Robust Generator Control with Robust Observer

Member	A. Sanai Sabzevary	(Waseda University)
(The late)	Yasuo Tamura	(Waseda University)
Member	Shinichi Iwamoto	(Waseda University)

The complexity of power systems and wide range of operating conditions are beyond limitations of modeling techniques used in the conventional controller designs. Thus in order to provide reliable system operation, it will be better that controllers be designed considering various sources of uncertainties in power systems, e.g., uncertainties in modelling, measurements and fault occurrences. Furthermore for many dynamical systems whose state equations include time varying uncertain parameters it is desirable to design a stabilizing state feedback controller which takes into account uncertainties [1]-[6]. This paper introduces a Riccati equation approach to synthesize a full state robust observer and a state feedback robust controller for generator control. The structure of the controller is fixed and in the design procedure only bounds of the system parameters are needed. The variation bounds of the power system parameter uncertainties are obtained by changing the parameters from their typical values. In this paper one circuit line opening is modeled as the main source of uncertainty. The effectiveness of the proposed control is demonstrated on a one machine to infinite bus system. Nonlinear simulations are carried out in the presence of faults followed by one circuit line opening with limiter consideration and with time varying uncertainties entering the output matrix. The result is compared with LQG control.

KEYWORDS: Power system, Generator control, Robust control, Robust observer, Riccati equation

1 Introduction

With the advancement of power technologies modern generators operate with reduced stability margins which make necessary more accurate knowledge of the limits of stable operation under dynamic conditions. An economically attractive solution to the problem of continually increasing demand for electrical energy is to increase the safety margins in power transmission without compromising system reliability and stability. However, the complexity of power system transients, dynamic uncertainty and cascade disturbance characteristics are beyond practical limitations of modelling techniques used in conventional generator control designs. Therefore a controller design based on a linearized model and fixed parameters may degrade because of drifts in operating conditions. Thus in order to provide reliable system operation the controller must be designed taking into account the various sources of uncertainties in power systems. The sources of uncertainties in power system control primarily include linear approximation, modelling errors, measurement errors, design parameters errors, etc.

Recently the problem of robust generator control design has been of interest of many researchers. For example, Ohtsuka, et al. [7], studied the H_∞ based robust generator control and have compared it with linear optimal control. T. Senjyu, et al. [8] studied the variable

structure design method for robust power system stabilizing control design. But in most cases, all the states of the system have to be measured or have to be available for measurements, which is practically impossible, or even if possible is of considerable cost.

This paper proposes an observer based robust state feedback controller to stabilize power systems, where the parametric uncertainties considered are time varying and may appear in the system matrices and the values of these uncertainties are considered to be bounded. Here we have considered one circuit line opening out of double circuit lines as the main source of uncertainty.

The controller is linear with fixed structure. In comparison to the other robust control design methods, the design method is a kind of extension of linear optimal control and during the design procedure only the knowledge of the bounds of the parameters is sufficient. The structure of the control is simple and is easy to implement. Furthermore since the controller is observer based, there is no need for all states to be measured or to be available for measurement.

The effectiveness of the proposed control is demonstrated on a one machine to infinite bus system and then through nonlinear dynamic simulations it is compared with LQG (Linear Quadratic Gaussian) control [9] [10], which is designed by the same method but without uncertainty considerations. Furthermore the effectiveness of the proposed robust controller is tested on

the nonlinear original system in the presence of faults followed by one circuit line opening with limiter consideration added and time varying uncertainties entering the output matrix. It is shown that the controller is effective in the presence of faults and parameter variations, and can enhance the stability of power systems.

2 System Model

A power system [11] consisting of a synchronous generator connected to an infinite bus through a transmission line is studied. The figure and block diagrams of the control inputs are shown in Fig. 1 and Fig. 2, respectively.

The original nonlinear equations which are used for simulations and nomenclature are found in APPENDIX I.

