Equilibrium control in the integrated commissioning of JT-60SA

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Abstract. We developed two control logics, an adaptive voltage allocation scheme and a plasma current centroid scheme [S. Inoue *et al.*, Nuclear Fusion 61, 096009 (2021)], to expedite the commissioning of JT-60SA, a large superconducting tokamak device. The efficacy of these schemes has been successfully validated through experimentation. First, we introduced an ISO-FLUX control scheme based on the plasma current centroid, which assumes filamentary currents in plasma and controls both position and shape within the ISO-FLUX control framework. The robustness of the PCC scheme was validated in JT-60SA experiments, demonstrating excellent controllability in the presence of significant eddy currents affecting the plasma current, such as immediately following plasma breakdown, where precise reconstruction of the last closed flux surface is unnecessary for equilibrium control. Subsequently, an adaptive voltage allocation (AVA) scheme was developed, which dynamically adjusts the balance between plasma shape and position control, and plasma current control under saturated power supply voltage conditions. In the presentation, how these two logics have facilitated the commissioning process for JT-60SA will be presented.

1. Introduction

In the startup stages of fusion devices, such as the integrated commissioning of JT-60SA, a large and superconducting tokamak device, the reliability of various equipment must be validated with plasma discharges. During this phase, equilibrium control is essential to maintain as a part of the infrastructure. In the commissioning phase of this large tokamak device, a myriad of systems are validated sequentially. This process often involves unforeseen equipment performances, such as sudden halts of electron cyclotron heating, diminished operational capacities (e.g., limited rated power supply voltages), and human errors. Each incident introduces disturbances to the equilibrium controller, presenting unique challenges in sustaining the desired plasma state. To optimize the number of shots in a constrained timeframe, it is crucial to devise a highly redundant logic before commencing commissioning. We have developed an ISO-FLUX control scheme based on the plasma current centroid, along with an Adaptive Voltage Allocation (AVA) scheme [1], which mitigates the interference between the plasma current (I_p) control and shape control. The Plasma Current Centroid (PCC) method employs filamentary currents in plasma, controlling both their position and shape within the ISOFLUX control framework. The AVA scheme has effectively prevented control instabilities that can arise from shot-to-shot variations in Electron Cyclotron Range of Frequency (ECRF) injection conditions and unoptimized I_p command values.

From a physics perspective, equilibrium control is indispensable. Fundamentally, plasma pressure scales with the plasma current according to Troyon scaling [2]. Moreover, an increase in plasma current for limiter configurations may be constrained by MHD stability considerations, thereby necessitating a highly elongated shape to increase the safety factor at the boundary. Given the pivotal role of equilibrium control, intensive development has been carried out on various devices. For instance, in JET, a control logic named the XSC (Extreme Shape Controller), capable of precisely controlling multiple control points, was developed [3] and was investigated to apply JT-60SA experiment [4]. In DIII-D, there has been a long-standing pursuit of model-based adaptive control [5], which has been recently validated experimentally in KSTAR as well [6].

Despite extensive efforts to refine equilibrium control logics in various devices, the new generation of large superconducting tokamaks has distinct characteristics compared to medium-sized or conventional conducting devices, such as substantially high coil inductance and thick walls that facilitate eddy current flow. Specifically, the L/R time constant of the vacuum vessel is around 0.1 s for ITER and JT-60SA. In these environments, specialized control logic is crucial to manage states with significant eddy currents and voltage saturation, which is the impetus behind the development of the AVA and PCC methods [1]. In this presentation, how these logics have expedited the integrated commissioning of JT-60SA, will be presented. We note that details of the control model can be found in [1].

