Integrated Real-Time Supervisory Management for Off-Normal-Event Handling and Feedback Control of Tokamak Plasmas

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Abstract—For long-pulse tokamaks, one of the main challenges in the control strategy is to simultaneously reach multiple control objectives and to robustly handle in real-time (RT) unexpected events (off-normal-events (ONEs)) with a limited set of actuators. We have developed in our previous work a generic architecture of the plasma control system to deal with these issues. Due to this generic feature, we are able to extend it with an advanced supervisor: Supervisory control and Actuator Management with ONEs (SAMONE) to deal with multiple ONEs and multiple control scenarios in this work. We first standardize the evaluation of ONEs and, thereby, simplify significantly the supervisor decision logic, as well as facilitate the modifications and extensions of ONE states in the future. Then, we present the recent developments of real-time decision-making by the supervisor to switch between different control scenarios (normal, backup, shutdown, disruption mitigation, and so on) during the discharge based on ONE states. The developed SAMONE has been implemented on the TCV tokamak, applied to disruption avoidance with density limit experiments, demonstrating the excellent capabilities of the new RT integrated strategy.

Index Terms—Integrated control, off-normal-event (ONE) handling, supervisory control, tokamak plasma control system (PCS).

I. INTRODUCTION

The development of an advanced tokamak plasma control system (PCS) has recently gained more attention with the requirements of a robust off-normal-event (ONE-plasma or subsystem/plant failures) handling and of an integrated control approach. These are crucial to ensure a feasible discharge both for the plasma and the plasma-facing components in long-pulse tokamaks, such as ITER. On the one hand, this advanced PCS will act as the first line of defense of disruption, where all the plasma energy is released in a few milliseconds, to avoid unnecessary mitigation actions. On the other hand, it must be able to reach the desired discharge performance by simultaneously fulfilling multiple control tasks (control objectives) with a minimal set of actuators and diagnostics. Our work on Supervisory control & Actuator Management with ONEs (SAMONE) extends the entire chain of the tokamak-agnostic layer in the PCS [1] with a standardized evaluation of ONEs and an advanced supervisor for multiple ONEs and multiple control scenarios. It demonstrates the efficiency of the proposed approach via the first applications on TCV.

Regarding ONE handling, several works have been focused on the use of a discharge manager to decide appropriate actions depending on the seriousness of the events [2]–[6]. In this work, different ONEs’ categories are distinguished, and several control scenarios are investigated as well. The basic idea of ONE handling is shown in [2], where a discharge management system plays the roles of both a ONE monitor to classify the events and a supervisor to select a control scenario. In [5] and [6], a supervisor is proposed for exception handling by changing the control segments, which are equivalent to our control scenarios. In [3], a supervisory logic, using finite-state machines,1 is developed for event detection. In this early stage, the simple threshold test on the individual event can only trigger a soft-shutdown or a mitigation scenario. In [4], based on disruption root causes, different decentralized handlers are deployed with their preassigned actuators to directly tackle ONEs.

However, in these works, the supervisory decision is done by the selection of reactions and the corresponding actuators via the prioritization of ONEs. This leads to a direct link between ONEs and actuators. In other words, the supervisor needs to be aware of ONE nature and tokamak specific actuator systems. Here, we propose a systematic way to handle ONEs by the supervisor. Therefore, more stages are necessary to clearly classify the danger level, the reaction level for each ONE, and a ONE-reaction to Scenario (OS) mapping is finally used to allow the supervisor to switch between

1A representation of an event-driven (reactive) system that can be in one of a finite number of states depending on its previous condition and the present values of its inputs.
different control scenarios (normal, backup, or shutdown scenarios, and so on). Since the supervisor only takes care of selecting an appropriate scenario, the actions to deal with ONEs, once they are detected, are (flexibly) customized as a list of prioritized control tasks in different control scenarios. This leads to an automatic actuator resource assignment of the actuator manager and control (feedback) actions of the controllers (see Fig. 2). The modular feature of the entire framework allows a simple and generic implementation, algorithm, or functionality of each component in the control system. Moreover, the proposed scheme is also generic for any tokamak; thus, it can be easily tested, developed, and maintained. For our previous related works, the readers can refer to [7] for the plasma state and event monitoring and to [1] for the generic actuator management strategy to deal with multiple control tasks and actuator sharing.

