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Bangbang controller design and implementation for EAST vertical instability control

Yuehang Wang[a,*], Bingjia Xiao[b,a], Lei Liu[b], Qiping Yuan[b]

[a] University of Science and Technology of China, Hefei, China
[b] Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China

HIGHLIGHTS

- The linearized plasma vertical response model is designed and analysed.
- The Bangbang controller for EAST vertical displacement is designed.
- The Bangbang controller is optimized for time delay of control system.
- We investigate efficacy of Bangbang controller with simulations.
- Performance of the controller is roughly given by experiments.

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ABSTRACT

In the EAST 2014 campaign, a new internal coil (IC) power supply was used in order to enhance the control over the plasma's vertical instabilities. The IC power supply now allows for current and voltage working modes with much higher peak voltages and currents and faster response time. In comparison the previous power supply only allowed for the current mode. A Bangbang and PID composite controller has been designed for the voltage mode based on optimal control theory and the RZIP rigid plasma response model. This paper will demonstrate that faster and enhanced controllability are realized with the combination of Bangbang and PID controller. For the large z position drift, the Bangbang controller will export the maximum voltage to achieve much faster power supply response and slow the vertical displacement events (VDEs). The PID controller is used for the small z drifts which will finally stabilize the VDEs with minimum z position oscillation. Furthermore, to evaluate the time latency of this control system and power supply, the stability and performance of the closed loop were simulated and analysed. This controller was finally implementation and test on EAST using the Quasi-snowflake shape which achieved growth rates of 500 s^{-1}. This paper shows that the new power supply using the bangbang + PID controller can significantly enhance the control over vertical instabilities.

1. Introduction

Some advanced plasma configurations, such as the Quasi-snowflake shape, which have high growth rates of vertical instability, were implemented in the EAST 2014 experimental campaign. The growth rate of the EAST Quasi-snowflake equilibria is higher than 500 s^{-1}. The vertical instability controllability of older EAST vertical displacement control system is shown in Fig. 1, which is smaller than 1.2 cm with a growth rate higher than 200 s^{-1} [3]. However, the increasing vertical displacement growth rate increases the risk of the vertical displacement event [10,11]. So the vertical displacement control system is required to be upgraded for safe and robust control.

In 2014, the Internal Coil (IC) power supply system was upgraded. In Fig. 2 is a comparison between new IC power supply and old IC power supply which could only use a current control mode, the voltage mode of the new IC power supply has been able to respond much faster. The communication time of the vertical control system has been upgraded from 1.0 ms to 0.5 ms. And the current rising time in voltage mode from 0 to 5.4 kA is 0.6 ms whereas before when using the current mode the rise time was more than 1.0 ms. Finally, more active control schemes are now available with the upgrade of the IC power supply system.

The scheme of vertical instability control is important and extensively studied in the fusion community. A summary of the

* Corresponding author.
E-mail addresses: wagn8901@mail.ustc.edu.cn (Y. Wang), bjxiao@ipp.ac.cn (B. Xiao), liulei@ipp.ac.cn (L. Liu), qpyuan@ipp.ac.cn (Q. Yuan).

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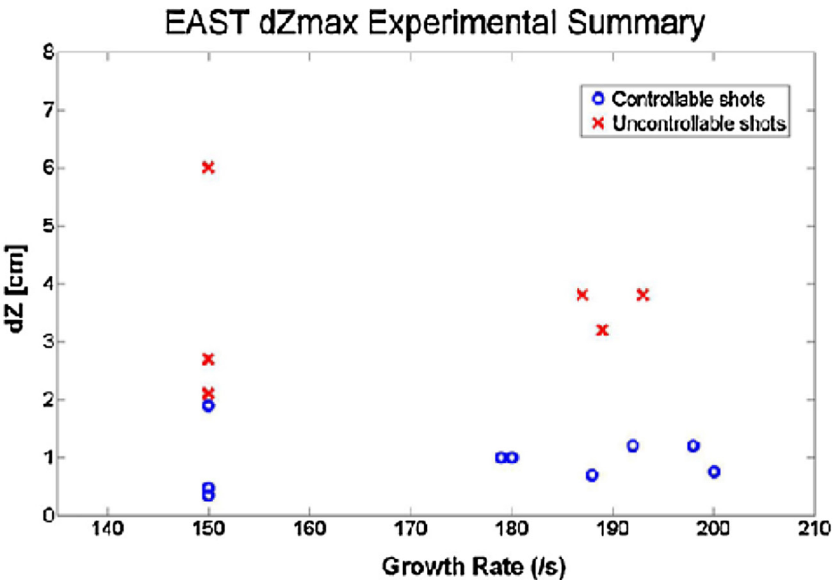

Fig. 1. Summary of EAST experiment measuring dZmax in 2012.

