Modeling control of diverted plasma of the T-15 tokamak

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1. Introduction

Presented work is associated with the development of magnetic plasma control system of modernized at the moment T-15 tokamak [1]. This system is designed to maintain given plasma current, its shape and position throughout the entire discharge scenario. For this purpose, poloidal magnetic field coils with power supplies are used. Fig. 1 shows the basic coils 1-9, the coil 10 to stabilize the vertical plasma instability, and passive stabilization system in T-15 tokamak. The simulations of the control object and control verification were carried out on a nonlinear numerical model realized in the DINA code [2]. Modern methods of regulators developing require a linear model of the control object. Using the identification method [3], linear models were obtained for several moments of the discharge scenario, in which the dynamic characteristics of the plasma differ substantially. For each of the models regulators are constructed to be applied at the appropriate stages of the discharge scenario. That is discussed in section 2 of the paper. The control system should ensure both high efficiency of changing the values of the controlled parameters if needed, and resistance to perturbations in the plasma. Simulations results of shape and position control of T-15 diverted plasma disturbed by poloidal beta drop are shown in section 3 and respectively control of X-point are presented in section 4.

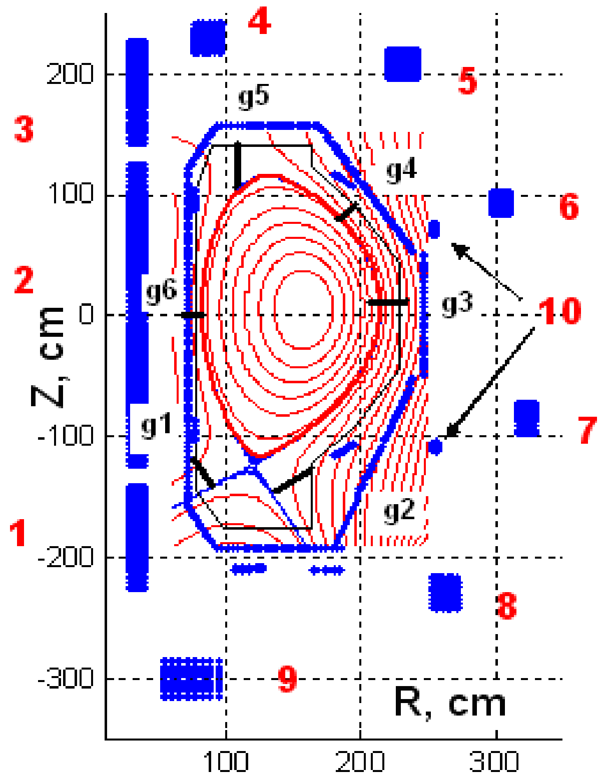

Fig. 1. Poloidal field system of T-15 and g1-g6 gaps between plasma and first wall

2. Synthesis of the regulators

Control of the shape and position of the plasma is carried out by maintaining 6 gaps between the plasma and the first wall (black lines g1-g6 in Fig. 1). For several moments of the discharge scenario, using the identification method [3], the linearized equations of the dynamics of the controlled plasma parameters are obtained in the form:

$$\begin{cases} \dot{\mathbf{x}}(t) = A\mathbf{x}(t) + B\mathbf{u}(t) \\ \mathbf{y}(t) = C\mathbf{x}(t) + D\mathbf{u}(t) \end{cases} \quad (1)$$

Here A, B, C, D are the matrixes that completely define the linear model, **x**(t) is the internal state vector, **y**(t) is the vector with measured parameters (plasma current, gaps between plasma and first wall, currents in PFCs), **u**(t) is the vector with voltages in PFCs. The eigenvalues of matrix A reflect the dynamic characteristics of the control object. For a quasi-stationary discharge stage, A has a positive eigenvalue corresponding to a vertical instability with a time about 15 ms.

