Feedback control design for non-inductively sustained scenarios in NSTX-U using TRANSP

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The spherical torus is being considered as an option for facilities designed to study fusion nuclear science [1] or to generate fusion power [2]. Such designs have little to no room for a central solenoid, and require the plasma current to be generated non-inductively. Recently completed upgrades to NSTX-U will enable the study of non-inductive scenarios, including start-up, ramp-up, and flattop current sustainment. This paper examines approaches to active control of such scenarios using TRANSP simulations. TRANSP is a time-dependent integrated modeling code for discharge prediction and interpretive analysis of tokamak experimental data. Its predictive mode has been used for scenario development on NSTX-U, including fully non-inductive scenarios [3], and has been used to explore approaches to non-inductive plasma current ramp up [4]. Recently, the ability to include feedback control algorithms in TRANSP simulations has been developed [5]. To mimic the earliest planned non-inductive scenario studies on NSTX-U, the simulations in this work begin with an inductively produced plasma and the Ohmic coil current is fixed throughout the simulation. An open loop reference simulation was done along with a series of simulations to study the sensitivity of the scenario to disturbances, including changes in density, profile shapes, and confinement. The actuators considered for feedback control in this work are the six neutral beam sources and the plasma boundary shape. The neutral beam sources allow the current drive deposition and heating to be tailored in real-time. The primary plasma boundary shape parameter that is considered in this work is the mid-plane outer gap. Increasing this gap size leads to increased bootstrap current and moves the neutral beam deposition further off-axis, tending to increase the central safety factor. To understand the response of the plasma current, stored energy, and central safety factor to these actuators and to enable the systematic design of control algorithms, a series of simulations were run in which the actuators were modulated around the reference values and a linear dynamic response model was fit to the resulting data. The simplified model was then used to design several PID control laws using different combinations of actuators and measurements. Simulations show that modest changes in the outer gap and heating power can improve the response time of the system, reject perturbations, and track target values of the controlled values. Simulations including beam modulations, which are used experimentally to approximate analog power requests, show small oscillations in current but significant oscillations in stored energy. This indicates that methods for reducing beam modulations should be explored. In general, a strong coupling between the controlled quantities is observed, which will make multi-variable control design an important next step.

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