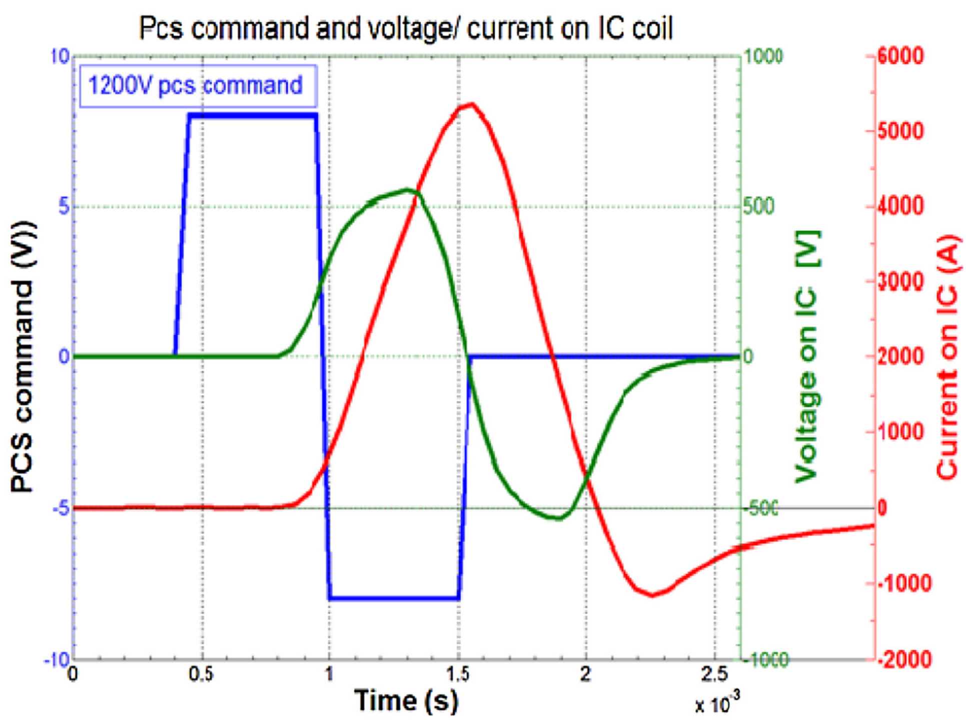

Fig. 2. IC voltage and current response for control command.

existing work with normal control method can be found in [4]. Some of the recent works begin to consider the saturation of coil currents and voltages. There were efforts to minimize the control demand for vertical control as in [5]. In [6,7] the authors have designed a new scheme of vertical control called the anti-windup controller to optimize the influence of saturation on the control system.

The goal of the Bangbang controller is to maximize the performance of the control system while subject to the constraints of the coil voltage saturation and the time delay of the control system in this paper. In Section 2, based on the plasma response model a time optimal controller for the ideal model was designed. Section 3 introduces the optimization results for the time delay of the control system. Section 4 shows the simulation results of the controller. Section 5 discusses the experimental results of the Bangbang controller. Finally, Section 6 presents the summary and conclusions.

2. Bangbang controller design with ideal model

2.1. Plasma model

The RZIP rigid plasma response model [2] has been widely used in tokamak plasma shape and displacement control. It can be expressed in the standard state-space model form.