To construct regulators, the method of linear-quadratic control is used, in which the control actions are calculated by the formula $\mathbf{u} = -K\mathbf{x}$. Matrix K is selected to minimize the functional $J = \int_0^{+\infty} \left(\mathbf{x}^{\mathrm{T}} Q\mathbf{x} + \mathbf{u}^{\mathrm{T}} R\mathbf{u} + 2\mathbf{x}^{\mathrm{T}} N\mathbf{u}\right) dt$. Using the matrices Q, R, N, the dynamic of the transient processes in a closed loop is tuned. During the calculation of the discharge scenario, the regulator operates, which is constructed according to a linear model corresponding to the current plasma equilibrium. To estimate the characteristics of the control system, below we show the effect of some perturbations of the T-15 plasma simulated for 1 MA scenario.

3. Impact of the β_p plasma disturbances

The main possible plasma disturbance to which the magnetic control system must keep the plasma current, position and shape is the sudden fall of beta poloidal β_p. This kind of disturbance is most likely while tokamak operation and is often used to evaluate the operation of control systems [4].

We show the simulation of the control system operation in result

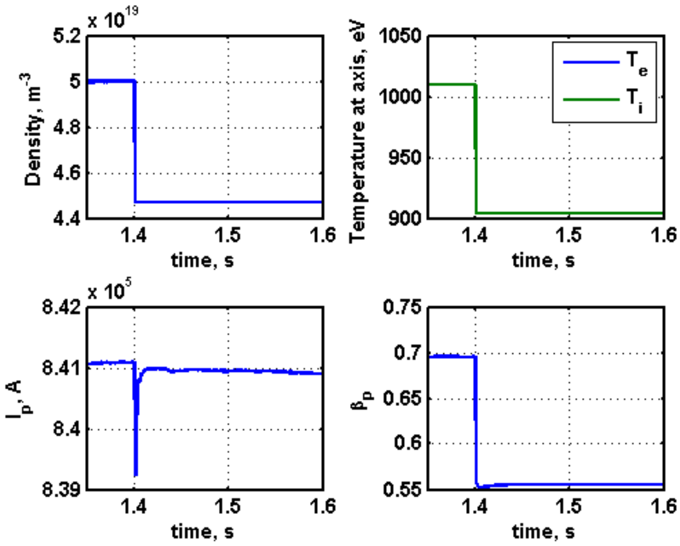

Fig. 2. Evolution of plasma parameters in the simulation of poloidal beta drop perturbation

of quasistationary stage of the discharge with instantaneous drop of β_p by ~0.15. The fall in β_p is achieved by the decrease of the profiles of the plasma temperature and density (Fig. 2). Fig. 3 shows the time evolutions of deviations of the gaps values from the references during β_p drop. One can see that the deviations of the gap values do not exceed ~1.5 cm and stabilize during ~50 ms, which indicates the good quality of the constructed control system.

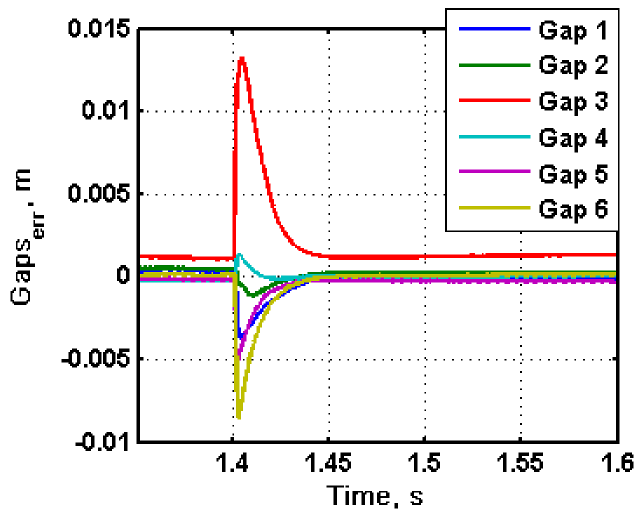

Fig. 3. Evolution of the plasma gaps in the simulation of β_p drop perturbation

4. Control of X-point

For tokamak-reactors, an important problem is the large value of thermal load on the divertor. A possible way to distribute the thermal load more evenly along divertor plates is the continuous periodic movement of the X point [5], which provides the movement of strike points also called "sweeping". The developed controller allows to do this by controlling the evolution of gaps g1 and g2, as well as to estimate the available parameters of such motion. To show this, in the quasi-stationary stage of the plasma discharge, the deviations of the gaps g1 and g2

