REFERENCE GOVERNOR FOR PLASMA SCALAR CONTROL TO PREVENT STABILITY LIMIT BREACHES IN TOKAMAKS

A Generic Framework to Enforce Multiple Stability Limits on Tokamak Plasma Operation

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A generic reference governor has been developed to dynamically adjust the reference values that each plasma scalar controller must track during a plasma discharge. The reference values are adjusted to prevent the breach of magnetohydrodynamic (MHD) stability limits. Breaching these limits during tokamak operation could lead to disruption in many cases. Such disruptions in reactor-grade tokamaks and fusion pilot plants could cause structural damage and large operational downtime. Fig. 1 shows a block diagram of the proposed reference governor incorporating diverse stability limit signals to adjust the reference values for various plasma scalar controllers.

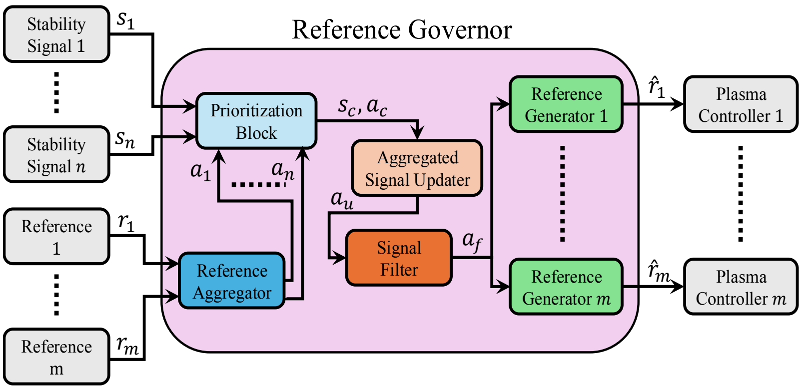

Figure 1: Reference governor block in the PCS.

The proposed reference governor has been tested extensively using ITER-based nonlinear simulations. Four different cases were considered: (i) electron density regulation using a proportional-integral (PI) controller without exceeding the Greenwald limit [1], (ii) electron density regulation using a reinforcement learning controller without exceeding the edge limit [2], (iii) deuterium–tritium density regulation using a PI controller without exceeding the Greenwald limit, and (iv) deuterium–tritium density regulation using a PI controller without exceeding the upper (Greenwald/edge) limit or falling below a prescribed lower limit. All four cases consider particle regulation in ITER by leveraging previously developed control-oriented simulation models [3] and closed-form stability limit equations [1, 2]. The simulations were carried out with and without the proposed reference governor in each case for comparative analysis. The simulation results for the first case are shown in Fig. 2. Fig. 2(a) presents the stability limit (Greenwald limit), the reference, and the feedback-controlled electron-density evolution when the reference governor is inactive. The predefined reference is chosen to remain below the Greenwald limit during the tokamak operation. The PI controller is designed, in turn, to track this predefined reference. However, an unexpected decrease in the Greenwald limit (stability signal) at around 25 seconds (simulated by a temporary drop in the plasma current) leads to a breach of the stability limit by the reference and, consequently, by the feedback plasma evolution. Fig. 2(b) presents the trajectories when the reference governor is active, showing that the reference governor dynamically adjusts the reference once the

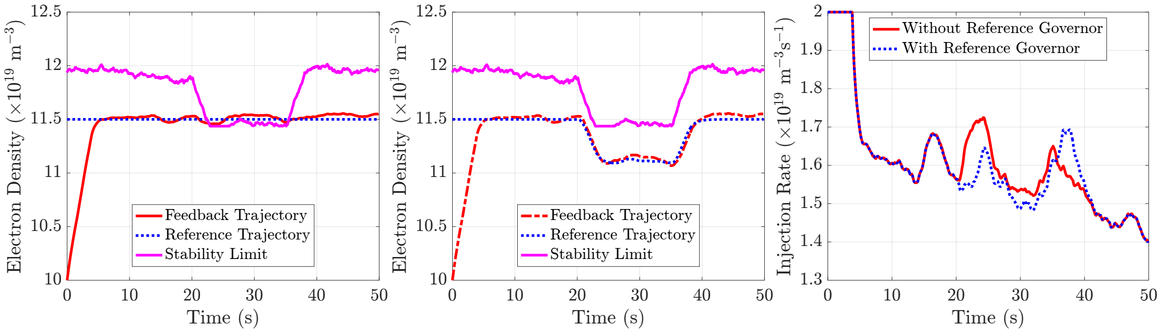

Figure 2: (a) - Without reference governor (left), (b) - With reference governor (center), (c) - Inputs (right).