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du \quad (1)$$

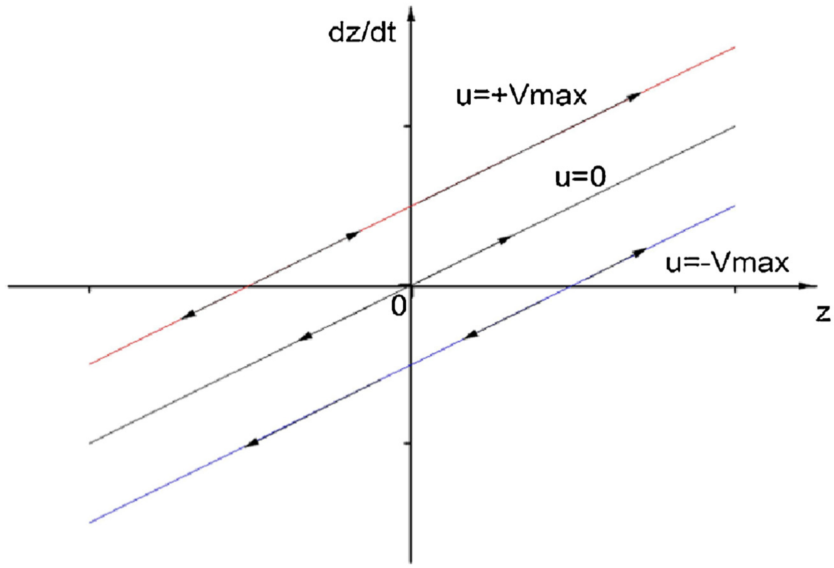

Fig. 3. system root locus in (z, dz/dt)space.

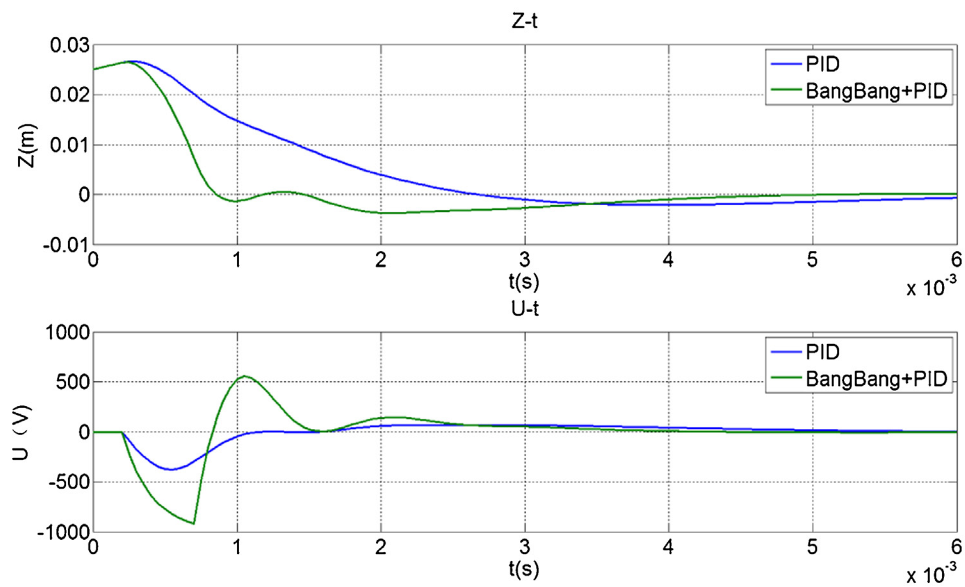

Fig. 4. compare Bangbang + PID control with PID control.

where the matrix D has always been ignored. The output vector y is used to describe the plasma model and thus the plasma response model can be given by

$$\dot{y} = CAC^{-1}y + CBu \tag{2}$$

Because the growth rate of the vertical displacement mode is much higher than other modes in this model [1,8], when we consider the vertical instability, the vertical displacement response can be given by

$$\dot{y}_z = \gamma_z y_z + CBu_{ic} \tag{3}$$

where the parameter γ_z is the maximum eigenvalue of the matrix, y_z is the eigenvector associated with γ_z.