Section II gives an overview of the generic PCS architecture developed in [1]. Section III zooms in the supervisor in the PCS, with the details of several evaluation levels of ONE and decision-making, as well as a concrete example for clarification. The developed PCS is implemented on TCV, and the first results of disruption avoidance experiments are discussed in Section IV. Finally, Section V concludes the work and gives some prospects for future works.

II. GENERIC PCS

The generic PCS presented in [1] is revisited hereafter with the main principles shown in Fig. 1. This PCS is clearly separated into two layers: the tokamak-dependent layer and the tokamak-agnostic layer. The tokamak-dependent layer includes various real-time (RT) state reconstruction codes for plasma and actuator states [7]. This layer thus converts specific plant signals to generic continuous-value states of the plasma and actuators that are used by the tokamak-agnostic layer and vice versa. For example, on TCV, the RT kinetic plasma equilibrium reconstruction can provide realistic pressure and current density profiles [8]; and the RT measures, combined with models, of heating sources provide the states of EC and NBI actuators ([9], [10]). Since the inputs to these models are tokamak dependent, they are in the tokamak-dependent layer. The SAMONE tokamak-agnostic layer specifically deals with the ONEs and the execution of control tasks according to the pulse schedule. Note that tokamak-agnostic is used in the sense that the functionality, algorithm, and implementation of each component are independent of the tokamak subsystems (diagnostics and actuators); even the inputs and outputs are tokamak-agnostic and, therefore, are well-standardized. However, the parameterization and specific usage (e.g., control tunable parameters, such as controller gains, thresholds, feedforward, and control references, can be adapted for each discharge and each tokamak) are specified by the user via the pulse schedule (user interface). Thus, the tokamak-agnostic layer can be directly transferable to different devices, independently developed and maintained; while the tokamak-dependent layer, also transferable, should be adapted (inputs/outputs) for each tokamak.

The task-based approach [1] is used in the tokamak-agnostic layer. In this approach, all decisions are made based on control tasks and not on controllers. Generic controllers themselves cannot choose actuators for their own interests. The controllers, on the one hand, request actuator resources (or virtual actuators [11]) to perform their tasks and, on the other hand, receive assigned generic actuator resources per task to try to fulfill their jobs. As a result, this scheme can avoid controller crosstalk, which is the main issue in integrated control [1], [11], [12]. It also allows us to design controllers in a more generic way, focusing on the physics properties of a given scenario. Moreover, the task-based approach greatly facilitates the interaction between the operators and the PCS software since they only need to specify the control tasks from physics goals (or pulse schedule), which are generic and similar among different tokamaks, regardless of the details of the relevant controllers and actuators.

A control scenario as predefined by the physicists or the operators becomes a list of prioritized control tasks [1], which will ensure that the plasma evolution is as close to the target scenario as possible. The pulse schedule is the interface between the control scenario and a given list of tasks. Note also that the pulse schedule and the tunable parameters for the components in the PCS, which are tokamak specific, are supplied via a user interface (Fig. 1).

The main function of each component in the tokamak-agnostic layer is summarized as follows.

1) A plasma and actuator event monitor [7] categorizes the state representation of the plasma, the events, and the actuators.
2) A supervisor evaluates the occurrence of ONEs and decides the appropriate control scenario (list of control tasks) and then activates and prioritizes relevant tasks.
3) An actuator manager defines the best actuator resource allocation to active tasks by solving an optimization problem based on the available actuator resources, the task priority and the resource requests from controllers; and later distributes commands to corresponding actuators [1].
4) Controllers execute control laws to fulfill their tasks with assigned resources and also ask for new actuator resources for the next time step [1].
The modular and interface-standardized features of the tokamak-agnostic layer allow us to reduce implementation errors and improve maintenance and development capabilities. For more details about the tokamak-agnostic layer and the interfaces of each component in this layer and how crosstalk is avoided with tasks priorities, the reader can refer to our previous work [1] and the references therein.

