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ABSTRACT
Validation by means of simulation is a crucial step when developing real-time control systems. Modeling and simulation are an essential tool since the early design phase, when the control algorithms are designed and tested. This phase is commonly carried out in offline environments such as Matlab® and Simulink®.

A MARTe-based simulator has been recently developed to validate the new JET Vertical Stabilization (VS) system. MARTe is the multi-thread framework used at JET to deploy hard real-time control systems.

This paper presents the software architecture of the MARTe-based simulator and it shows how this tool has been effectively used to evaluate the effects of Edge Localized Modes (ELMs) on the VS system. By using the simulator it is possible to analyze different plasma configurations, extrapolating the limit of the new vertical amplifier in term energy of largest rejectable ELM.

1. INTRODUCTION
To achieve high performance in tokamaks, plasmas with elongated poloidal cross-section, characterized by large vertical instability growth rates, are needed. Such elongated plasmas are vertically unstable, hence position control on a fast time scale is an essential feature of all machines. The achievement of the fast time performance is strictly dependent on the flexibility and reliability of the real-time systems that operate the plant during the experiment. In large experimental plants like JET [1] or ITER [2], it is crucial to have an architecture that supports model-based development to validate software modules against a plant model. Such an architecture permits to minimize the risks related to the development of complex plant control systems. Furthermore, simulation tools can be effectively adopted also during the deployment of real-time systems. Indeed, offline testing of the full real-time system permits to debug the code and to validate the real-time version of the control algorithms before running them on the plant [3]. Such an approach permits to minimize the risk of malfunctions and to reduce the time needed for the commissioning on the plant, yielding a cost reduction. Eventually, by using such a simulation environment, it is possible to perform offline analyses addressed to the fine tuning of the control algorithms for specific operative scenarios. In order to adopt such an approach the real-time framework has to satisfy some key requirements: in particular it must allow to run the real-time code in an offline (non real-time) environment, interfacing it with a plant simulator. On the other hand, reliable plant models must be available.

A MARTe-based simulator has been recently developed at JET tokamak, and it has been used to validate the new JET Vertical Stabilization (VS) system [4]. MARTe [5] is the multi-thread framework used at JET to deploy hard real time control systems. Thanks to the modularity of its software architecture, MARTe allows to interface the real-time control system with a C++ version of the plasma magnetic linear model. It also allows to use different linear models (corresponding to different plasma equilibria) in different pulse phases, in order to simulate a complete JET pulse.

This work describes the software architecture of the MARTe-based simulator. As an example case

study, it is shown how this tool has been effectively used to evaluate the effects of Edge Localized Modes (ELMs) on the VS system [6]. In particular, a drop of energy due to an ELM occurrence is simulated by a variation of both poloidal beta and internal inductance [7]. These parameters are considered as a disturbances applied to the plasma linearized model. By using the simulator it is possible to analyze different plasma configurations, extrapolating the operational limit of the new vertical amplifier in term energy of largest rejectable ELM.
The paper is structured as follows: the VS simulator is introduced in the next section, while in Section 3 the case study is presented. Eventually some conclusive remarks are drawn in Section 4.

2. THE VERTICAL STABILIZATION SIMULATOR

The new VS control system represents the first MARTe based control system that has been successfully developed and deployed at JET [8]. Within the MARTe environment, the end users are required to define and implement algorithms inside a well defined software block named Generic Application Module (GAM), which is executed by a real-time scheduler. The JET VS system was implemented by using MARTe under the Real Time Application Interface (RTAI)/Linux operating system. The adoption of a standard framework for the development of real-time systems, model-based design and validation is effective approach to reduce the time needed for commissioning a new system on the plant.

Exploiting the MARTe modularity it is possible to add different modules to the structure of the VS system, in order to implement a complete closed-loop simulator that permits to study the VS behaviour. In particular, in Fig. 1, the four GAMs shown in yellow have been specifically developed to simulate the plant.

The VS simulator has been very useful first during the commission phase of the new VS system, especially to tune the controller parameters and to study the behaviour of the new control law.

In the following we present both the software architecture of the VS simulator and its human machine interface.

2.1 SOFTWARE ARCHITECTURE

The VS simulator is MARTe based and as mentioned before, it mimics the same structure of the VS system. By adding four different modules to the structure of the VS system it is possible to implement a complete closed-loop simulator of the same code that runs on the real plant. In particular the four simulation GAMS depicted in yellow in Fig.1 have been added:

- state–space GAM: it allows to simulate the plant behaviour by receiving the voltage applied by the Enhanced Radial Field Amplifier (ERFA) as input, and produces the estimation of the plasma vertical velocity and the amplifier current as outputs. The state–space model can be configured by using the CREATE–L [9] code. This GAM allows to load different linearized model to take into account the different plasma configurations, allowing to simulate a complete JET pulse.

