MACHINE PROTECTION AND ADVANCED PLASMA CONTROL IN TORE SUPRA TOKAMAK

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Abstract

A tokamak is a complex device combining many sub-systems. All of them must have a high reliability and robustness to operate together. Sub-systems include their own safety protections, but a more integrated level of protection is required to ensure the safety of the full device. Moreover, plasma operation with several megawatts of additional injected power requires a highly reliable advanced control system, as off-normal events may seriously damage the in-vessel components. Such an integrated control system, including protection algorithms, has been developed on Tore Supra. In the following the implementation of the Plasma Safety Control system is described as well as its real time network topology. The hierarchy of strategies applied, when more and more severe failure appears, is detailed. Finally few examples of active protections daily used in Tore Supra are given.

INTRODUCTION

The Tore Supra tokamak is a large superconducting magnetic fusion facility. It has been devoted to long-duration high-performance plasma discharge research. Such a device combines several sub-systems (cryogenic plant, toroidal and poloidal magnetic field system, cooling water loops, fuelling and vacuum pumping, heating and current drive…) which must operate together at their nominal level. Thus a high reliability and a robust control are requested [1].

By enhancing the performance, in particular with increased heat loads up to mean ITER heat load per unit surface, the margin to the technological sub-system limits is a crucial issue, requiring a fast response of the control system to react at any perturbation.

Uncontrolled plasma displacement, off-normal events, plasma instability growth which could seriously damage the in-vessel components must stay under control. The major risk is the overheating of components which could lead to the melting of the first wall components followed by a water leak and/or a severe damage of power launchers.

An integrated plasma control system, including safety and protection algorithms, is thus mandatory to operate the device. Since the beginning of Tore Supra operation in 1988, such a control system has been developed and continuously upgraded to meet the new requirements requested by plasma physic studies.

The first section describes the underlying ideas which have driven the development of the plasma safety control system (PSC). The next section is devoted to the implementation of the PSC within the real time network dedicated to plasma control. The last section provides few examples of active protections daily used in Tore Supra to operate long duration high power plasma discharges.

PLASMA SAFETY CONTROL SYSTEM

The PSC system is a part of the plasma control system dedicated to the control of the plasma discharge at its reference parameters [2]. It has been originally implemented in the Poloidal Field (PF) system controller as it firstly acts on PF system. Figure 1 displays the exchange of information between surveyed active sub-systems and the safety supervisor. Additional diagnostics provides also data to the supervisor. The supervisor is capable at any time to enable (or disable) additional heating, trigger a soft plasma shutdown when too degraded conditions are reached, or fire a fast plasma killer by massive gas injection (see last section for applications).

The aim of the supervisor is to develop alternative path when margins to sub-system limits become too small. The control can evolve towards more and more degraded levels, from the nominal one to the fast shutdown of the plasma.

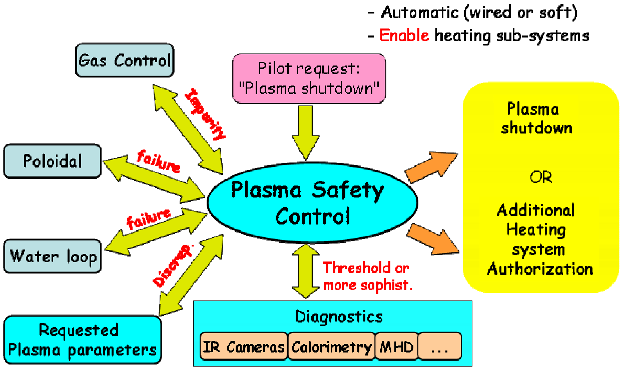

Figure 1: PSC topology: central controller, sub-systems under control and diagnostics providing information.

At first level the supervisor may try to re-equilibrate the loads within a sub-system over less solicited parts when one of the limits is close to be reached. An example is the global position and shape control which actuates the poloïdal coil currents: When a coil current is close to its limit, the demand is shared over adjacent coils.

The second level is a modification of the plasma parameters (position, gas fuelling, additional injected power…) in order to preserve the plasma discharge, but in a degraded mode. The supervisor analyzes at any time the capability to recover the nominal plasma scenario.

The third level, the soft plasma current shutdown, is initiated when irreversible plasma conditions are detected. No strategy to recover the nominal plasma exists or is known or is implemented. An example is the low level magnetohydrodynamic (MHD) activity (see last section).

Finally, when loads are uncontrolled, or when plasma parameters indicate that the probability the plasma will undergo a disruption (loss of confinement in few milliseconds) becomes too large, a fast plasma shutdown is initiated.