2.2. Time optimal control

When considering the controller design for vertical displacement, the linearized plasma model can be given as

$$\dot{z} = \gamma_z z + CB_{ic}u_{ic} \tag{4}$$

With the initial states

$$z(t_0) = z_0 \tag{5}$$

considering the time optimal control, the time cost performance function

$$J = t_f - t_0 = \int_{t_0}^{t_f} dt \tag{6}$$

where t_0 and t_f are the start and final time of control. The Hamilton function of the system is given by

$$H(z, u, \lambda, t) = 1 + \lambda^T\{\gamma_z z(t) + CB_{ic}u(t)\} \tag{7}$$

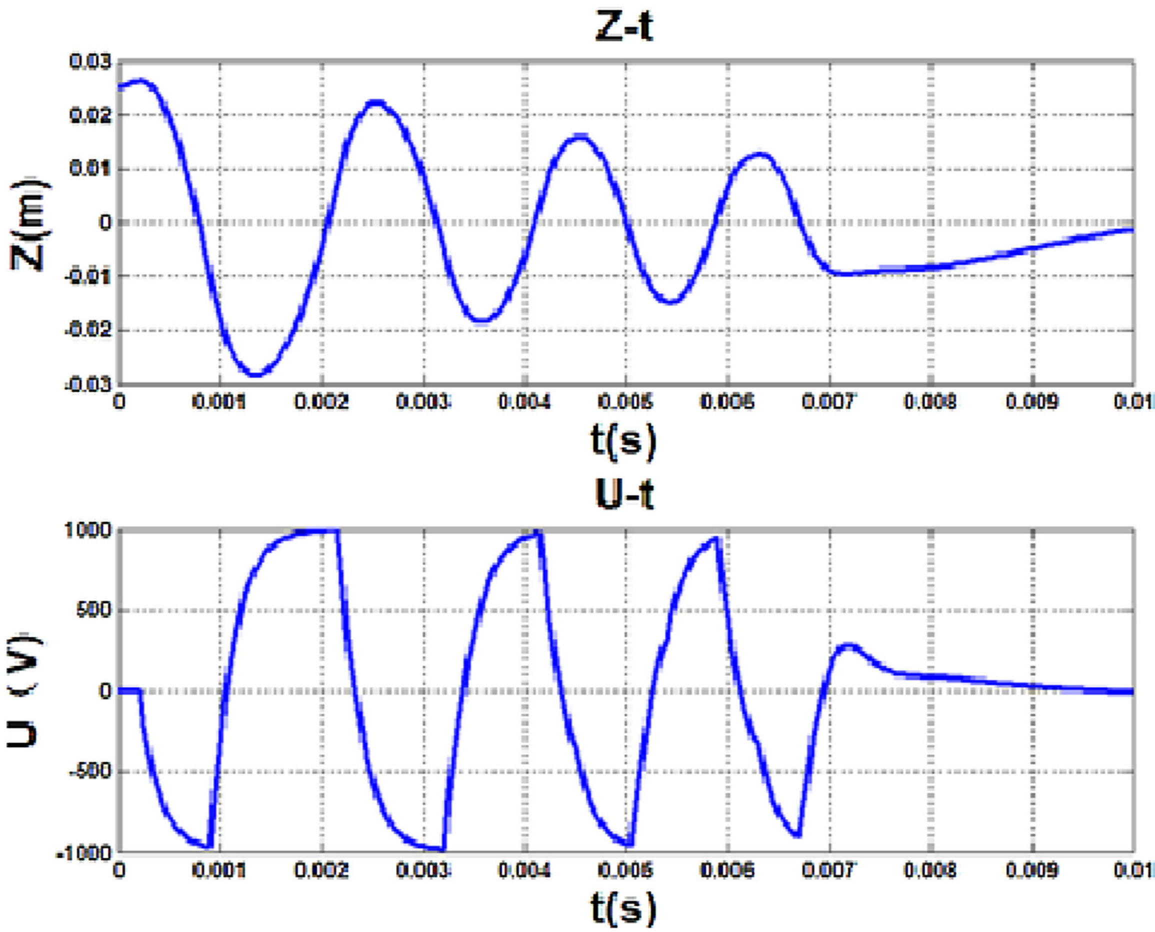

Fig. 5. The simulation result without optimal the controller for time delay(K = 0).

