DEVELOPMENT OF EQUILIBRIUM CONTROL SIMULATOR AND EXPERIMENTAL VALIDATION OF ADVANCED ISO-FLUX EQUILIBRIUM CONTROL DURING THE FIRST OPERATIONAL PHASE OF JT-60SA

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To achieve robust control of multiple frequency-domain control targets, including tokamak plasma shape control, plasma current control, and vertical position instability, a nonlinear simulation model was compared with experimental results from the first operational phase of JT-60SA (IC1). Based on these evaluations, an improved ISO-FLUX control scheme was developed, and prediction and mitigation of vertical instability (VI) was further demonstrated. We revealed the linearity and nonlinearity of plasma responses to coil current variations and identified the applicability range of the linear model, demonstrating that a nonlinear response-based simulator is essential. Here, the linear model assumes that displacement of the plasma linearly scales with the current of the conducting structures, such as non-rigid model of [1], while in the nonlinear model, the plasma equilibrium is self-consistently solved with the conducting structures, which is essential for self-consistent simulation of the vertical displacement event, and thus determines the resultant plasma displacement [2]. We developed various control logics by using a “nonlinear” MHD Equilibrium Control Simulator (MECS), which addresses universal challenges in the next-generation large-scale tokamaks, such as ITER and DEMO: the increase in inductance due to coil scaling, voltage saturation, and interference among multiple control objectives (current, position, and shape of plasmas). The developed control logic, the adaptive voltage allocation (AVA) scheme [3], contributed to various achievements: the world's largest plasma volume (160 m³) and the highest current (1.2 MA) as a superconducting tokamak, in the IC1. Furthermore, the vertical instability associated with high elongation (~1.7) was successfully predicted and controlled to a specified direction using the newly developed control logic [4]. Remarkably, throughout two months of operations (>200 discharges), no controller gain adjustments were required, highlighting the importance of the “nonlinear” equilibrium control simulator.

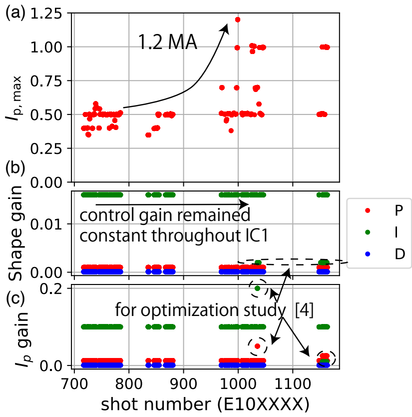

Fig. 1 the relationship between (a) the maximum Ip and (b,c) the control gains used in the controller during IC1. The horizontal axis represents the shot number. The maximum Ip 1.2 MA was achieved without gain optimization.

In the JT-60SA control system, conventional PID control with an advanced ISO-FLUX scheme [3] has been adopted for both plasma current control and shape control. Figure 1 shows the relationship between (a) the maximum achieved plasma current (I_p) and (b,c) the control gains used in the controller during IC1. The horizontal axis represents the shot number, displaying data from the E100700 series, where feedback control started, up to the E101163 series. P, I, and D represent the proportional, integral, and derivative. It is evident that the maximum plasma current I_p exceeds 1.2 MA, setting a record as superconducting tokamaks. At the same time, the PID gains remained unchanged, except for a few shots of untended experiments.

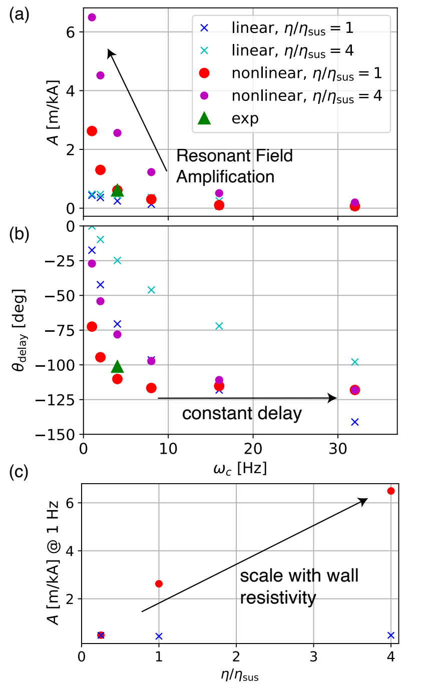

Fig. 2 comparison between a linear and a nonlinear plasma responses model against sinusoidal coil current. Wall resistivity (η) is also scanned, and its dependence is summarized in figure (c). Nonlinear model successfully reproduces experimental data in JT-60SA (figure (a) and (b)). The amplification factor A scales with η, which indicates the resonant field amplification. η_{sus} denotes the original wall resistivity.

Figure 2 shows the comparison between a linear and a nonlinear plasma response. Wall resistivity (η) is also scanned, and its dependence is summarized in figure (c). Here η_{sus} denotes the original wall resistivity. Sinusoidal voltages with opposite polarity were applied to the upper and lower poloidal field coils of JT-60SA, and their frequency was varied. The experimental data of IC1 is shown by a triangle mark in figure (a) and (b). Regarding the amplification factor A, defined as the vertical displacement of the plasma (Δz) divided by the change in coil current (ΔI), the nonlinear model showed amplification at $\omega_c \sim 0$. Not only in A but also in the phase delay, the experimental results showed good agreement with the nonlinear model, despite being limited to a single data point at 4 Hz. The dependence of A on the wall resistivity at 1 Hz is summarized in figure (c). Clearly, the amplification factor A scales with η, which is a signature of resonant field amplification, where amplification is governed by the growth rate of the vertical instability, thus scales with the wall resistivity η since the vertical instability is the axisymmetric resistive wall mode.