III. SUPERVISOR DECISION

We will focus on a strategy of supervisor decision to deal with ONEs (e.g., magnetohydrodynamic instabilities, such as neoclassical tearing mode (NTM), locked mode, or the events when the plasma/actuator states approach the physical/technical limits, such as density limit, actuator amplitude limit, and actuator energy limit), which can lead to plasma disruption or plasma performance deterioration. Here, the centralized supervisor plays the main role to decide the action for ONE handling. Associated with the centralized actuator resource allocator, this supervisory level can ensure a nonconflicting and flexible use of available actuators. A series of control scenarios is prepared in the pulse schedule corresponding to various actions to be selected in real time by the supervisor.

Fig. 2 presents the relevant modules of the tokamak-agnostic layer, as well as a zoom of the supervisor that determines the control scenario output, based on the discrete-value plasma state and actuator state inputs. For each ONE, first the danger level and the ONE-reaction level are determined. Then, a ONE to Scenario mapping is used to decide the appropriate control scenario based on a given set of ONEs and the associated ONE-reaction levels. Two finite-state machines are used to classify the danger level and the reaction level of each ONE (Fig. 2). It is important to notice that the thresholds for the transitions from one state to another in the finite-state machines are customized in the user interface as tunable parameters, which can be quickly modified between discharges. Two lists of states of these finite-state machines are also shown in Table I.

### A. Danger Level

Five (states) levels of danger are defined in Table I(a). The classification of a ONE danger level is based either on one generic state (amplitude state, position state, and so on)
or on the combination of various generic states from the plasma event monitor. On the other hand, in order to avoid ambiguity, while several ONEs simultaneously appear and their combination can significantly change the situation, a virtual ONE using their combination should be created as a new independent event. For example, a locked mode in low danger level will really become significant if there is also an observed increase in radiated power. In this case, an additional combined event is defined separately from the lock mode and the radiated power events. This is important and significantly simplifies the supervisor level by avoiding an additional decision level related to “what should I do if I have this ONE1 and that ONE2.” This is moved to the definition of ONEs and their reactions.

B. ONE-Reaction Level

The danger level is then used to define the ONE-reaction level whose states are listed in Table I(b) and are enumerated from 0 to 4, corresponding to the five basic types of control scenarios that we consider at this stage (see Section III-C). Examples of finite-state machines for ONE-reaction are shown in Figs. 3(a) and 4(a). It is worth noting that some states are irreversible, for instance, state levels 3 and 4. These states correspond to irreversible actions, such as soft-shutdown or mitigation. It is important to note that, depending on the customized danger thresholds per ONE, it is possible that a ONE can never get to some danger levels. However, we still need to define fine corresponding ONE-reactions (see example in Section III-D). Also, the mapping between the danger levels and the ONE-reaction levels is specific for each ONE, thus, they are not always 1-1 corresponding (see Fig. 3(a), the difference between NTM21 and NTM43 events).

C. ONE-Reaction to Scenario Mapping

To select the control scenario to be executed in the current time step, an OS mapping [see Fig. 3(b)] based on the combination of the ONE-reaction levels of all active ONEs is thus necessary. A finite number of control scenarios is derived from the given pulse schedule. We define five basic types of control scenarios: normal, recovery, backup, soft-shutdown, and disruption-mitigation. Several control scenarios of the same type can be defined. For example, we often have one normal, which is the desired/original/basic scenario, one soft-shutdown, and one disruption-mitigation, but several recovery and several backup scenarios depending on the considered ONEs and the control actions on them. For instance, with two ONEs, three recovery scenarios can be considered and a predefined OS-mapping is compulsory as in Table II. Otherwise, in the simple case where there is only one basic scenario per type, the default OS-mapping, where the highest ONE-reaction level directly corresponds to the effective scenario, e.g., Table IV(b), is used. It is important to emphasize that any relevant combination of ONEs is included in the list of ONEs; therefore, the OS-mapping defines the relevant scenario considering all relevant ONEs and any combinations through a well-defined (long) table.

Finally, a list of control tasks is determined by the user for each control scenario in order to achieve the desired control action, as shown in the example in Table III.

Once the appropriate control scenario is selected based on the actual plasma situation, the relevant control tasks will be activated, and the corresponding references are taken into account according to the user setting for each control scenario before the discharge. The actuator manager and the controllers perform their normal functionality without any judgment on the ONEs.

