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Development of magnetic control for the EU-DEMO flight simulator and application to transient phenomena

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ABSTRACT

This paper presents a first implementation of DEMO tokamak (Donné, 2019) [1] configuration including CREATE magnetic controllers in the Fenix flight simulator environment. Fenix is based on the 1-D transport code ASTRA (Pereverzev and Yushmanov, 2002 [2] and Fable et al., 2013) [3] , coupled with the 2-D equilibrium solver SPIDER (Ivanov et al., 2005) [4] . Following the successful demonstration on ASDEX Upgrade (Herrmann and Gruber, 2003) [5]) , it was clear that this environment could be fruitfully used to simulate DEMO scenarios including both magnetic and kinetic control strategies. In order to design magnetic controllers, first a systematic validation of the plasma linearized dynamic response has been successfully carried out. This dynamic response has been used to design and tune a first version of magnetic controllers including vertical stability, plasma shape and plasma current control. Simulations of both the plasma flat-top phase including H to L transition, and of the ramp-up phase are presented to show the effectiveness of the proposed simulator and of the magnetic control solution.

1. Introduction

The challenges of future large tokamaks operation, implying also increased time and cost of experiments, makes attractive the development of a so-called *flight simulator* which can simulate the entire pulse with a good compromise between realism and computational time. This kind of tool plays an important role during the tokamak design phase to run a high number of alternative scenarios in a short time, but also during operation for control design purposes to validate algorithms designed on simple models and to support waveform generation and controller tuning. Few codes have been developed in this area, comprehensive of equilibrium solver, transport simulation modules, and eventually magnetic and kinetic controllers to fully simulate the behavior of a plasma discharge. The presence of a magnetic closed loop control is a key factor to manage instability and equilibrium during simulation.

In [6] the coupling of DINA equilibrium solver with CRONOS transport code for the simulation of ITER discharges was studied; in [7] a more advanced integration between DINA and JINTRAC [8] is documented with the aim of optimizing the ITER 15 MA DT baseline scenario; in [9] the coupling of JINTRAC and CREATE-NL is proposed for different ITER scenario simulations. Other examples are CORSICA [10] used to design and simulate ITER scenarios with a light transport module, the DINA model of TCV based on DINA-CH [11] and the Tore Supra GMFS flight simulator [12].

Fenix flight simulator [13] was developed at IPP for ASDEX Upgrade [5] and implemented on the ITER Plasma Control System Simulation Platform (PCSSP) [14] to support the pulse design and the closed loop control tuning. Fenix is built connecting the plasma/tokamak simulator in the form of S-function with a set of other Simulink blocks implementing the control system algorithms and actuator models. A simplified model of the plasma/tokamak reduced in complexity and less time consuming, compared to other models, is used in Fenix because sufficiently representative of the most important plasma dynamics and non-linearities e.g MHD limits, plasma transport, confinement transitions, interactions between plasma regions with closed and open field lines, as well as heating and fueling actuators physics. This allows to test and verify multiple scenarios and controllers within a reasonable time frame.

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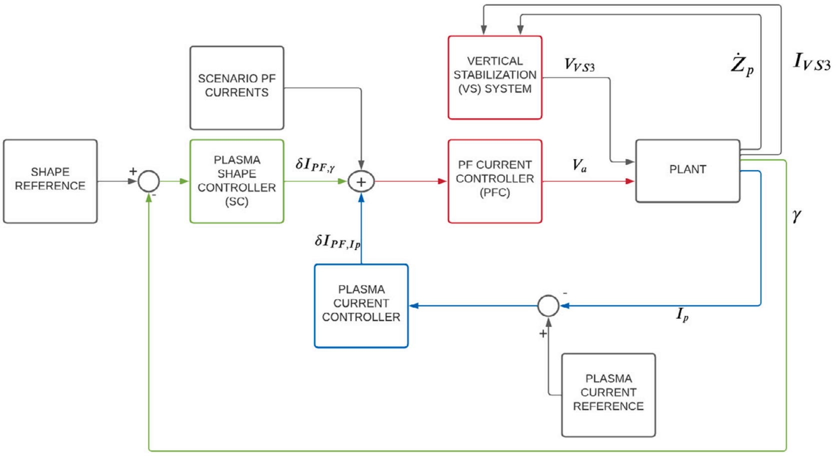

Fig. 1. Simplified schematic view of the magnetic control architecture.