where λ is the covariant of system. Both u and λ for time optimal control should satisfy the Hamilton canonical equation, thus:

$$\dot{\lambda}^*(t) = -\frac{\partial H(z^*, u^*, \lambda^*, t)}{\partial z}$$
$$\dot{z}^*(t) = \frac{\partial H(z^*, u^*, \lambda^*, t)}{\partial \lambda} \quad (8)$$

And the output value of the controller is limited by the performance of the power supply

$$|u(t)| \le V_{\max} \quad (9)$$

where the parameter $V_{\max}$ is the maximum output voltage of the IC power supply. Using the minimization principle [12], the value of the Hamilton function with the time optimal control should at its minimum

$$1 + \lambda^{*T}[\gamma_z z^*(t) + CB_{ic}u^*(t)]$$
$$= \min_{|u(t)| \le V_{\max}}\{1 + \lambda^{*T}[\gamma_z z^*(t) + CB_{ic}u(t)]\} \quad (10)$$

This results in a relationship for the time optimal control

$$u^*(t) = -V_{\max} sgn\{CB_{ic}\lambda^*(t)\} \quad (11)$$

With this result, the output value of the optimal controller can be graphed as displayed in Fig. 3 without solving Hamilton canonical equation. The three lines in Fig. 3 each represent a different mode with its respective output value, and we can only choose these three output values if we want to get the time optimal control. When the mode of operation is in the upper half of the plane, the dz/dt will be positive and so the point will move right, and when it is in the lower half of the plane, the point will move left. The controllable region is between the upper line's y-intercept and the lower lines y-intercept. The stable position is the origin. There are three separate situations for optimal control: (1) z > 0, the control law should choose a negative value; (2) z = 0, the control law should choose the zero value; (3) z < 0, the control law should choose a positive value.

3. Optimization of the time delay

The time delay of the control system must also be considered for the EAST vertical displacement control system as it can cause a shock to the plasma around the target position. For a controller with time delay, the Bangbang controller and PID controller are combined and the optimal control law is given by

$$u(t) = \begin{cases} V_{\max} \ sgn(z) & \text{if } |z| > Z_{\lim} \\ K_p z + K_d \dfrac{dz}{dt} + \displaystyle\int K_i z dt & \text{if } |z| \le Z_{\lim} \end{cases} \quad (12)$$

where the parameter $Z_{\lim}$ is related to the time delay and the plasma response, it should be larger than the amplitude of the shock which can be approximated as

$$Z_{\lim} \sim BC_{ic} \ V_{\max} \ T_{ps} \sim 1cm \quad (13)$$

where the T_{ps} is the time delay of control system. Because of the time delay, large vertical displacement drfit will trigger a large over-shoot in Bangbang control system. In Eq. (14), Kdz/dt has been