D. Example

In this section, two NTM events, NTM21 and NTM43, are considered to be simultaneously detected. Their danger states are determined based on the discrete-value states of
TABLE II
CUSTOMIZED OS-MAPPING FOR TWO ONEs

| ONE1 - reaction | ONE2 - reaction | scenario |
|-----------------|----------------|----------|
| 0               | 0              | normal   |
| 1               | 0              | recovery 1|
| 0               | 1              | recovery 2|
| 1               | 1              | recovery 3|
| 2               | 0              | backup 1 |
| ...             | ...            | ...      |

TABLE III
NTM EVENT: EXAMPLE OF TASKS FOR EACH DEFINED CONTROL SCENARIO

| control scenario | list of control tasks                                                                 |
|------------------|----------------------------------------------------------------------------------------|
| normal           | normal tasks (e.g., β control / Pheat feedforward)                                      |
| recovery 1       | NTM24 stabilization + normal tasks                                                     |
| recovery 2       | NTM43 stabilization + normal tasks                                                     |
| recovery 3       | NTM24 + NTM43 stabilization + normal tasks                                             |
| ...              |                                                                                        |
| backup 1         | β control / Pheat feedforward with new references + NTM21 stabilization               |
| ...              |                                                                                        |
| soft-shutdown    | set of tasks for controlled ramp-down                                                 |
| mitigation       | set of tasks for disruption mitigation                                                |

Note that β reference, feedforward reference, etc., are tunable parameters which are given from the user interface.

their amplitudes from the plasma event monitor. Due to the different danger potential of the considered events, their state machines for the ONE-reaction level are not the same. For instance, the NTM43 is not very dangerous; it only leads to a reduction of neutron productions; thus, the reaction is either no-action (0) or recovery (1). On the other hand, the NTM41 requires all actions up to mitigation (4) since a 2/1 mode can trigger disruptions. Depending on the reaction level associated with these ONEs and the predefined OS mapping, the control scenarios are different for the two situations, as shown in Figs. 3 and 4: backup 1 and mitigation, respectively.

In Table III, some relevant tasks are listed associated with each control scenario in this example. A control scenario will be chosen by the supervisor for each instant; thus, the considered tasks in this scenario will be activated based on the task activation conditions (time intervals, event triggers, and so on). Regarding the first situation where the backup 1 scenario is selected, three tasks NTM21 stabilization, β control, and heating feedforward can be simultaneously activated. The actuator manager determines the best actuator resource allocation per task based on the actuator states and the requests for actuator resources per task from the controllers. Three corresponding controllers, NTM controller, performance controller, and feedforward controller, are used to carry out the three considered tasks, respectively. The controllers execute their control laws and do their best to fulfill their given tasks with the assigned resources. Here, the NTM controller commands to move the EC power into the launcher angles (targets) and uses all EC power that it receives at the target. The performance controller in this case is a PID controller, which asks to modify the heating power according to the gap between the RT estimated β (corresponding to the total thermal energy) and its reference. The feedforward controller reproduces a heating power command, which is configured by the user before the discharge. All the commands from the controllers are combined and then sent to the tokamak-dependent layer, where they are converted into the specific actuator commands, e.g., heating power into voltage and radial deposition location of EC power into launcher angles.

IV. EXPERIMENTAL RESULT

The proposed PCS with SAMONE has been implemented in MATLAB/ Simulink, from which C code was generated and included in the TCV digital real-time control system [13], [14]. An application for disruption avoidance experiments is presented in Fig. 6, where the discharge is pushed toward the H-mode density limit disruption by a gas-flux ramp. The main purpose of disruption avoidance experiments is to avoid the abrupt loss of energy confinement or even to recover the plasma to the previous stable states. However, in this experiment, we aim to control the plasma to slowly approach the density limit for detailed physics studies. Several new modules have been implemented in the TCV PCS to determine in RT: the factor $H_{98y2}$ characterizing the energy confinement time and the normalized edge density $n_{e\text{ edge norm}}$ [15], [16]; together, we derive the distance $d_{n_{e\text{ edge}}} \text{ or } d_{n_{e\text{ edge norm}}}$ (see Fig. 5). This distance is the key factor used by the supervisory layer to determine an appropriate control scenario. In this example, two ONEs are considered: $d_{n_{e\text{ edge}}} \text{ or } d_{n_{e\text{ edge norm}}}$ for the NBI energy limit. The supervisor evaluates the dangers from these ONEs to switch between different scenarios: normal, recovery, and soft-shutdown, in which three sets of relevant control tasks are configured beforehand.