This paper presents the first steps toward an implementation of the DEMO [1] model in Fenix, a preliminary cross-validation of the plasma linearized dynamic response used for control design purposes, and the design and testing of magnetic control laws.

2. Magnetic control system architecture

An important step toward the dynamic simulation of plasma scenarios is the definition of magnetic control laws. In fact, in the absence of this closed loop control action, elongated plasma are vertically unstable and the plasma boundary displacements have a deep impact also on transport and kinetic aspects of the simulation. DEMO magnetic control scheme, adopted for the first simulations described in this paper, is an ITER-like controller based on a lower level current controller in the so called *Current Control Mode*.

In this kind of control mode, shape and plasma current controllers exploit currents flowing in the PF circuits (see Fig. 1) as actuators. The adopted magnetic control architecture consists of the following components.

Vertical Stabilization Controller (VSC). This control algorithm stabilizes the plasma unstable mode using a dedicated in-vessel circuit available in the actual DEMO configuration. Assuming a linear feedback of the current in the in-vessel coils and of the vertical speed of the plasma centroid, control gains are obtained by solving a constrained optimization problem on a time interval with a duration of 1 s. The optimization cost function used in the optimization is a quadratic weighted combination of the vertical speed of the plasma centroid, and of the voltage control effort in the presence of an initial vertical displacement on the unstable mode of 10 cm. Constraints on the maximum voltage available (3 kV) were imposed.

PF Current Controller (PFCC). This control action tracks the reference currents in the superconducting PF circuits. Reference currents are the sum of the scenario nominal currents and the feedback corrections received from the plasma current and shape controllers. The design of the PFCC consists in a *multiple input–multiple output* state feedback, whose gain is obtained with a trial and error procedure based on a Linear Quadratic Regulator (LQR) approach setting the closed-loop settling time to about 1 s.

Plasma Current Controller (PCC) is a Proportional–Integral (PI) *single input–single output* controller tracking the plasma current reference by generating a current request to the PFCC. The reference currents generated by the PCC are a modulation of a predefined pattern called *transformer current* pattern optimized to control plasma current while minimizing the effect on plasma shape.

Plasma Shape Controller (SC). Plasma shape can be described using a finite number of distances between the plasma boundary and the first wall, named gaps. The SC tracks the plasma boundary by controlling to zero the error between the reconstructed gaps and the corresponding reference gaps with a multiple input–multiple output PI action. Two artificial gaps are defined to control the position of the strike points. Similarly to the plasma current control loop, this block generates an additional request to the PFCC. Gains are designed adopting an XSC-like approach described in [15].

3. Plasma linear dynamic response validation and basic controller design

Magnetic control laws are tuned using plasma linearized models obtained via the CREATE-L [16] code. To assure the effectiveness of this model-based approach, a dynamic response validation was first carried out, comparing the ASTRA/SPIDER [2] [3] [4] non-linear code simulation results with the CREATE-L linearized model results (with a simulation time step of 2.5 ms).

The validation approach was set in a virtual analogy to the commissioning of the control oriented simplified models with real experiments. In such a perspective, the first comparison was done driving the coils with voltage waveform and comparing the “measured” currents and magnetic sensors output with the simulation results.

Fig. 2 shows the $CS3U$ voltage waveform used to drive one of the simulations without plasma. In Fig. 3 the comparison of the numerical results obtained with ASTRA/SPIDER and CREATE-L model are shown. These are in good agreement.

After these simulation without plasma, a flat top equilibrium was obtained both in CREATE-L and in ASTRA/SPIDER and the first step was to compare the plasma vertical unstable mode. In fact, to make further comparisons (i.e. in the presence of shape and/or plasma current variations) a vertical stabilization is needed.

A 5 cm Vertical Displacement Event (VDE), i.e. displacement of the vertical plasma centroid position on the unstable mode, is then considered. In Fig. 4, the results of a simulation in the absence of VS control action is shown. It appears that the two growth rates predicted by ASTRA/SPIDER and CREATE-L are very similar. The main source of difference at the beginning is the transient induced by the fact that Fenix is not perfectly in equilibrium at the initial time. Then plasma shape modifies (e.g. elongation decreases and plasma gets closer to the passive structures) and the amplitude of the growth rate in the nonlinear simulation reduces accordingly.

