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Stability Region Evaluation of Control Inputs by Fuzzy-Type Lyapunov Function for Nonlinear Control System

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ABSTRACT: Electric Power system is a large scale nonlinear control one. Therefore, nonlinear control is desirable for the stabilizing, and it is thought that to establish an analytical method for optimal control inputs of AVR (automatic voltage regulator) and GOV (governor) is an important subject.

In this paper, as a simple case, one-machine infinite-bus electric power model system with GOV is treated under the three kinds of control inputs; (i) fuzzy control input, (ii) linear control input and (iii) no control input. Next, the stability for each case is analyzed, and the three-dimensional stability regions and the control responses are evaluated and compared. Finally, it is concluded that the linear control input does not necessarily give a good region and response, and the fuzzy one is better than others.

1. INTRODUCTION

Nonlinear control[1] is desirable for stabilizing electric power system[2], because the system is a large scale nonlinear control one. Recent years, the technology of intelligent system has been especially developed, and the application[6]-[10] of nonlinear control has already begun to electric power system. For example, the study of applying fuzzy control[3]-[5] to electric power system has been advanced. In particular, the stability analysis for determining fuzzy control inputs is an important subject.

On the other hand, the method, in which the control input is added to a nonlinear system and the system can be strictly transformed into a linear one, has been applied to robotics[11],[12] and electric power systems[13]. The method[14],[15] proposed by the authors is as follows: For the stability analysis of nonlinear system, first the original system is rewritten to a fuzzy system, and next the fuzzy-type Lyapunov function is constructed for the analysis as shown in Fig.1. Also, we have proposed a fuzzy decentralized control[16] for applying the method to multi-machine electric power system. In the study, we identify decentralized systems by the identical model equation on the basis of one-machine infinite-bus electric power system at each generator bus. Namely, every decentralized system corresponds to the nonlinear control system in Fig. 1 and the stability is analyzed through the fuzzy system.

The authors have applied a fuzzy-type Lyapunov function to the stability analysis and the stability region evaluation of one-machine infinite-bus electric power model system with GOV, and have reported[14],[15] on the availability. In this paper, the model system is treated[17],[18] under the following three kinds of control inputs in GOV; (i) fuzzy control input, (ii) linear control input and (iii) no control input, and the three-dimensional stability regions and the control responses are compared and evaluated. The linear control input does not necessarily give a good region and a good response, and the fuzzy one is better than others. Finally, it is concluded that the quality of linear and nonlinear control inputs can be evaluated by the fuzzy-type Lyapunov function for the model system from the standpoint of stability analysis.

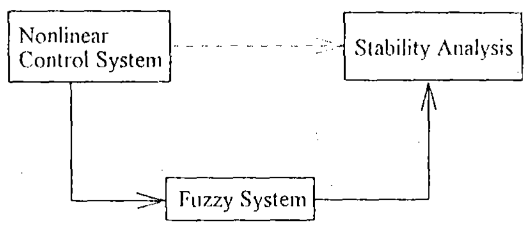


Fig.1. Concept of the proposed method.

2. FUZZY SYSTEM OF MODEL SYSTEM[14],[15]

In one-machine infinite-bus electric power model system (Fig.2), the GOV system is expressed by the first order approximation of the turbine, and then the following swing equations are obtained;

$$\frac{dx_1}{dt} = x_2, \tag{1}$$

$$\frac{dx_2}{dt} = \frac{1}{M}\{-Dx_2 + x_3 + Pm_0 - Pe(x_1)\}, \tag{2}$$

$$\frac{dx_3}{dt} = -\frac{1}{Tg}\left\{x_3 + \left(\frac{Kg}{\omega_0}\right)x_2\right\} + \frac{u_g}{Tg}, \tag{3}$$

$$Pe(x_1) = \frac{E'qV_\infty}{x_{12} + x'_d}\sin(x_1 + \delta_s) \quad , \tag{4}$$

where

$$X = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta Pm \end{bmatrix} = \begin{bmatrix} \delta - \delta_s \\ \omega - \omega_0 \\ Pm - Pm_0 \end{bmatrix}, \tag{5}$$