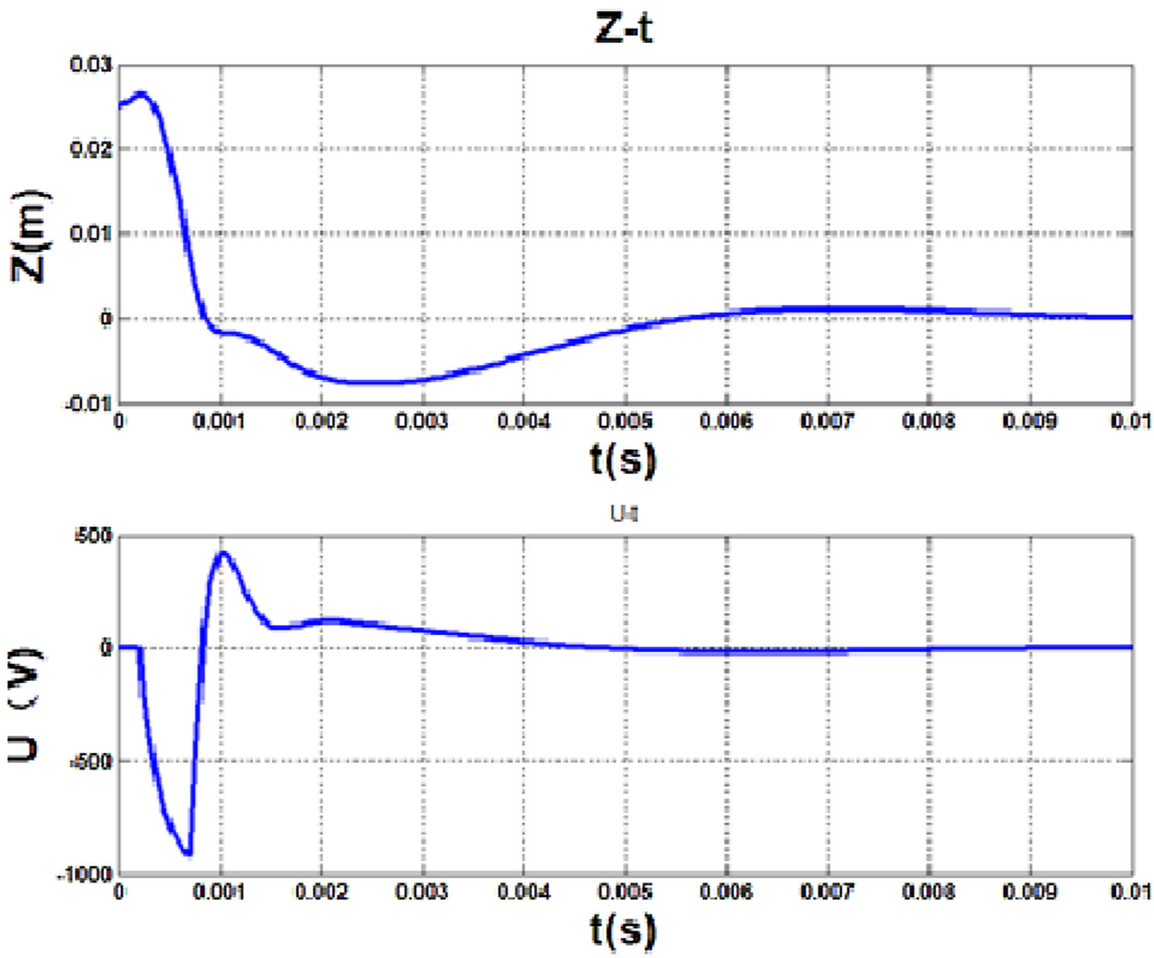

Fig. 6. The simulation result with optimal controller for time delay ($K = 1 - e^{\gamma_z T_{ps}}$).

used to optimize the over-shoot. The output value will be changed to

$$u(t) = \begin{cases} V_{\max}\ sgn\ (z + K\dfrac{dz}{dt}) & \text{if } |z| > Z_{\lim} \\ K_p z + K_d\dfrac{dz}{dt} + \displaystyle\int K_i z dt & \text{if } |z| \le Z_{\lim} \end{cases} \tag{14}$$

To minimize the over-shoot, a controller that acts as early as possible so that the z position will remain in the region that the PID controller can work. The vertical position can be valued with a constant controller output value.

$$z = Me^{\gamma_z t} - \frac{C_z B_{ic}}{\gamma_z} u_{ic} \tag{15}$$

The system states for the switching time of the Bangbang controller should satisfy the following equation and inequalities:

$$\begin{aligned} & z + K\dot{z} = 0 \\ & -Z_{\lim} < Me^{\gamma_z T_{ps}} - \frac{CB_{ic}}{\gamma_z} u_{ic} < Z_{\lim} \end{aligned} \tag{16}$$

Using this, it is possible to get the range of the parameter K

$$\begin{aligned} & \frac{-Z_{\lim} + \dfrac{CB_{ic}}{\gamma_z} u_{ic}(1 - e^{e^{\gamma_z T_{ps}}})}{-\gamma_z Z_{\lim} + CB_{ic} u_{ic}} < K \\ & < \frac{Z_{\lim} + \dfrac{CB_{ic}}{\gamma_z} u_{ic}(1 - e^{e^{\gamma_z T_{ps}}})}{\gamma_z Z_{\lim} + CB_{ic} u_{ic}} \end{aligned} \tag{17}$$

In particular, it is possible to find the critical K value that can make the z position come to the original plant when the switching output is activated. To let the $Z_{\lim}$ in Eq. (17) equals 0, we can get the critical value of K

$$K = 1 - e^{\gamma_z T_{ps}} \tag{18}$$

4. Simulation results

To examine the controller, the RZIP model was used to simulate the response of the controller. In the simulation, the effect of the current command changing on the poloidal field (PF) coil was ignored because the time scale of the PF coil is much longer than the time scale of the VDE [9].