Fig. 5 shows the result of a simulation with the designed VS system active. The settling time of the vertical speed predicted by the two codes is very similar. The main difference is due to the fact that the CREATE-L simulation is driven by an initial displacement of the state on the unstable mode, while ASTRA/SPIDER, like in an experiment,

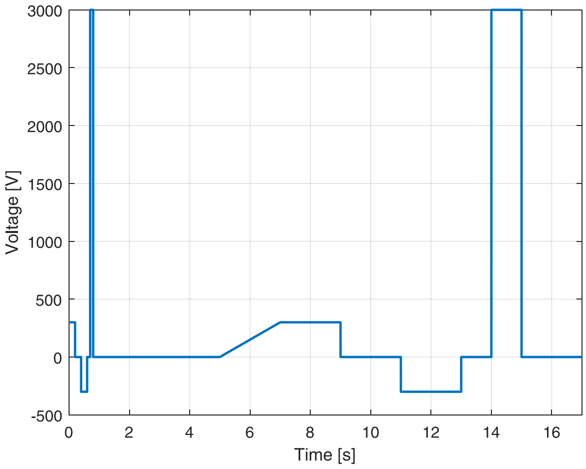

Fig. 2. Voltage waveform applied to the different circuits for the validation of the vacuum model.

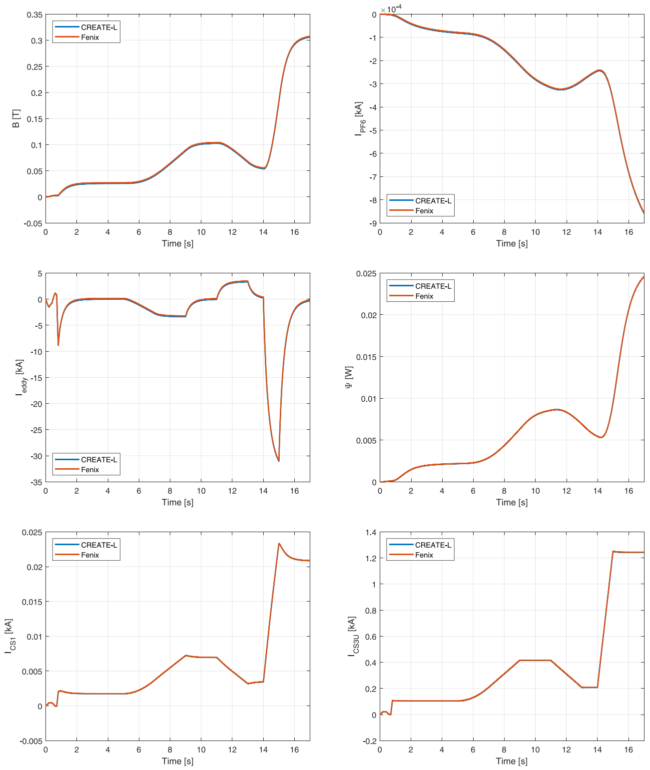

Fig. 3. Results of a simulation obtained driving $CS3U$ circuit with voltage waveform shown in Fig. 2. Active currents, passive currents, fields and fluxes are in good agreement between ASTRA/SPIDER (red line) and CREATE-L (blue line).

was excited with a kick on VS3 circuit implying the same displacement amplitude.

The proof of validity of the linearized model is however the fact that VS controller design on this model robustly stabilize the nonlinear plasma with the desired closed loop time constant.

An extensive campaign of simulations to validate the linearized model on the shape and plasma current response was then carried out with satisfactory results. The proof of this is the success of the shape and plasma current control design discussed in the next section.