Fig. 1 One machine to infinite bus system

Fig. 2-(a) Exciter-voltage regulator system

Fig. 2-(b) Governor system

The linearized equations used are $\dot{x} = Ax + Bu$ and $y = Cx$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ a_{21} & -\frac{D}{M} & a_{23} & 0 & 0 & \frac{1}{M} & 0 \\ a_{31} & 0 & a_{33} & 1 & 0 & 0 & 0 \\ a_{41} & 0 & a_{43} & -\frac{1}{T_e} & -\frac{\mu_e}{T_e} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_s} & 0 & 0 \\ 0 & -\frac{1}{\omega_0 T_g} & 0 & 0 & 0 & -\frac{\sigma}{T_g} & -\frac{1}{T_g} \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{T_a} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}^T$$

$$C = [0 \ 1 \ 0 \ 0 \ 0 \ 0 \ 0]$$

$$x = [\delta' \ \omega' \ \Psi_F' \ v_F' \ v_s' \ P_i' \ g_f']^T, u = [u_v \ u_g]^T$$

$$u_v = \frac{\mu_s u_1}{T_s}, \quad u_g = \frac{\mu_a u_2}{T_a}$$

$$a_{21} = -\frac{1}{M} \left\{ \frac{v_0 \cos \delta_0 \psi_{F0}}{X_d' T_{d0}'} + \frac{(x_d' - x_q) v_0^2}{X_d' X_q} \cos 2\delta_0 \right\}$$

$$a_{23} = -\frac{v_0 \sin \delta_0}{M X_d' T_{d0}'}$$

$$a_{31} = -\frac{(x_d - x_q) v_0 \sin \delta_0}{X_d'}$$

$$a_{33} = -\frac{X_d}{X_d' T_{d0}'}$$

$$a_{41} = -\frac{\mu_e v_0}{T_e v_{t0}} \left\{ \frac{x_q v_{d0} \cos \delta_0}{X_q} - \frac{x_d' v_{q0} \sin \delta_0}{X_d'} \right\}$$

$$a_{43} = -\frac{\mu_e}{T_e v_{t0}} \frac{x_e v_{q0}}{X_d' T_{d0}'}$$

3 Robust Control Theory

This paper employs the theory developed by I.R. Petersen [12].

System description and preliminary derivation: Since the power system parameters can not be exactly known [13][14], the following model which may include various kinds of uncertainties is considered:

$$\dot{x}(t) = [A_0 + \Delta A(r(t))]x(t) + [B_0 + \Delta B(s(t))]u(t) \quad \dots (1)$$

$$y(t) = [C_0 + \Delta C(v(t))]x(t)$$

where, $x(t) \in R^n$ is the state, $u(t) \in R^m$ is the control and $y(t) \in R^q$ is the measured output. A_0 , B_0 and C_0 are system nominal matrices, and $\Delta A(r(t))$, $\Delta B(s(t))$ and $\Delta C(v(t))$ are time varying structured uncertainties in A , B and C , respectively. $r(t)$, $s(t)$ and $v(t)$ are vectors of uncertain parameters and are the only information available about the time varying uncertainties, and $y(t)$ is the output.

For all uncertainties the pair $(A_0 + \Delta A, B_0 + \Delta B)$ is controllable and the pair $(A_0 + \Delta A, C_0 + \Delta C)$ is observable. Uncertainties are measurable but bounded. $r_i(t)$, $s_i(t)$ and $v_i(t)$ are time varying uncertainties for ΔA , ΔB and ΔC , respectively.

$$|r_i(t)| \leq \bar{r} \quad \forall_i = 1, 2, \dots, k$$

$$|s_i(t)| \leq \bar{s} \quad \forall_i = 1, 2, \dots, l$$

$$|v_i(t)| \leq \bar{v} \quad \forall_i = 1, 2, \dots, p$$

$$\Delta A(r(t)) = \sum_{i=1}^k A_i r_i(t)$$

$$\Delta B(s(t)) = \sum_{i=1}^l B_i s_i(t)$$

$$\Delta C(v(t)) = \sum_{i=1}^p C_i v_i(t)$$

where, A_i , B_i , C_i are of the "rank-1" type matrices (a "rank-1" matrix is the product of a column vector and a row vector). Then A_i , B_i and C_i above can be decomposed as below because of the "rank-1" assumption:

$$A_i = d_i e_i^T \quad (\text{rank-1 matrix}) \quad \forall_i = 1, 2, \dots, k$$

$$B_i = f_i g_i^T \quad (\text{rank-1 matrix}) \quad \forall_i = 1, 2, \dots, l$$

$$C_i = h_i w_i^T \quad (\text{rank-1 matrix}) \quad \forall_i = 1, 2, \dots, p$$