2. Effect of the AVA scheme

In this proceeding, the key results to explore the effect of an Adaptive Voltage Allocation (AVA) scheme will be investigated. The AVA scheme resolves interference between I_p control and shape control, particularly due to the increase in plasma elongation during I_p ramp-up. The effects of the AVA scheme were initially confirmed through the simulator, which we call the MHD equilibrium control simulator, MECS [7, 8], and subsequently validated during the integrated commissioning of JT-60SA, contrasting its efficacy with sequences without the AVA scheme, as depicted in figure 1. Here, I_p was ramped up to 500 kA at 1 s, maintained at a flat top until 2 s, and then increased to 700 kA. Feedback control commenced at 1 s. Following the initiation of feedback control, a discrepancy between the targeted and actual values of I_p was observed, which caused voltage saturation as shown in figure (b) in the absence of the AVA scheme. On the other

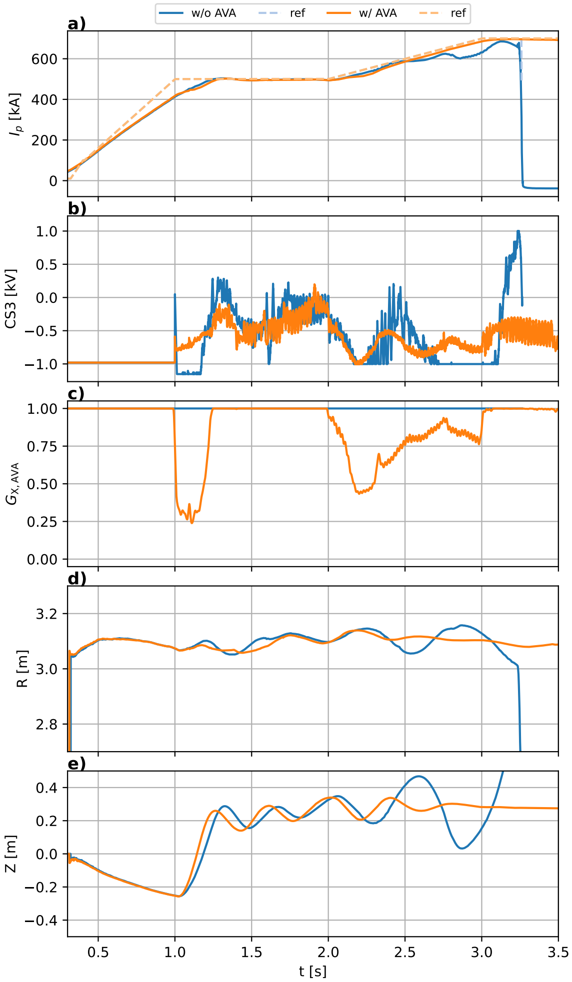

Figure 1. Temporal evolution of a) plasma current, b,c) radial/vertical position of plasma current centroid, d) $G_{\mathrm{X,AVA}}$, and e) ECRF injection command. In the case w/o AVA (blue lines), the AVA scheme is turned-off, while is activated in the w/ AVA case. I_p is ramped-up to 700 kA by using the AVA scheme with diverted shape.

hand, in the case with the AVA, the automatically adjusted gain, $G_{\mathrm{X,AVA}}$, optimized the balance between the plasma current and the position and the shape control, which can be seen as the drop of the $G_{\mathrm{X,AVA}}$ in figure (c). In the absence of the AVA, the vertical/horizontal shape control failed as shown in figure (d) and (c), which are successfully resolved by introducing the AVA scheme, and achieved successful ramp-up to 700 kA.

3. Summary

We developed novel logics to accelerate the JT-60SA experiment [1], which were successfully validated in the integrated commissioning of JT-60SA. In the integrated commissioning of a large and superconducting tokamak like JT-60SA, the integrity of myriad devices is sequentially validated. This process often encounters unexpected equipment performance, acting as a perturbation to the equilibrium control, therefore necessitating redundant control logics to maximize shots within a limited timeframe. We developed an ISO-FLUX control scheme based on the plasma current centroid, and secondly, an Adaptive Voltage Allocation (AVA) scheme [1], which resolves interference between the I_p control and shape control, and accelerated the integrated commissioning of JT-60SA.

Acknowledgements

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