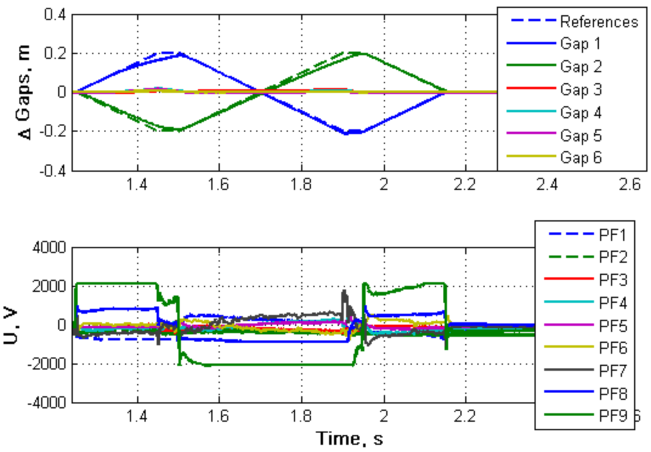

Fig. 4. Plasma gaps and voltages while periodic motion of the X-point with an amplitude of gaps g1 and g2 equals 20 cm

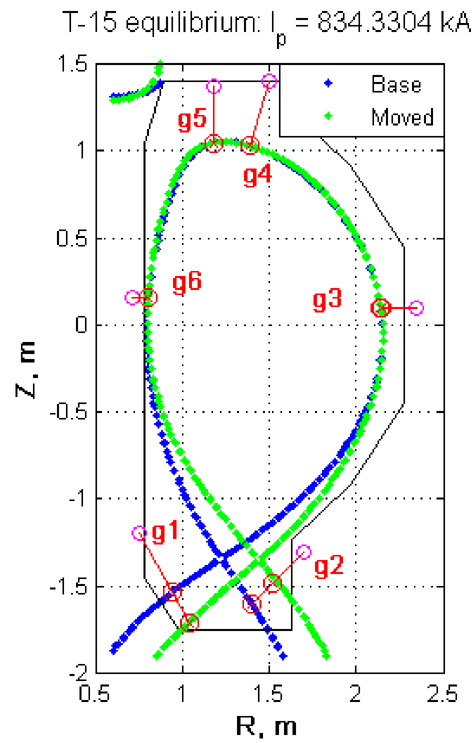

Fig. 5. The plasma separatrix while periodic motion of the X-point with an amplitude of gaps g1 and g2 equals 20 cm

were modeled, and the minimum time during which the desired deviation can be reached was estimated.

Fig. 4 shows the time traces of gaps and voltages in poloidal field coils for case when the amplitude of the gaps change is 20 cm. In the Fig. 5 the separatrix of the plasma is shown at both initial position and at the moment of maximum deviation. One can see that during 150 ms the 20 cm deviations of the gaps g1 and g2 can be achieved. This corresponds to moving of X-point in the horizontal direction by around 25 cm.

The speed limit of gaps g1 and g2 displacement is related to the saturation of the voltages of coils 8 and 9, which are placed closest to the X-point (Fig. 4).

5. Conclusions

Using the plasma-physical code DINA, linear models of the behavior of T-15 plasma were obtained for divertor phase of 1 MA scenario. These linear models are used to construct regulators, which provide the magnetic control of plasma current, position and shape during plasma scenario. DINA modeling results of plasma evolution in the presence of perturbations are shown. Satisfactory operation of the control system for the β_p drop perturbation is demonstrated. Deviations of the gap values do not exceed ~1.5 cm, which stabilize during ~50 ms. Beside the efficiency of the control of separatrix in the T-15 divertor area is demonstrated. It is shown that the 20 cm deviations of the gaps g1 and g2 can be achieved during 150 ms, which is limited by saturation of the power supplies voltages of poloidal field coils 8 and 9.

Acknowledgments.

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