Greenwald limit value decreases. As a result, the plasma state (feedback trajectory) remains below the Greenwald limit. Once the stability limit rises again, the reference governor reverts the reference to its predefined values. Fig. 2(c) shows the particle injection rates prescribed by the PI controller to track the references in two subcases (with and without the reference governor). As expected, the deviation in the particle injection rates is seen only when the reference governor adjusts the reference.

The reference governor presented in this work has demonstrated its ability to handle distinct stability limits and prescribe multiple scalar references simultaneously while remaining computationally inexpensive and agnostic to both plasma properties and controllers. Existing reference governors, also referred to as proximity controllers in the literature, are designed to be problem-specific (i.e., tailored to particular plasma control problems) [4, 5, 6]. Thus, any changes in the underlying plasma control objectives may require a redesign of the reference governor. Furthermore, existing proximity controllers are designed to enforce a single stability limit, which may not be sufficient in certain cases. For instance, particle density must remain within upper and lower limits, particularly during the ramp-up phase, to avoid disruptions [7]. In addition, some existing reference governors rely on real-time optimization frameworks, which can be computationally expensive. The proposed reference governor effectively addresses these challenges. In a tokamak plasma control system (PCS), it acts as an independent pre-processing block that receives "stability signals" $(s_1, \ldots, s_n)$, which indicate predicted stability limits, and the predefined references $(r_1, \ldots, r_m)$ for each plasma controller, as shown in Fig. 1. The choice of individual references $(r_1, \ldots, r_m)$ and stability signals $(s_1, \ldots, s_n)$ does not impact the operation of the reference governor, thus making the proposed solution plasma-property and controller agnostic, meaning it can adapt to different types of plasma scalars and controllers. Since stability limits are typically defined by nonlinear combinations of multiple plasma states, the reference aggregator block nonlinearly combines the predefined reference values $(r_1, \ldots, r_m)$ to produce metrics $(a_1, \ldots, a_n)$ that can be directly compared with the stability limits $(s_1, \ldots, s_n)$. Based on the proximity of the aggregated signals $(a_1, \ldots, a_n)$ to the limits $(s_1, \ldots, s_n)$, the prioritization block selects and transmits the most critical stability signal (s_c) along with its associated aggregated signal (a_c). This prioritization allows the reference governor to effectively handle multiple stability limits. The signal updater block then modifies the selected aggregated signal value (a_c) by adding a safety margin based on its proximity to the stability limit (s_c). To reduce the effect of noise from the stability limit signals, the updated aggregated signal (a_u) is passed through a low-pass filter. The filtered signal (a_f) is later converted into updated "safe" references $(\hat{r}_1, \ldots, \hat{r}_m)$ by exploiting the nonlinear function used in the reference aggregator block. The "safe" references $(\hat{r}_1, \ldots, \hat{r}_m)$ are finally passed to the individual plasma scalar controllers. Each scalar controller adjusts the actuator inputs to track the updated reference values. Since the computation of $\hat{r}_1, \ldots, \hat{r}_m$ only involves solving differential equations based on the low-pass filter equation and evaluating nonlinear functions, the overall computational cost is low.

The proposed reference governor effectively adjusts the references for plasma-scalar controllers in real time to avoid violations of stability limits. Simulation results illustrate its ability to achieve the desired stability limit avoidance. Reference governors, as the one proposed in this work, will play a critical role in the disruption-free control frameworks envisioned for ITER and future fusion reactors.

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