failure results in a plasma soft stop because no hardware redundancy is implemented.

Crucial diagnostics includes an internal basic validation process to provide certified RT information to the controllers. As an example, the monitoring of plasma impurity is performed by a VUV spectrometer. The measured signal is the integrated emissivity along one sight line. If the signal amplitude is too low (below a predefined threshold), the RT data transmitted to the controller is set to 0 (invalid value). While this diagnostic is used for the machine protection during the RF heating phase of the plasma, invalid measurements make the controller reducing the injected RF power and triggering a plasma soft stop. Another example is related to the measurement of the plasma density by an infrared interferometer. If interferometric data become unavailable during the discharge, the fuelling controller is able to switch automatically to a complementary diagnostic, the Bremsstrahlung emission and the discharge is pursued normally.

The actuators include their own failure detection processes, a simple operational status is provided to their respective controllers. Thus any failure can be detected but, up to now, no RT mitigation strategy is applied because of the complexity of the actuators themselves (high electrical power and RF wave handling).

Failures of network processes used to interconnect the subsystems are also monitored in RT. For that purpose, a time stamp is associated to any data sent through the Scramnet network. While the typical loop cycle of diagnostics and controllers doesn't exceed tens of milliseconds, any discrepancy between the time stamp of the data read through the Scramnet and the actual time of the acquisition unit results in a failure of communication and a plasma soft stop is triggered. The timing system is programmed in such a way that it automatically generates an event on the timing network if no event has been sent for a predefined duration. A failure is then identified as an absence of event for too long time and a plasma soft stop is triggered.

The VME RT diagnostics and controllers use 2 Power PC CPUs. The 1st CPU runs several tasks in parallel such as the management of the plasma events through the timing network. The 2nd CPU is devoted to RT data processing and management of actuators. The intercommunication between the CPUs is fulfilled by the VME bus through a shared memory. Any internal failure of the acquisition units is monitored by checking that the 2nd CPU receives the plasma events through the 1st CPU (at least one event every predefined δt seconds).

Table 1: Summary of Hardware Failure, Detection Procedure and RT Mitigation Procedure

Source		Usage - Measurement	Failure detection	Action
Diagnostics	VUV spectrometer	Plasma impurity content	Signal < Threshold	Additional power reduction. Plasma soft stop
	Infrared cameras	Temperature of plasma facing components	Shutter closed	Additional power reduction
	Magnetics	Plasma position and shape measurement	Sensor failure (measurement discrepancy)	Plasma soft stop
	Interferometry	Plasma density	Unavailability or fringe jumps	Switch to complementary diagnostic (Bremsstrahlung)
Actuators	Poloidal	Plasma pos & shape control	Return a status to the controller	Plasma soft stop
	Gaz injection	Plasma fuelling	Not implemented	NA
	Heatings	Plasma heating	Internal failure detection	NA
Controller internal failure (comm. between CPUs)		Plasma control	No event received since predefined durat.	Plasma soft stop
Scramnet network		Data exchange	Comparison data time stamp and current time	Plasma soft stop
Timing and event distribution network		Synchronisation and event distribution	No event received since predefined duration	Plasma soft stop

PLASMA OFF-NORMAL EVENTS HANDLING

The plasma off-normal events can be divided into 2 categories: those related to the machine protection and those related to a degradation of the plasma performance. Their handling requires the analysis of a large amount of information to obtain a global view of the plasma state. So, a central control unit is used to collect the data, to identify any off-normal event and to decide which mitigation strategy to apply.

The Tore Supra machine protection has been improved over the years. Several machine protection means and mitigation procedure are already routinely used [2, 3]. We discuss here an example related to the protection of the in-vessel components against overheating. This issue is crucial to avoid melting and/or water leak causing a tokamak shutdown for several weeks. A dedicated controller has been set-up for that purpose on Tore Supra [4]. It uses the infrared thermography diagnostic and temperature thresholds coupled to each components technological limits. In this example, we consider the Tore Supra ion cyclotron resonance heating (ICRH) system which consists of 3 antennae. Once an overheating is detected, the injected power is reduced on the corresponding antenna [2] (Fig. 2). This mitigation procedure ensures the protection of the system but the requested injected power and subsequently the plasma performance are not met.

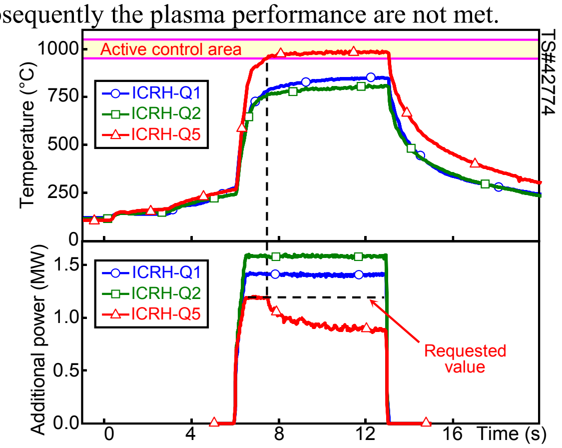

Figure 2: Injected power reduction due to the detection of an overheating on Q5 ICRH antenna.

In some case a degradation of the plasma performance is observed without any machine protection issues. Such degradation is usually related to magnetohydrodynamic (MHD) activity in the plasma. Recently an automatic detection and basic mitigation procedure have been tested as shown in Fig. 3. A strong MHD activity is detected at 25.5s and as a result the plasma performance is greatly reduced (central temperature drop). When such activity is detected, the control algorithm reduces the additional power injected by the Lower Hybrid Current Drive (LHCD) system to its minimum value (about 200kW) for 2 s in order to exit from the deleterious plasma state. This drastic change of the actuator allows the plasma to recover from the MHD regime, and start again from a neat situation where the power can be progressively increased again until the preset end of the heating at 30 s.

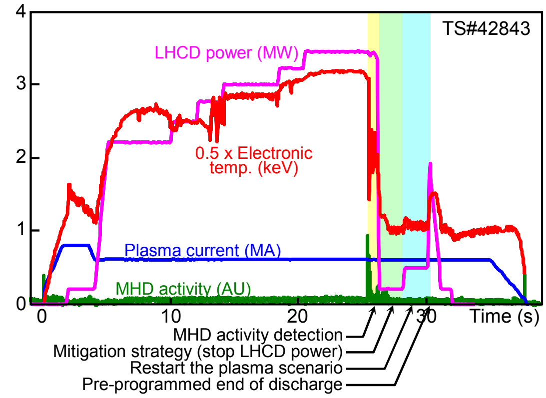

Figure 3: Example of mitigation procedure applied to a plasma performance degradation event.

FUTURE WORK

The improvement of failure detection and mitigation strategies is under development at Tore Supra. The following topics are under investigation:

- Enhancement of data validation procedures. Any information provided by a diagnostic or a controller must be internally validated before being shared with other sub-systems.
- Many inputs are necessary to identify a default and many causes of default exist with various severities needing a classification of events. The selection of the best mitigation strategy is not trivial; an expert system shall be developed to improve the reliability.
- The mitigation strategies have also to be improved. For example, considering a multi-antenna heating system (Fig. 2), the reduction of injected power due to the overheating of one antenna could be compensated by the others; this is not the case at present.

The algorithms used to detect failures, ensure machine protection and plasma performance are becoming more complex and need specific developments. The implementation of a tokamak flight simulator to help development and testing of new failure detection procedures and mitigation strategies has recently started at Tore Supra [5].

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