Using a simulator equipped with the nonlinear response, we developed the Adaptive Voltage Allocation (AVA) scheme [3], a logic designed to resolve the issue of interference between multiple control targets—specifically, plasma current and position-shape control—under high inductance conditions where power supply voltages tend to saturate, as in large superconducting tokamaks like ITER and DEMO. Effects of the AVA scheme are shown in figure 3. In the AVA scheme, a margin $G_{\mathrm{X,AVA}}$ for the allowable voltage of plasma current control is evaluated. Based on this new proxy, the control input for Ip is suppressed, thereby mitigating interference between Ip and shape control. Without the AVA scheme, interference leads to voltage saturation in coils as shown in fig. 3(c), resulting in vertical position oscillations. By applying the AVA scheme, these oscillations were suppressed, enabling the achievement of the world's highest plasma current for a superconducting tokamak, reaching 1.2 MA. During IC1, coil currents were limited to ±5 kA (see fig. 3(b)). However, in upcoming experiments, this limit will be extended to 20 kA, allowing the plasma current to potentially reach ~5 MA.

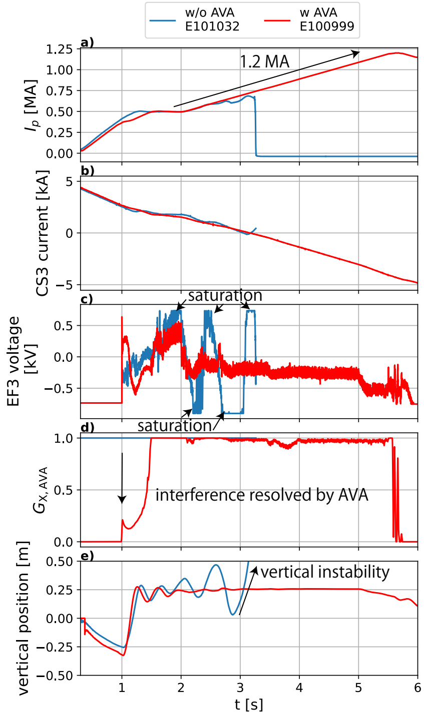

Fig. 3. Time evolution of (a) plasma current, (b,c) CS3 current/EF3 voltage, (d) $G_{X,AVA}$, and (e) vertical position. The control failure was successfully resolved by the AVA scheme, and achieved 1.2 MA.

Lastly, during IC1, the prediction and directional control of vertical instability (VI) with a highly elongated shape was demonstrated. In IC1, the maximum accessible elongation is ~1.7 with 90 s^{-1} of VI growth rate [5]. VI arises due to the breaking of the balance between the suppressing effect of the control and the free energy of VI, which leads to precursor oscillations. The vertical axis in figure 4 represents the decay index, which correlates with the growth rate of VI; a more negative value indicates greater instability. The red decision curve in the figure was predicted using a support vector machine (SVM) trained on the discharges represented by the blue lines. Inside this curve, VI is predicted to be unstable. By utilizing the oscillatory nature of VI, the extrema of the velocity at the oscillation center (blue dot points) was used as training data. In discharge E101156, the prediction was tried, and after the detection, the applied voltage was set to zero, intentionally driving downward VI. While avoidance is favorable, limiting the direction of VI allows the thermal and electromagnetic stress loads to be restricted to an intended direction, providing better protection. During IC, predictions were made using two variables. However, in preparation for Op-2, the system has been expanded to include multidimensional predictions with 10 variables and significant improvements in prediction performance have been confirmed [5].

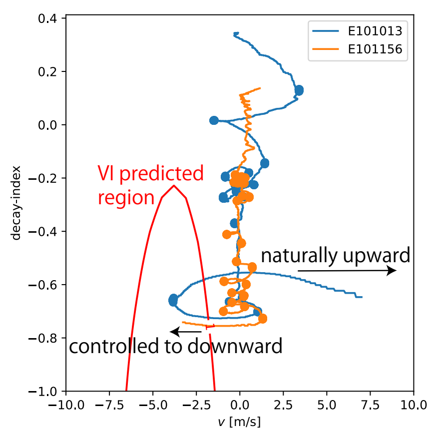

Fig.4. SVM model for the vertical instability prediction in IC1. The model was constructed from the data of E101013 and was validated in another sequence, E101156. An ellipse is drawn by the predictor to indicate the region inside which the VI is unstable.

In summary, this paper will report not only the importance of nonlinear plasma responses in the equilibrium control simulator and the logic development for VI direction control but also other essential fundamental works, such as the installation and calibration methodologies for magnetic diagnostics, the evaluation of plasma kinetic energy [6], and the incorporation of this into advanced control strategies for future operation [7].

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