REAL TIME CONTROL NETWORK

The Tore Supra real time control (RTC) system is sketched in figure 2. Two groups of nodes can be distinguished: real time diagnostics and sensors which provide measurements to the plasma controller, and a set of controllers which act on corresponding sub-system. The real time environment needs the sharing of a lot of information between all these nodes. The information is exchanged through a shared memory ring (SCRAMNet® from SYSTRAN Corporation) working at 150MHz. Twenty nodes are actually active. Passive nodes record and furnish information to the integrated plasma control system. Active nodes (controllers) act on dedicated sub-systems parameters. External sub-system status is also included in the process to help to the decision. A central timing system provides the time stamp of measurements.

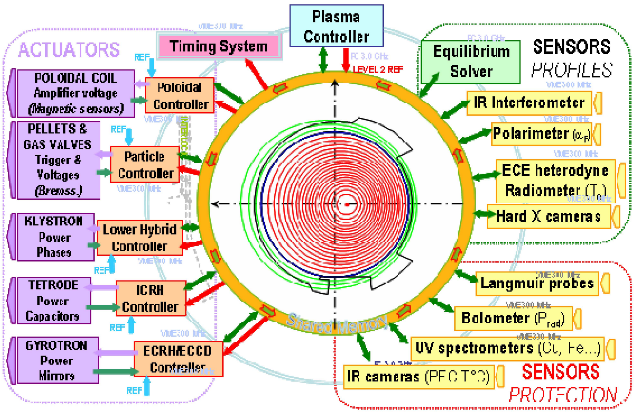

Figure 2: RTC network implemented on Tore Supra.

EXAMPLES AND APPLICATIONS

The detection of a rapid Cu impurity increase during an additional power phase indicates a arcing in front of the power launcher. To avoid a possible melting, the PSC transiently reduces the power reference value down to 25%. When the impurity level goes down below a given threshold, the power is increased again progressively. Figure 3 shows such a power reduction observed during a 6 minutes discharge [3]. A 3MW lower hybrid power P_{LH} was used to generate the 0.5MA plasma current. This one gigajoule of exhaust energy record discharge was performed with no primary flux consumption (zero loop voltage). At 260s Cu impurity is detected. The PSC reacts and the lower hybrid power is reduced (fig.4). After the event, the requested LH power to quickly recover the nominal plasma current was slightly higher than before.

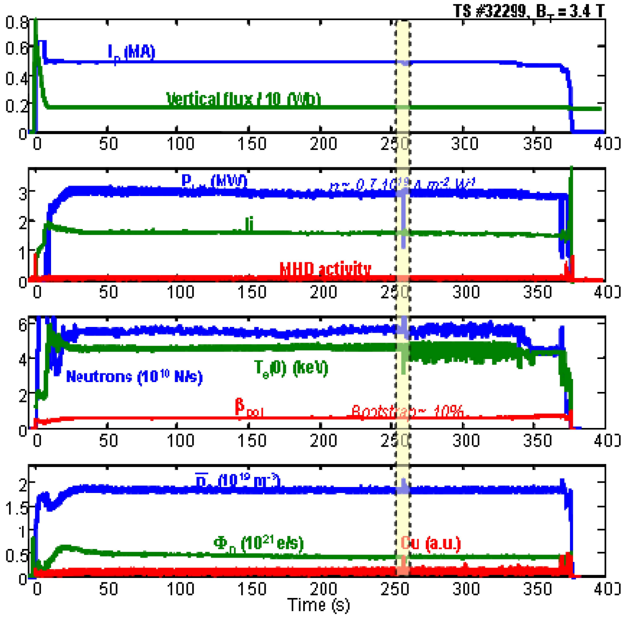

Figure 3: 1GJ discharge, 6mn duration, 3MW power.

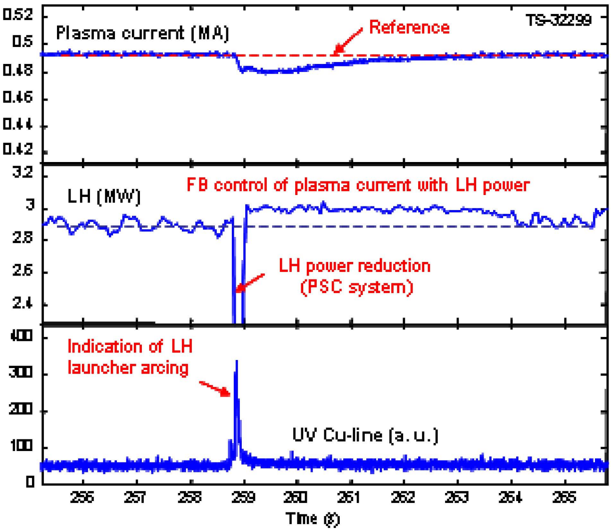

Figure 4: PSC reaction after an impurity event detection.

The nominal plasma parameters are thus recovered, but central electron temperature Te(0) fluctuations (fig.3) observed after the event indicate a slight change in the current profile. Nevertheless global performance is maintained (neutrons production).