- waveform generator GAM: it allows to add inputs that are not modified by the closed–loop, e.g., the plasma current, which is an input for the simulator and it is not modified by the VS system.
- ERFA logic GAM: it allows to simulate hysteretic characteristic of ERFA and adds some noise to simulate a real acquired signal.
- noise GAM: the plasma vertical velocity measurement used for the vertical stabilization in JET, is reconstructed by means of a suitable linear combination of flux and field time derivative measurements, This reconstructed signal is obviously affected by error. The main sources of errors are: errors due to the violation of hypotheses assumed by the reconstruction algorithm; noise due to power electronics; noise due to measurement instrumentation & signal conditioning electronics; noise due to plasma activity. The noise GAM allows to add ta noise signal to the plasma vertical velocity computed by the model, in oder to model all these sources of uncertainty.

2.1 HUMAN - MACHINE INTERFACE

At JET the plant control systems are configured using a distributed system named Level-1. This system is used by the expert users to set up all the VS system parameters before the experiment.

MARTe provides a web interface which enables the browsing of its internal components, allowing the user to navigate into the GAMs' structure and check the values of the parameters loaded in the VS system.

The human-machine interface of the simulator has been designed as similar as possible to the VS Level-1 interface. Thanks to this choice, by using the simulator, the user can access to all the parameters available on the plant during the experiment.

The Level-1 interface for MARTe based systems is divided in two levels:

1. Real-time executor level, which allows the user to load the MARTe skeleton configuration; where the can specify what GAMs are to be executed together with their basic parameters. It is important to note that this level is common to all MARTe-based applications;
2. Application level, which is customized for the VS system. This level is designed to allow the user to set each controller parameter before the experiment and to configure the GAM parameters using fully featured graphical user-interface.

The user interface of the simulator presents the same structure of the Level 1. This interface is realized by using the Matlab GUI Application. As shown on Fig.2 (yellow bloks) this interface is structured in two level: the former allows to load the machine configuration file, the latter allows to change it by setting the controller parameters and to add the different linearized model of plasma. In particular:

- Set VAM & others: allows to change the parameter of the Vertical Amplifier Manager (VAM) GAM and to add as waveform the signals that are not modified by the closed–loop.
- Set Scheduler: allows scheduling the experiment because every JET discharge is logically

divided into a number of time windows. As shown on Fig.3 For each time windows it is possible to set several control mode and several controlled variables.

- Set Model. allows to load different linear models (corresponding to different plasma scenarios) in different pulse phases, allowing to simulate a complete JET pulse.
- Set Control: allows to set all the parameters of the controller which are independent from the scheduling of the pulse. These global parameters are set by using a waveform editor
- Set ERFA Logic: allows to set the amplifier parameters.

3. A CASE STUDY: LARGER REJECTABLE ELM

The VS simulator has useful to study the operational limits of the VS system in the presence of very strong localized MHD plasma instabilities, named ELMs. ELMs manifest themselves as strong magnetic perturbations associated with a burst of D-alpha radiation and a loss of particles and energy from the plasma periphery. Moreover an ELM event is characterized by a loss of the diamagnetic energy that is strictly related to a variation of poloidal beta and the relationship is given by [7]:

$$\Delta W = \frac{3}{8}\,\mu_0 R_0 I_p^2 \Delta\beta$$

where Ip is the plasma current, R0 is the major radius and $\Delta\beta$ is the variation of poloidal beta.

Because the perturbation affects the magnetic fields creating a strong variation in the plasma speed measurement, the VS sees an ELM as a rapid increase of plasma speed (ZPDIP) followed by a rapid inversion and a slower decay (Fig. 4). This causes the firing of ERFA and a resulting vertical excursion of the plasma, in some cases associated with loss of control.

For these reason it is very important to characterize the behaviour of the VS system in term energy of largest rejectable ELM.

Since an ELM event creates a strong variation in the plasma speed measurement, it can be modelled as a disturbance for the VS system. In particular, by using the CREATE-L model, a representation of the plant behaviour is given in the state space form. A characterization of ELMs by means of poloidal beta and internal inductance variations has been carried out via simulation, using both experimental magnetic signals and CREATE-L models. By considering the identified quantities as disturbances for the system the closed loop simulations have been performed by using MARTe simulator. In particular, the input of the system are the amplifier voltage and the identified quantities, instead the output are the amplifier current and the estimation of the vertical velocity.