Fig. 4 shows the performance of the Bangbang controller and PID controller. The simulation result shows that the larger $Z_{\lim}$ that was chosen is correct, and the Bangbang controller can stabilize the system faster than the PID controller.

Figs. 5 and 6 shows that the different values of K will bring the vertical displacement to a different response. The critical value of K is important to stable the system.

5. Experimental

Shot 52444 (Fig. 7) is the discharge which uses the combination of the Bangbang and PID controllers to recover the vertical position. The VDE is triggered by 500 V with 4 ms duration IC voltage at 4.4 s. When the z displacement is larger than 1 cm, the Bangbang controller is activated and outputs the maximum voltage. When the

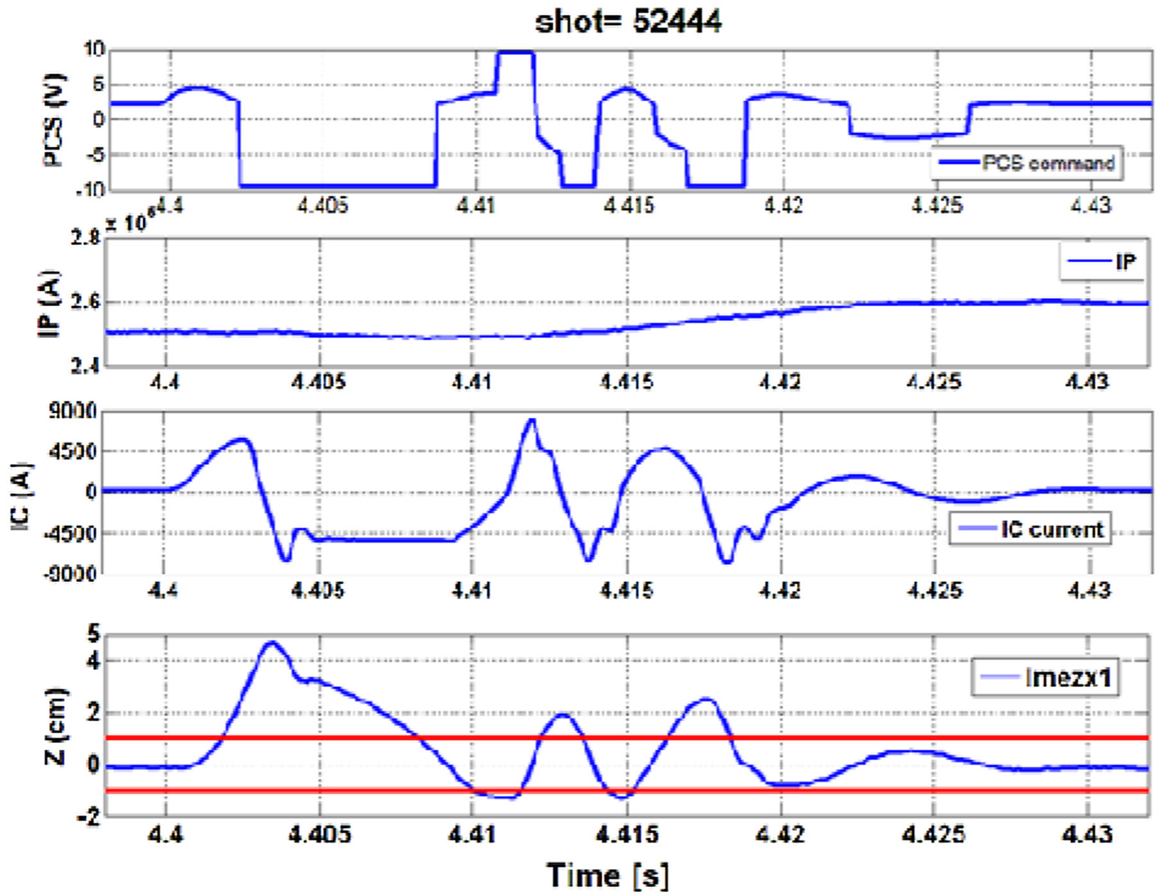

Fig. 7. Experiment result of Bangbang controller, the VDE growth rate is about 530/s.