here

- M : inertia constant (sec²/rad),
- D : damping coefficient (sec/rad),
- δ : rotor phase angle of generator (rad),
- ω : rotor speed of generator (rad/sec),
- x'_d : d-axis transient reactance (pu),
- Pm : mechanical power input (pu),
- Pe : electrical power input (pu),
- Tg : GOV time constant (sec),
- Kg : GOV gain,
- u_g : control input for GOV (pu),
- x_e : line reactance (pu),
- x_t : transformer reactance (pu),
- x_{12} : total reactance between generator and infinite-bus (pu),
- V_∞ : infinite bus voltage (pu),

here, the sub-symbols "o" and "s" denote the value at the desired equilibrium point "before" and "after" clearing the fault, and $Pm_0 = 0.636(pu)$ and $\delta_s = 0.828(rad)$.

Next, for rewriting eqs. (1)-(4), we introduce two linear subsystems $S_i(x_1) = k_i x_1 + Pm_0, (i = 1,2)$ for the nonlinear function $Pe(x_1)$ of eq. (4). Then the membership function (weight function) $w_i(x_1)$, which is necessary to compose the fuzzy system, is expressed by;

$$w_1(x_1) = \pm\{Pe(x_1) - S_2(x_1)\}, \tag{6}$$

$$w_2(x_1) = \pm\{S_1(x_1) - Pe(x_1)\}, \tag{7}$$

the sign + in the decode is for $x_1 \geq 0$, and the sign − for where $x_1 < 0$. Therefore, $Pe(x_1)$ is given without trial and error and approximation as;

$$Pe(x_1) = \left\{\sum_{i=1}^{2} w_i(x_1)k_i \Big/ \sum_{i=1}^{2} w_i(x_1)\right\}x_1 + Pm_0. \tag{8}$$

Moreover, we treat a fuzzy control input u_g as the supplementary control input for GOV ;

$$u_g = -\left\{\sum_{i=1}^{2} w_i(x_1)F_i \Big/ \sum_{i=1}^{2} w_i(x_1)\right\}X, \tag{9}$$

$$X = [x_1 \;\; x_2 \;\; x_3]^T, \tag{10}$$

$$F_i = [f_{i1} \quad f_{i2} \quad f_{i3}], (i = 1,2). \tag{11}$$

Then, we substitute eqs. (8) and (9) for eqs. (1)-(4), and have the fuzzy system;

$$\dot{X} = \left\{\sum_{i=1}^{2} w_i(x_1)A_i \Big/ \sum_{i=1}^{2} w_i(x_1)\right\}X, \tag{12}$$

where the fuzzy system matrix A_i is given as ;

$$A_i = \begin{bmatrix} 0 & 1 & 0 \\ -k_i/M & -D/M & 1/M \\ -f_{i1}/Tg & -(-Kg/\omega_0 + f_{i2})/Tg & -(1 + f_{i3})/Tg \end{bmatrix}. \tag{13}$$

Here, we need

$$w_i(x_1) \geq 0 \text{ and } \sum_{i=1}^{2} w_i(x_1) > 0, \tag{14}$$

and the stability analysis is possible in the interval of x_1 satisfying the above condition. Also, it should be noted that the interval becomes a restriction for the three-dimensional stability region to be discussed later.

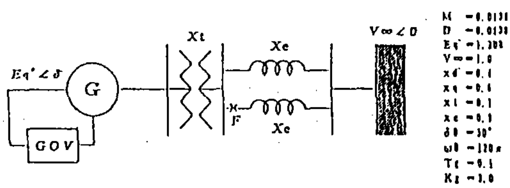


Fig.2. Model system.

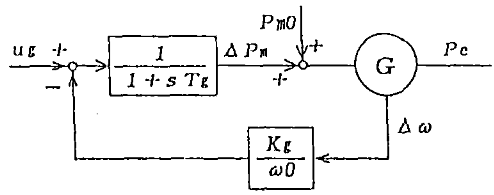


Fig.3. GOV block diagram.

