§12. Multi-Input Multi-Output (MIMO) Control System for the Fusion Reactor with the State Equation

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1. Introduction

In the operation of the fusion reactor, many plasma parameters have to be controlled simultaneously. While, we should pay attention that actuators and diagnostics which can be installed into the reactor will be limited because of the high heat flux and the neutron flux. In addition, each actuator and each parameter are not one to one corresponding. For example, the NBI can control not only the fusion power but also the plasma current. To design the control system of the Demo or the commercial reactors, these problems have to be taken into consideration. To address these problems, we should consider what parameters should be controlled, what actuators and diagnostics can be installed, and what control logic should be applied. These issues are interlinked, as shown in Fig. 1.

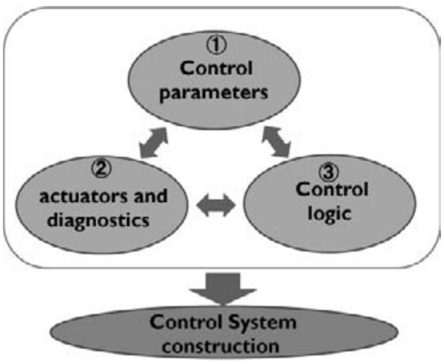

Fig. 1. The concept of the fusion reactor control system.

In this research, we focus on the construction of the control logic. The system that multiple parameters are controlled by multiple actuators, is called MIMO (Multi-Input Multi-Output) system. To design the MIMO system controller, introduction of the state equation is familiar method [1].

2. The state equation

The state equation expresses the physical model of the system. In this case, we use the zero-dimensional equations given by eqs. (1) and (2). For future, the profile control will be needed and the state equation for the profile control will have to be constructed, but control logic developed here might be applicable for the profile control.

The equation (1) expresses the time evolution of the plasma current I, the amount of the plasma particle N and the total plasma energy W, where actuators I_{ind}, N_{puff} and P_{NBI} are the induced current, the gas-puff, NBI, respectively. The equation (2) expresses the control parameters, where I, P_{fus} and n_e are the plasma current, the fusion power and the plasma density, respectively.

$$\frac{d}{dt}\begin{pmatrix} I \\ N \\ W \end{pmatrix} = \begin{pmatrix} -\frac{I}{\tau_j}+\frac{1}{\tau_j}\left(C_{bs}\varepsilon^{0.5}\beta_p I+\frac{\gamma}{n_{20}R}P_{NBI}\right)+\dot{I}_{ind} \\ -\frac{N}{\tau_p}-\frac{n^2}{2}<\sigma v>V+N_{puff} \\ -\frac{W}{\tau_e}+\frac{E_\alpha}{4}n^2<\sigma v>V-C_B n_{20}^2 T_{10}^{1/2}V+P_{NBI} \end{pmatrix} \quad (1)$$

$$\begin{pmatrix} I \\ P_{fus} \\ n_e \end{pmatrix} = \begin{pmatrix} I \\ \frac{E_\alpha N^2}{V}<\sigma v> \\ \frac{N}{V} \end{pmatrix}. \quad (2)$$

The deviation from the equilibrium condition of eqs. (1)-(2) is considered, by the linearization of these state equations, and we can summarize the equation for the perturbation as follows;

$$\frac{d}{dt}\Delta\boldsymbol{x} = \boldsymbol{A}\Delta\boldsymbol{x}+\boldsymbol{B}\Delta\boldsymbol{u} \quad (3)$$

$$\Delta\boldsymbol{y} = \boldsymbol{C}\Delta\boldsymbol{x} \quad , \quad (4)$$

where $\boldsymbol{x}$ is the I, N and W, $\boldsymbol{u}$ is the I_{ind}, N_{puff} and P_{NBI} and $\boldsymbol{y}$ is the I, P_{fus} and n_e , respectively, and Δ denots the deviation from the equilibrium value.

Next, we assume that $\Delta\boldsymbol{y}$ is required to decrease exponentially, as follows;

$$\frac{d}{dt}\Delta\boldsymbol{y} = -\boldsymbol{K}\Delta\boldsymbol{y} \quad , \quad (5)$$

By using eqs. (3)-(5), we can design the controller.

At first, we designed the multiple PID controller from the state equation, and demonstrate the plasma control simulation with eq (1). The typical result is shown in Fig. 2.

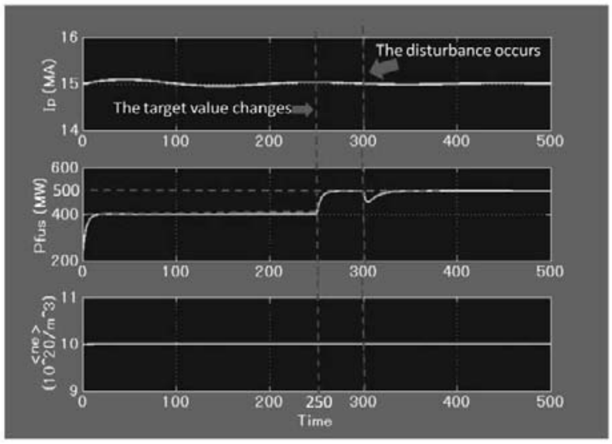

Fig. 2. The time evaluation of the plasma current I_p, the fusion power P_{fus} and the plasma electron density $< n_e >$. I_p and $< n_e >$ is kept in the constant target value. P_{fus} follows the target value from 400MW to 500MW at 250sec and is recovered from the disturbance at 300sec.

[1] Graham C. Goodwin *et al.*, *Control System Design* (Prentice Hall, 2000).