Thanks to these simulations it has been possible to find the maximum controllable ELM by multiplying the disturbances for a factor α Since the poloidal beta and internal inductance variations are strictly related to a loss of diamagnetic energy, with this simulations we are able to find the maximum controllable ELM from the VS system in term of maximum diamagnetic energy loss. The tolerable poloidal beta (β) drop ($\Delta\beta$) scales with $1/I_p$, whereas the tolerable energy drop ($\Delta W \propto \Delta\beta Ip2$) scales with I_p. ELM transients are characterized by fast dynamics (hundreds of μs) followed by a slow β drop (tens of ms).

In Pulse No: 78452 with $I_p = 3MA$, and a relatively high growth rate of the vertical instability ($\gamma = 200s^{-1}$), the VS system tolerated a considerable energy drop ($|\Delta W|$>1.5MJ) with an excursion of the ERFA current ($|\Delta I_{ERFA}| = 2.5kA$) well below its operational limit. Simple extrapolations based on scaling laws and more accurate simulations based on the CREATE-L model show that the tolerable energy drop for a 4MA plasma would have been well beyond 2MJ, with a dramatic improvement with respect to the previous VS system with the old radial field amplifier FRFA.

As shown on Fig.5(a) the ELM effect on the VS system in characterized of two phases. The first one is a fast phase in which the simulated trace is very close to the experimental behaviour.
On the contrary during the slow phase the simulated behaviour is very different from the experimental one. As shown on Fig. 5(b) this experimental behaviour is essentially due to a shape controller effect that is not taken into account by the VS simulator.

CONCLUSIONS

A MARTe-based simulator for the JET VS system has been presented. This simulator has been effectively used to test offline the VS software during the commissioning of the system.Furthermore the this simulator has been used to assess the system performance by tuning the controller parameters. Since the VS simulator is MARTe, and exploiting the modularity of this framework in future it will be to study the coupling between the VS system and the shape controller at JET, by simply adding the shape controller GAM.

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REFERENCES

[1]. Fusion Science and Technology **53** (2008), special issue.
[2]. Nuclear Fusion **47** (2007), special issue.
[3]. G. Ambrosino et al., IEEE Transactions Plasma Science, **38**(7), 2010, pp. 1662-1669.
[4]. F. Sartori et al., Fusion Engineering Design, **85**(3-4), 2010, pp. 438-442.
[5]. A. Neto et al., IEEE Trans. Nuclear Science, **57**(2), 2010, pp. 479-486.
[6]. H. Zohm, Plasma Physics and Controlled Fusion, **38**, 1996, pp. 105–28.
[7]. O. Barana et al., Fusion Engineering Design, **66-68**, 2003, pp. 697-701.
[8]. T. Bellizio et al., IEEE Trans Plasma Sci., to appear, 2010, doi: 10.1109/TPS.2010.2053721.
[9]. R. Albanese and F. Villone, Nuclear Fusion, **38**(5), 1998.