An IR thermography system is now routinely used for the safety of plasma facing components, including heating antenna and launchers [4]. It consists of 12 IR cameras (so far 8 implemented) and seven actively cooled endoscopes. A real time survey has been implemented. The dedicated controller analyses the IR frames, applies mask to define regions of interest, computes the surface temperature, and makes the comparison to a set of technological limits. Depending on the specific zone considered, specific power from a given antenna/launcher, or the total power, are reduced to maintain the surface temperature within the technological limits.

This controller is also able to identify arcing in front of launcher. In that case the corresponding launcher power is transiently reduced down to 25%. Figure 5 shows such an event and the corresponding controller reaction.

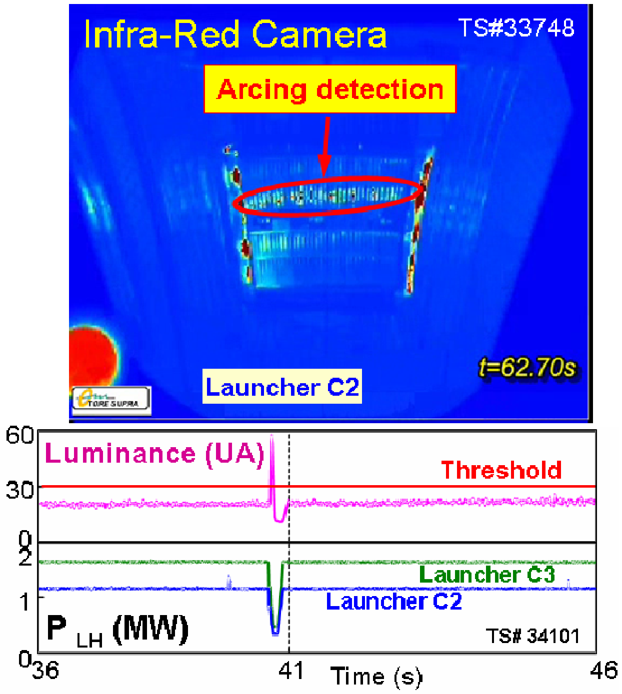

Figure 5: arcing detection using IR thermography.

When no recovery strategy has been defined, or when the plasma parameters are too much degraded, a soft plasma shutdown is automatically initiated. MHD activity is one possible trigger of such a soft shutdown (fig. 6).

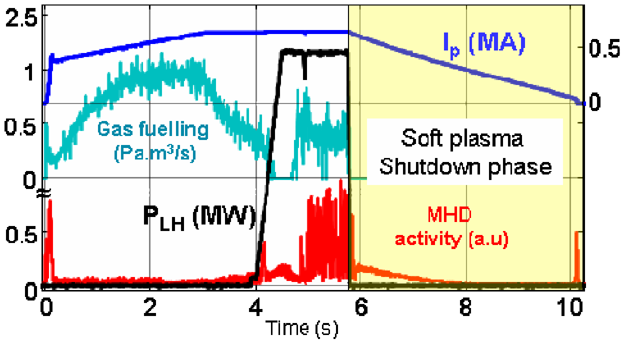

Figure 6: soft plasma shutdown.

MHD activity might occur when performing zero loop voltage (ie no flux consumption) discharge (current profile being different than in inductive operation). The plasma confinement being degraded, the PSC triggers a soft plasma shutdown. The plasma position is still under control, while gas fuelling and additional heating powers are switched off. The decision to stop the discharge is taken when the MHD activity exceeds a pre-programmed threshold during a pre-set time.

When plasma parameters (radiated power, MHD activity, amount of impurity…) through an online RT analysis indicate that the plasma will undergo a disruption, a fast plasma shutdown is initiated. A huge amount of neutral gas is injected within few milliseconds. The disruption and its consequences on the components (mechanical forces on machine structure, first wall heat load …) are thus mitigated. An other benefit is the action of neutral gas injection on fast electron generation. These electrons are accelerated during disruption in the large toroidal electric field generated by the plasma thermal quench. Associated current may reach several hundred of kiloamperes at few tenth of MeV. This electron beam hits the first wall components and severe damages are often observed. It has been demonstrated that a helium injection suppress such a fast electron formation [5]. Even if some promising results are reported, mitigation of disruption effects is still an issue for future large tokamaks.

FUTURE PLANS

The present PSC is included within the PF control system. A project in development is to implement The PSC in a central controller to extend its capability over the other actuators. The hierarchy of alternative strategies describes in this paper will be preserved. This expert system will be continuously improved to take benefit of the progresses of knowledge. It will directly provide its requests to the dedicated controllers of individual actuators. This topology enables easier implementation of advanced recovery strategies. The tracking of instructions sent to individual sub-system controllers will be easier. The development of advanced recovery strategies will be strongly requested to control burning plasma in future tokamaks.

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