3. COMPARISON OF SUPPLEMENTARY CONTROL INPUTS FOR GOV

For composing a fuzzy-type Lyapunov function for the fuzzy system(12), we select the second order test function;

$$V(X(t)) = X^T(t) P X(t). \tag{15}$$

From $\dot{V} < 0$ and the condition(14), we have the Lyapunov inequality as

$$A_i^T P + P A_i = -Q_i < 0, Q_i > 0, (i = 1,2). \tag{16}$$

The positive definite matrix P can be calculated by the P-region method. If a P exists, eq. (15) gives a fuzzy-type Lyapunov function, and swing eqs. (1)-(4) are asymptotically stable in the restriction of x_1 explained before.

We treat the fuzzy control input u_g as given by eq. (9), and compare three kinds of control inputs as;

Case 1) We treat the case $(F_1 \neq F_2)$ that the fuzzy control input (9) is added as a nonlinear control one;

$$u_{g1} = -\left\{\sum_{i=1}^{2} w_i(x_1) F_i \Big/ \sum_{i=1}^{2} w_i(x_1)\right\} X, (F_1 \neq F_2). \tag{17}$$

Case 2) In case of $F_1 = F_2 (= F)$, u_g is a linear control input;

$$u_{g2} = -FX. \tag{18}$$

Case 3) For $F_1 = F_2 = 0$, ug has no control input;

$$u_{g3} = 0. \tag{19}$$

We want to consider the quality of each control on the stability region and the control response in the following. First, the values of the feedback gain F_i, which are obtained by the P-region method (see details in Reference (15)), in Case 1)-3) are

Case 1) $F_1 = [0.135 \quad 0.11 \quad 2.16]$
$F_2 = [0.01 \quad 0.75 \quad 1.0]$

Case 2-a) $F_a = [0.035 \quad 0.18 \quad 2.16]$

Case 2-b) $F_b = [-0.291 \quad 0.2536 \quad 1.1644]$

Case 3) $F_1 = F_2 = [0 \quad 0 \quad 0]$

Here, we select two examples F_a and F_b in case 2). Next, the P-region for Case 1)-3) are shown in Fig.4. The $P^{(1)}$-region or the $P^{(2)}$-region in Fig. 4 is a set satisfying the Lyapunov inequality $A_1^T P + P A_1 < 0$ or $A_2^T P + P A_2 < 0$, respectively. Therefore, since the common matrix P exists, the stability of eqs. 1)-4) is guaranteed. Under this condition, P of eq.(16) can be described as

$$P = \begin{bmatrix} p_1 & p_2 & \pm 1 \\ p_2 & p_3 & p_4 \\ \pm 1 & p_4 & p_5 \end{bmatrix}, \tag{20}$$

without losing generality, and the fuzzy-type Lyapunov function is given by

$$\begin{aligned} V(x_1, x_2, x_3) &= x^T P x \\ &= p_1 x_1^2 + 2 p_2 x_1 x_2 \pm 2 x_1 x_3 + p_3 x_2^2 \\ &\quad + 2 p_4 x_2 x_3 + p_5 x_3^2 \\ &= Vc, \end{aligned} \tag{21}$$

where the threshold value Vc is a constant determined as the three-dimensional stability region by eq. (21) dose not exceed the restriction of x_1.

As shown in Fig. 4, since the P-region for Case 1)-3) exists, P can be composed by selecting any point in the P-region. For example, each P which can be composed at the point × in the P-region is;

$$P_{1)} = \begin{bmatrix} 50 & 2.9 & -1 \\ 2.9 & 1.8 & 3.4 \\ -1 & 3.4 & 35.2 \end{bmatrix}, \quad Vc = 71.3, \tag{22}$$

$$P_{2-a)} = \begin{bmatrix} 2.15 & 0.18 & -1 \\ 0.18 & 0.16 & 1.4 \\ -1 & 1.4 & 22.5 \end{bmatrix}, \quad Vc = 3.0, \tag{23}$$

$$P_{2-b)} = \begin{bmatrix} 0.9 & -0.036 & -1 \\ -0.036 & 0.094 & 0.6 \\ -1 & 0.6 & 7.11 \end{bmatrix}, \quad Vc = 0.49, \tag{24}$$

$$P_{3)} = \begin{bmatrix} 14.7 & 0.4 & -1 \\ 0.4 & 0.45 & 3.7 \\ -1 & 3.7 & 200.77 \end{bmatrix}, \quad Vc = 5.0. \tag{25}$$

The three-dimensional stability region is shown in Fig.5. Clearly, the fuzzy control input is better than others. The linear control input Case 2-a) is better than Case 3), but Case 2-b) seems not to be better. Each control response is shown in Fig.6. Also the fuzzy control input Case 1) gives the longest critical clearing time. It is found that linear control inputs Case 2-a) and 2-b) do not necessarily have a good stability region and a good control response.