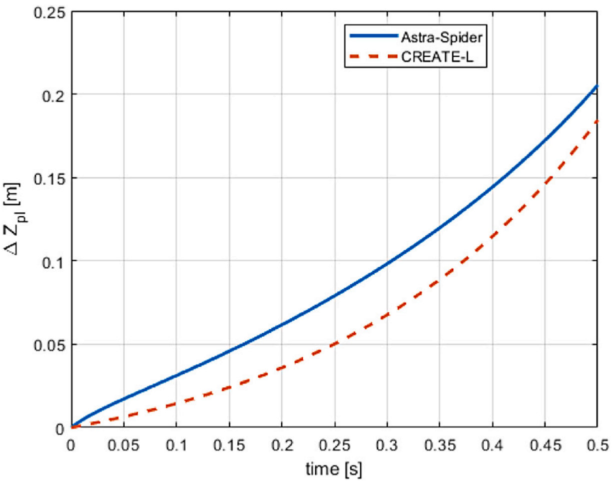

Fig. 4. Comparison of the exponential unstable vertical dynamics obtained with the CREATE-L linearized model and a nonlinear simulation with ASTRA/SPIDER.

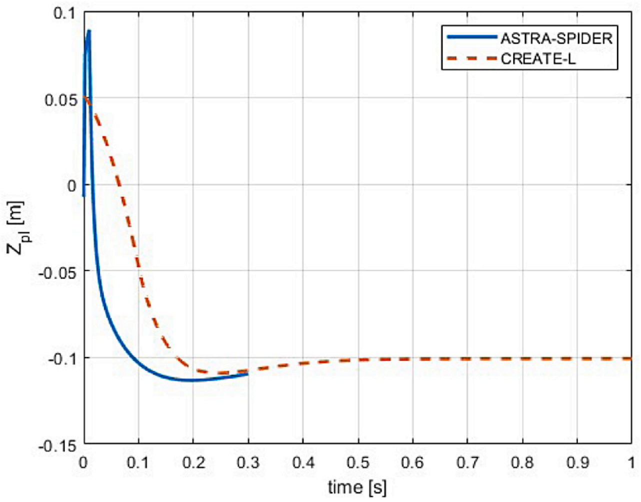

Fig. 5. Comparison of the plasma centroid vertical position time trace following a vertical displacement of 5 cm with CREATE-L linear model and ASTRA/SPIDER in the presence of a VS control action.

4. Numerical results

To prove performance of the proposed controllers including plasma current and shape, in some of the most challenging scenario phases, two ASTRA/SPIDER simulations starting from a reference plasma with $Ipl \approx 19$ MA, $li_3 \approx 0.8$ and $\beta_{pol} \approx 1.4$ are presented:

- Simulation #1: plasma transition from a high confinement regime to a low confinement regime (H to L transition) [17].
- Simulation #2: ramp-up phase in which the plasma volume and current increase to the reference values.

4.1. Simulation #1 - H to L transition

This simulation is characterized by a halving of poloidal beta with an exponential decay having a time constant equal to 4 s at $t = 20$ s. The time traces of the main quantities are reported in Figs. 6 and 7. Plasma current is controlled to the initial value, plasma centroid evolution

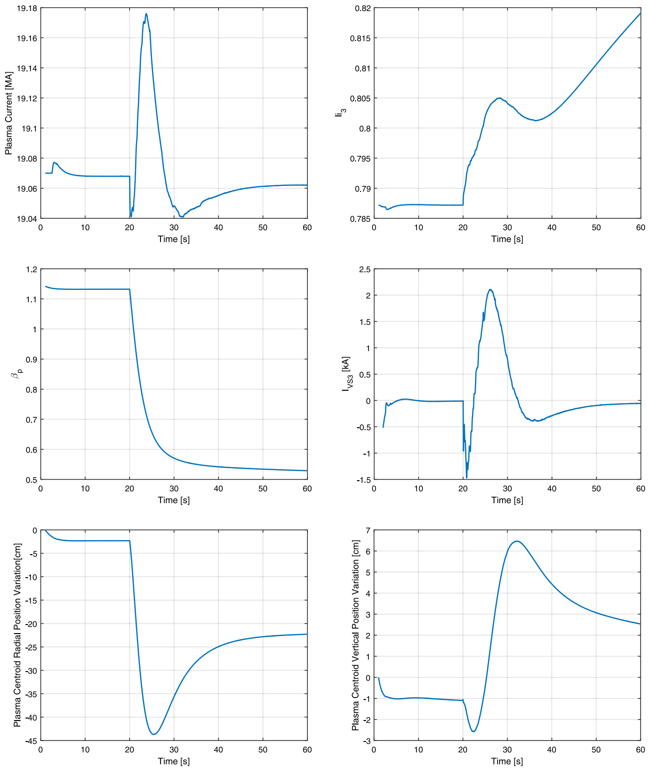

Fig. 6. H to L transition — plasma related quantities time traces.