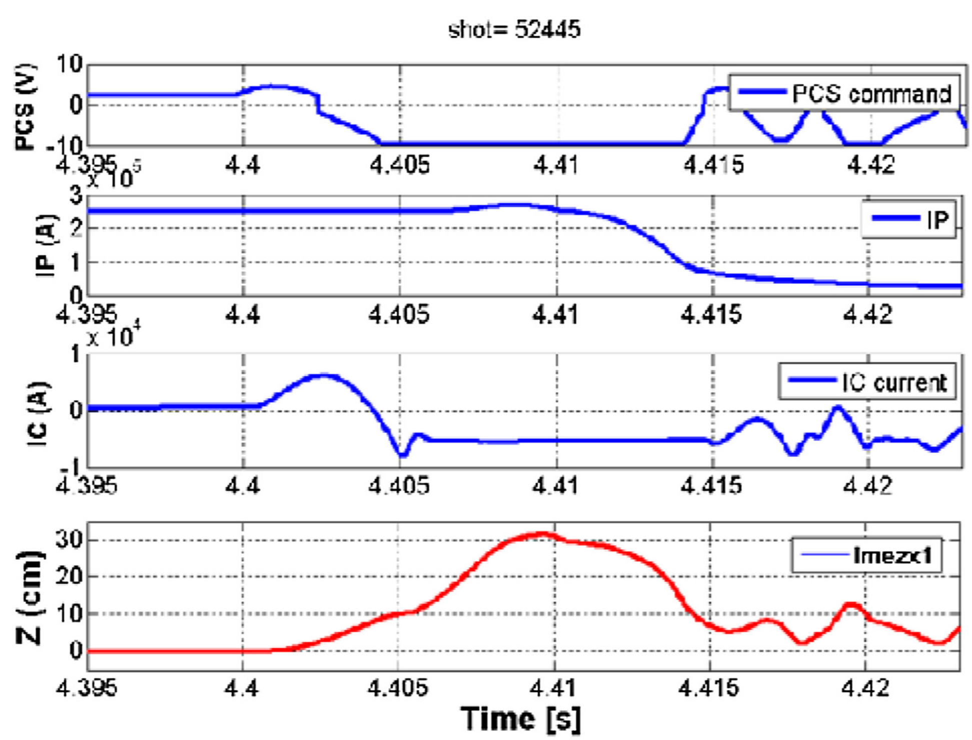

Fig. 8. comparison shot that only using PID controller, the VDE growth rate is about 530/s.

displacement is smaller than 1 cm, the controller switches to the PID control. This shot shows that the combination of the Bangbang and PID controller can successfully recover the vertical position from a vertical drift of 4.6 cm. This result is much larger than the maximum controllable vertical drift recovery (ΔZ_{max} = 1.2 cm) of the PID controller under IC current mode in the 2012 campaign [3]. As a comparison, shot 52445 repeats shot 52444, but uses the PID controller under IC voltage mode to recover the vertical drift and consequently lost control of the vertical position, as shown in Fig. 8.

In routine EAST experimentation, the vertical center of the plasma current (Z_c) is estimated via a large number of magnetic sensors, i.e. lmsz signal, and the dz/dt is given by the difference of lmsz, which has a large noise ratio. A method to directly calculate the value of the time derivative of Zc is necessary because the noise ratio found in dz/dt is large. The method [13] which calculates the dz/dt by loop voltage signals was developed for EAST.

6. Summary and conclusions

The scheme of the IC control system is very important for the EAST vertical instability control. In this paper, a time optimal controller called the Bangbang controller for the EAST vertical instability control has been designed and optimized. The simulation and experimental results demonstrate that the Bangbang controller has been very effective in guaranteeing stability of plasma vertical displacement. The maximum controllable vertical displacement has been improved to 4.6 cm. There will be more experiments showing the ΔZ_{max} in future EAST campaigns.

Acknowledgments

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