Calculating the probability of locking to an error field for a saturated magnetic island surrounded by a resistive wall

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We present a framework for estimating the probability of locking to an error field in a rotating tokamak plasma. This framework leverages machine learning methods trained on data from a mode-locking model, including an error field, resistive magnetohydrodynamics modeling of the plasma, a resistive wall, and an external vacuum region, leading to a fifth-order ordinary differential equation (ODE) system. Tearing mode saturation by a finite island width is also modeled. We vary three pairs of control parameters in our studies: the momentum source plus either the error field, the tearing stability index, or the island saturation term. The order parameters are the time-asymptotic values of the five ODE variables. Normalization of them reduces the system to 2D in control space and facilitates the binary classification into locked (L) or unlocked (U) states, as illustrated by Akcay et al., [Phys. Plasmas 31, 032301 (2024)]. This classification splits the control space into three regions: $\hat{L}$, with only L states; $\hat{U}$, with only U states; and a hysteresis (hysteretic) region $\hat{H}$, with both L and U states, where bifurcations between the L and U states can occur. The classification of the ODE solutions into L/U is used to estimate the locking probability, conditional on the pair of control parameters, using a neural network. A probability of locking is a true representation of the underlying hysteresis, representing the propensity of the mode to lock given a perturbation to the plasma. We also explore estimating the locking probability for a sparse dataset, using a transfer learning method based on a dense model dataset. This technique retains the qualitative characteristics of the locking probability and allows us to obtain good estimates of it from a small number of experimental or simulation data points, making the model highly useful in these contexts, and offering the potential for application to real time control.