In Fig. 6 (second panel), the danger level of the $d_{n_{e\text{ edge}}} \text{ or } d_{n_{e\text{ edge norm}}}$ is low from ① when the distance is below the first critical threshold $d_{\text{critical1}} \text{ or } d_{\text{critical2}}$ and is medium from ② when the distance is below the second threshold $d_{\text{critical2}} \text{ or } d_{\text{critical3}}$; while the actuator $A_{\text{actuator}}$ danger is high when the NBI energy reaches the threshold 95% of the total energy of 1.3 MJ (which is not the case in this experiment) and is no otherwise. Here, the customized ONE-reaction levels based on the danger level of each ONE are specified in Table IV.

The control scenario (third panel) is based on the combination of the reaction levels of the two ONEs, which is recovery if the highest danger level reaches medium from ②; otherwise, it remains normal. According to the chosen scenario, different control tasks are activated and prioritized (fourth panel).
Fig. 5. Time-evolution of the edge density limit $d_{\text{ne, edge}}$ on the state plane $(H_{95}, d_{\text{ne, edge}})$ (colored dots), the empirical disruption limit (black line), and different user-defined critical thresholds (red-dashed lines).

In the normal scenario, the feedforward task $FF_{\text{power,nor}}$ asks for a constant heating power of 0.65 MW, and the $FF_{\text{gas,nor}}$ commands a fast gas-flux ramp. The disruption-avoidance task $DA_{\text{power,nor}}$ modifies the power according to the distance $d_{\text{ne, edge}}$ only when it is below the $d_{\text{critical},1}$, and the $DA_{\text{gas,nor}}$ reduces the gas-flux ramp. In the recovery scenario, the $FF_{\text{power,rec}}$ is the same as the $FF_{\text{power,nor}}$, while the $DA_{\text{power,rec}}$ asks for the maximum power, and the $DA_{\text{gas,rec}}$ keeps the gas flux constant. Consequently, on the one hand, the NBI power (last panel) is composed of a constant power 0.65 MW ($FF_{\text{power,nor}}$) and an extra power ($DA_{\text{power,rec}}$) increasing proportionally up to the maximum heating power of 1.3 MW. On the other hand, the gas flux is first increasing fast ($FF_{\text{gas,nor}}$), then slowly ($DA_{\text{gas,nor}}$) at ①, and, finally, is frozen ($DA_{\text{gas,rec}}$) at ②. It is important to note that the threshold $d_{\text{critical},2}$ identical to the disruption limit, which is associated with the medium danger instead of a higher danger level, is a particular choice in this test. This allows us to continue a slow and well-controlled approach to the density limit for detailed physics studies.

A soft-shutdown scenario is also set up with two feedforward tasks to cut off both the NBI power and the gas flux in a controlled manner when the distance $d_{\text{ne, edge}}$ goes below the $d_{\text{critical},3}$. However, this threshold is not well-determined at this stage and the discharge disrupted at ③ [4] before that situation happens. Since the thresholds are empirically defined, we need to collect more data from the experiments. Therefore, in this experiment, it is intentionally chosen quite far from the disruptive limit in order to reach disruption to contribute to the physics program. We also aim to find better critical thresholds using machine learning techniques in our upcoming work.

V. CONCLUSION

This work presents a supervisory strategy to deal with ONEs. Each ONE is evaluated for its danger level and the necessary reaction; then, a global decision is made to define an appropriate control scenario. The presented control architecture has been successfully implemented and tested on
the TCV tokamak in the context of density limit disruption avoidance experiments, employing the exposed control scenario switching methodology. It has been fruitfully capable of smoothly reaching density limits in various plasma discharges. This architecture will be used for different integrated control objectives, such as simultaneous controls of L-H mode, NTM, \( \beta \), and \( q \)-profile, in the upcoming experiments.

ACKNOWLEDGMENT

The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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