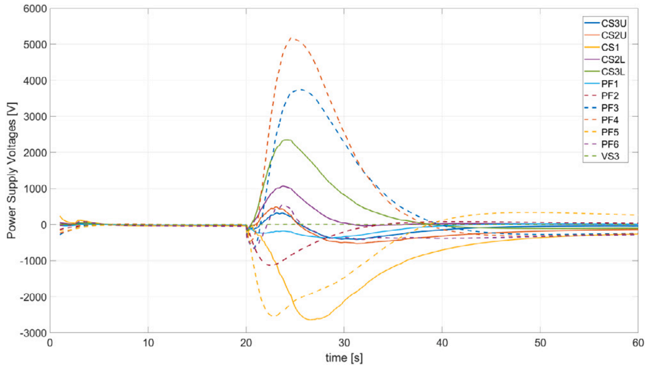

Fig. 7. H to L transition — power supply voltages time trace.

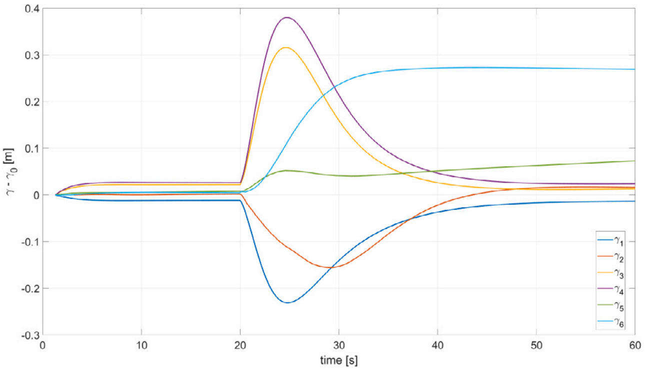

Fig. 8. H to L transition — gaps variation with respect to the initial values.

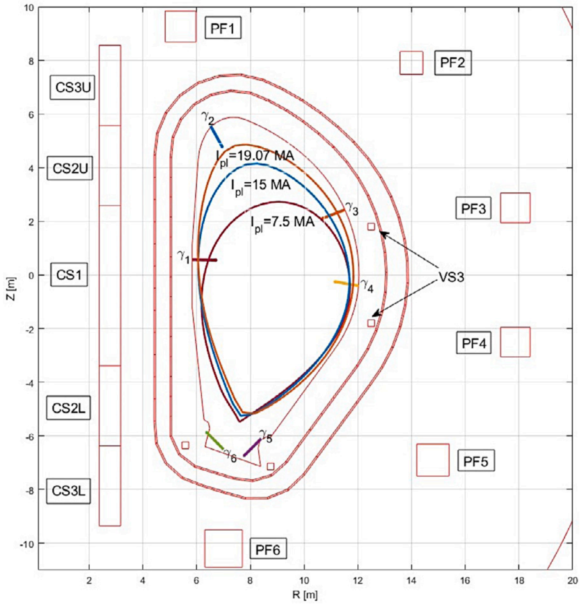

Fig. 9. Ramp-up sequence of plasma shapes.

denotes a stable behavior, while power supply voltages are within the limits. The gaps variation shown in Fig. 8 are acceptable considering that no plasma-wall contact takes place. Strike points position recovery is slower than gap response but effective.

4.2. Simulation #2 - Ramp-up

This simulation includes the ramp-up segment in plasma diverted configuration, L to H transition and part of the flat top. Fig. 9 shows plasma shapes in correspondence of $I_{pl} = 7.5$ MA, $I_{pl} = 15$ MA and $I_{pl} = 19.07$ MA. The applied control action is obtained with a linear interpolation of two set of control gains tuned on the $I_{pl} = 7.5$ MA and $I_{pl} = 19.07$ MA plasmas. Gains are interpolated with the actual value of the plasma current.

The time traces of the main quantities are reported in Fig. 10, showing the capability of following the reference plasma current time trace, with unsaturated power supply voltages, reported in Fig. 11, and gaps error with respect to the reference values becoming negligible at steady state (Fig. 12). It is important to note that the gap γ_2 is initially not controlled because it is ill defined due to geometrical reasons.