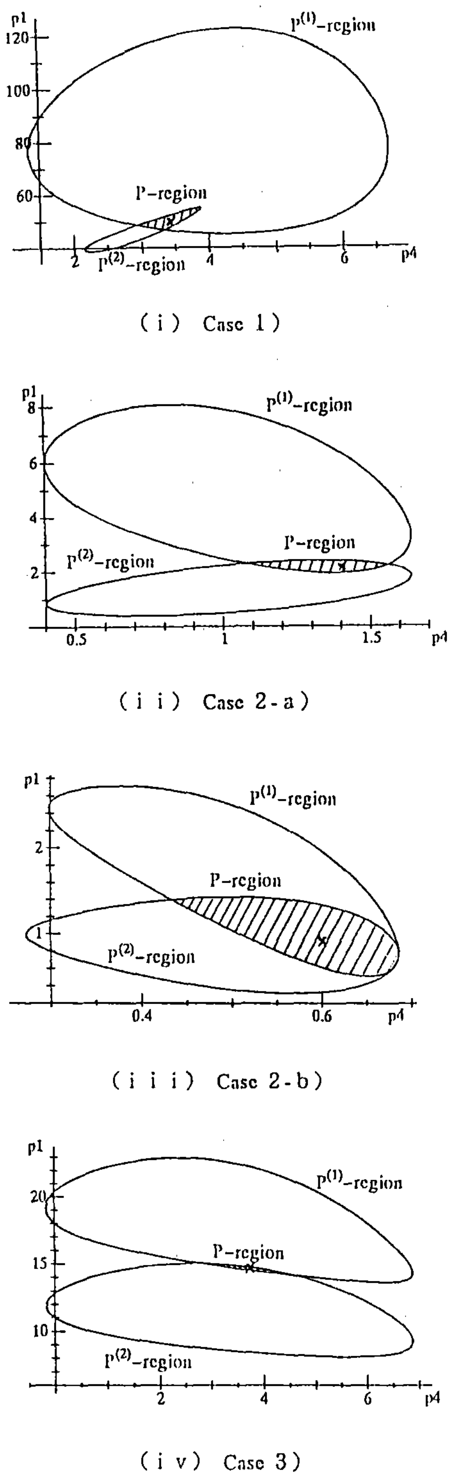


Fig.4. P-region (shaded).