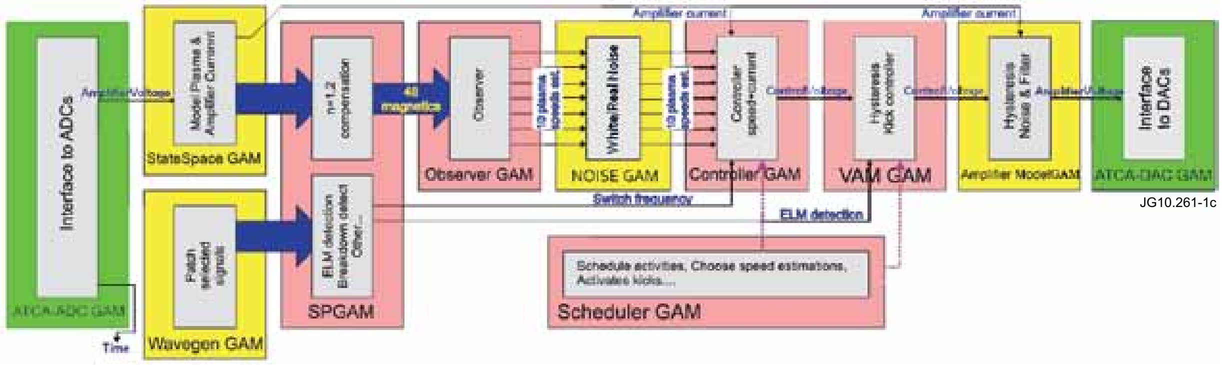

Figure 1: Block diagram of the VS software architecture

Figure 2: MATLAB GUI Interface of the simulator

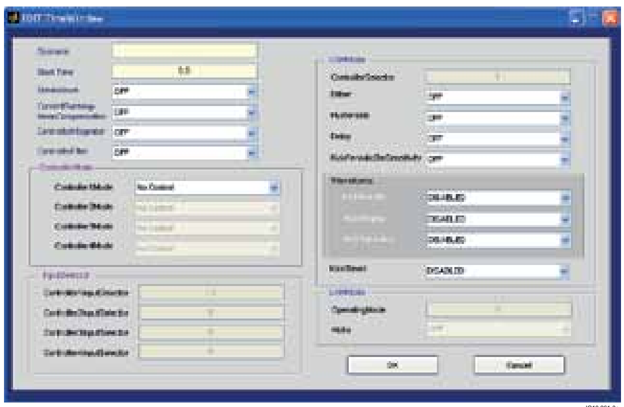

Figure 3: Interface of the simulator to set the controller parameters for each time wondows,

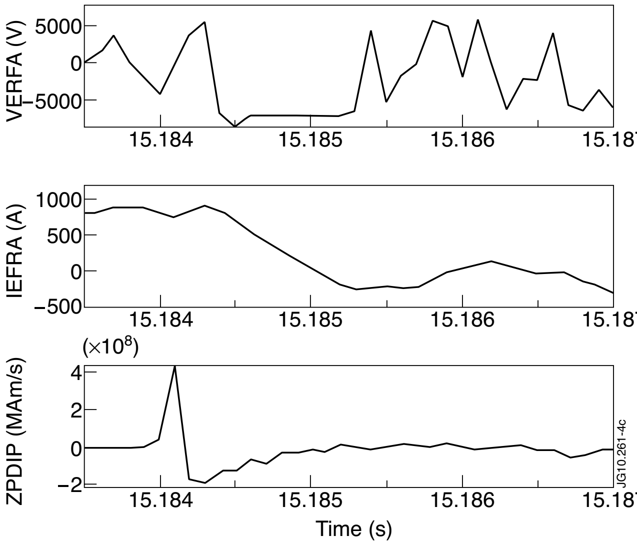

Figure 4: Effect of an ELM event on the VS parameters.

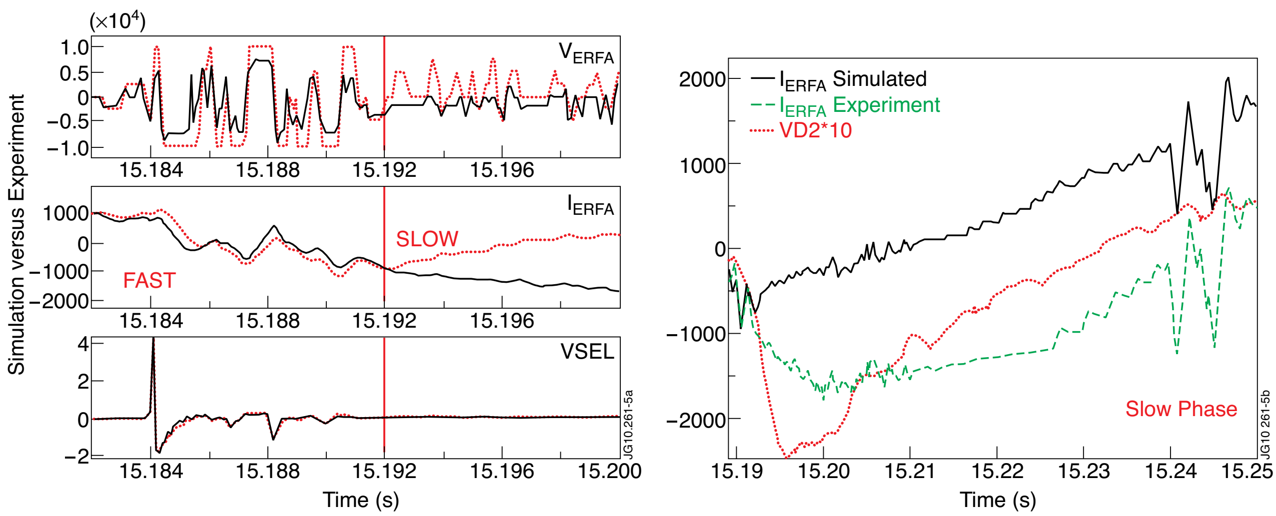

Figure 5: Comparison between experimental data and simulation during an ELM event.