5. Conclusions

Plasma discharge simulation codes taking into account closed loop control actions are of paramount importance in the tokamak design phase to run a high number of alternative scenarios in a short time. During operations they are useful for control design purposes and to support waveform generation and controller tuning. In view of further DEMO scenario studies, Fenix flight simulator has been equipped with CREATE magnetic control modules that has shown good capabilities in controlling the plasma. In fact, two challenging conditions as the ramp-up and the H to L transition has been simulated. Future work will be aimed at producing simulation of different scenarios also including plasma limiter phases, and at obtaining a full integration of plasma magnetic and kinetic control.

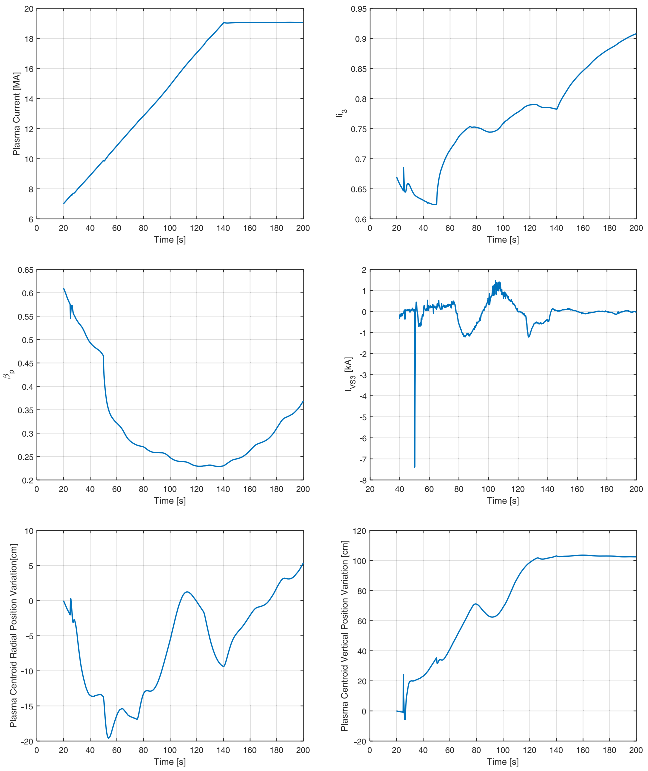

Fig. 10. Ramp-up — plasma related quantities time traces.

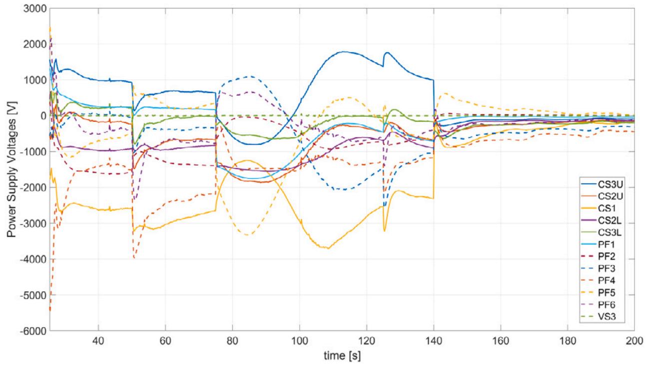

Fig. 11. Ramp-up — power supply voltages time trace.

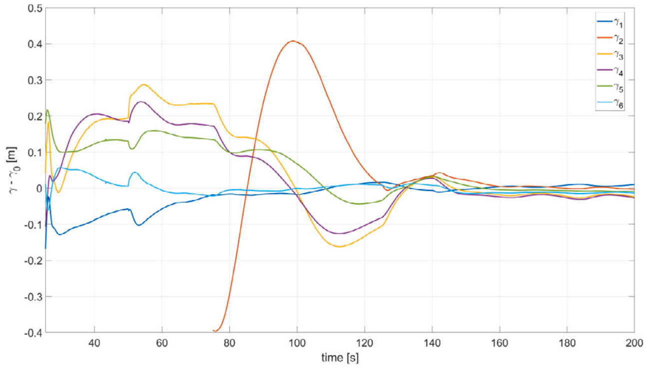

Fig. 12. Ramp-up — gaps tracking errors with respect to the reference values.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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