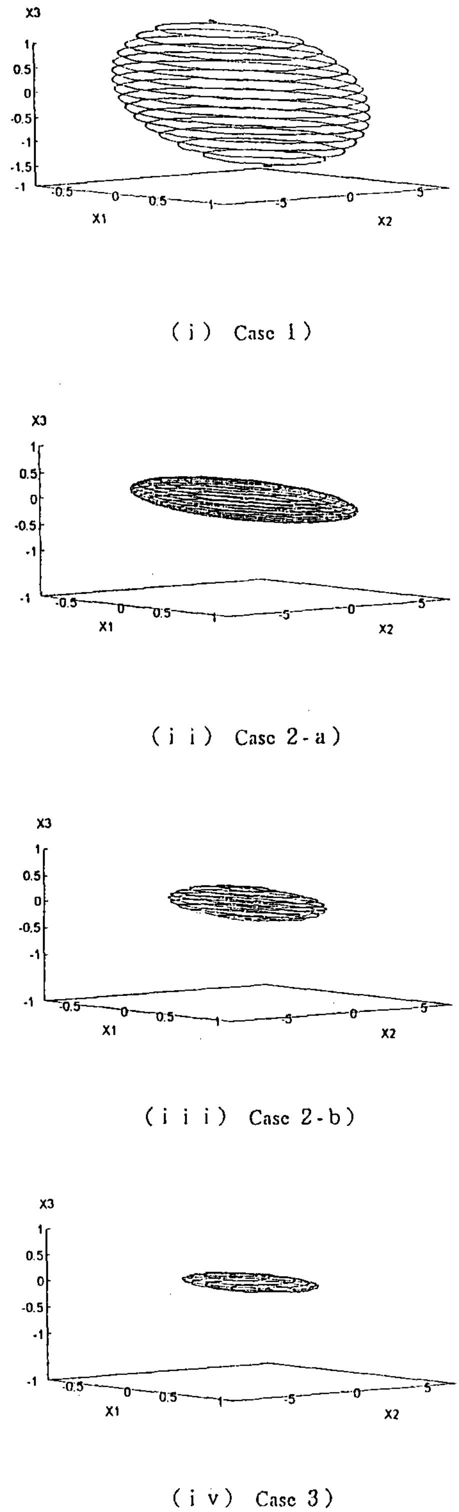
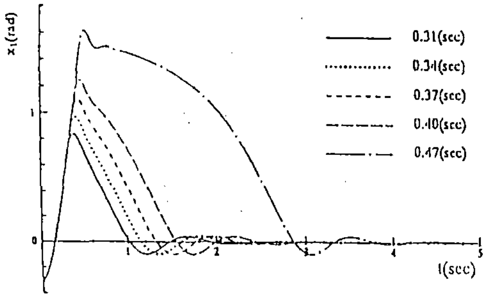
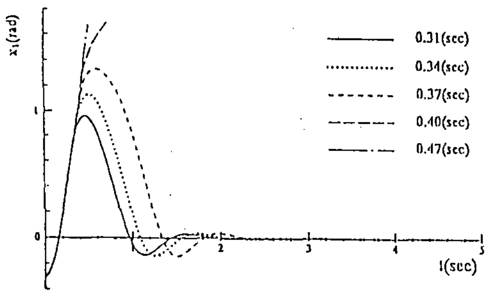


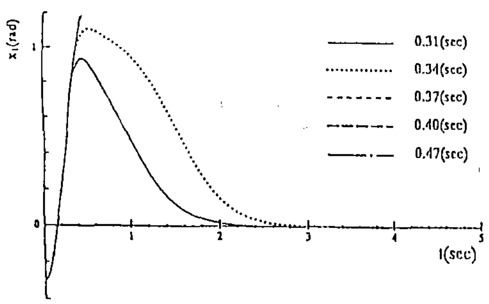
Fig.5. Three-dimensional stability region.



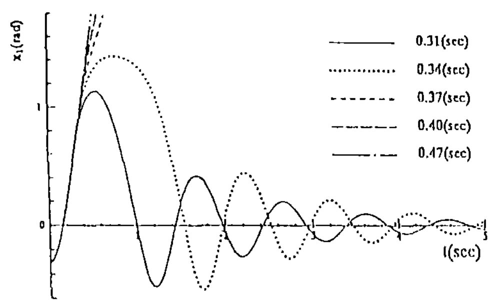
(i) Case 1)



(i i) Case 2 - a)



(i i i) Case 2 - b)



(i v) Case 3)

Fig.6. Control response.

4. CONCLUSIONS

In this paper, we have rewritten the model system (Fig. 2) to the fuzzy system (12), and have evaluated the three-dimensional stability regions (Fig. 5) by constructing the fuzzy-type Lyapunov function. In the evaluation, the P-regions, the stability regions and the control responses (Fig. 6) are compared for the three kinds of control inputs in GOV, and the result can be summarized as follows;

1) The fuzzy control input is better than others.
2) The linear control input does not necessarily give a good stability region and a good control response.

Thus, it is found that the quality of the control inputs can be evaluated without approximation by the fuzzy-type Lyapunov function in the model system treated as a nonlinear control system.

The authors have pointed out that the analysis based on one-machine infinite-bus model system is important in an application of the proposed method to the fuzzy decentralized control. Therefore, this paper will become an analytical index for the problem to select the control input in GOV. As indicated in the conclusions of the previous paper (17), we would like to consider other future subjects toward the application of the method to real electric power systems as our final goal.

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