Then we define the following notations:

$$T \triangleq \sum_{i=1}^k d_i d_i^T \quad U \triangleq \sum_{i=1}^k e_i e_i^T$$

$$V \triangleq \sum_{i=1}^l g_i g_i^T \quad W \triangleq \sum_{i=1}^l f_i f_i^T$$

$$X \triangleq \sum_{i=1}^p h_i h_i^T \quad Y \triangleq \sum_{i=1}^p w_i w_i^T$$

Now suppose that some of the states of the system (1) are inaccessible for measurement. Then it is required to design an observer and a feedback controller of the following form to guarantee the stability of the system for all admissible uncertainties.

$$\dot{z} = A_0 z(t) + B_0 u(t) - L(C_0 z(t) - y(t)), \quad u(t) = K z(t)$$

where: $z(t) \in R^n$ is the observed state, L is a suitable $n \times q$ observer gain matrix and K is a suitable $m \times n$ feedback gain matrix. What required here are the matrices L and K which take into account uncertainties ΔA and ΔC . The design procedure is explained in APPENDIX II.

4 Simulation Study

For the initial load and terminal voltage of the synchronous machine ($P_0=0.735$, $Q_0=0.034$ and $v_0=1.058$) the initial values of currents, voltages flux linkages and torque angles are calculated as follows:

$$\begin{aligned} v_{F0} &= 1.3616, & \Psi_{F0} &= 9.6396, & \delta_0 &= 0.887, \\ v_{i0} &= 1.031, & v_{d0} &= 0.36676, & v_{q0} &= 0.9636. \end{aligned}$$

Since $\delta_0 = 0.887$ radians (50.8214 degrees) it can be said that the system is in a heavy-load condition and is close to its dynamic stability limit. Substituting these

nominal values into A matrix the following numerical values are obtained. The nominal output matrix is considered to be $C_0 = [0 \ 1 \ 0 \ 0 \ 0 \ 0 \ 0]$.

$$A_0 = \begin{bmatrix} 0 & 1.0000 & 0 & 0 & 0 & 0 & 0 \\ -3.5934 & -0.0253 & -0.4245 & 0 & 0 & 4.7125 & 0 \\ -0.5918 & 0 & -0.1913 & 1.0000 & 0 & 0 & 0 \\ 0.9824 & 0 & -0.7613 & -1.0000 & -10.000 & 0 & 0 \\ 0 & 0 & 0 & 0 & -2.0000 & 0 & 0 \\ 0 & -0.0318 & 0 & 0 & 0 & 0.4500 & -10.0000 \\ 0 & 0 & 0 & 0 & 0 & 0 & -100.0000 \end{bmatrix}$$

It is known that the parameters in synchronous generators may have uncertainties because of factors such as machine internal temperature, machine aging, magnetic saturation, the coupling effect between machine and external system, and most importantly faults [15]-[16]. Namely due to changes in system operating conditions and various underlying factors, machine parameters are subject to variations. Here, we assume that the transmission line reactance, x_e has +100% variation which is equivalent to one circuit line opening out of double circuit lines for fault conditions or stability test experiments. The uncertainty matrix ΔA is calculated as follows (only relevant entry elements which have those parameters are affected):

$$\Delta A = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1.5732 & 0 & 0.1796 & 0 & 0 & 0 & 0 \\ 0.2503 & 0 & 0.0339 & 0 & 0 & 0 & 0 \\ -0.4868 & 0 & -0.1172 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

We assume $r(t)=r_1(t)=r_2(t)$ and $\bar{r}=1$. Following the design procedure explained in Section 3, first we write ΔA as follows

$$\Delta A = A_1 r(t) + A_2 r(t)$$

$$\Delta A = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1.5732 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.2503 & 0 & 0 & 0 & 0 & 0 & 0 \\ -0.4868 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} r(t) + \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.1796 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.0339 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.1172 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} r(t)$$

Because of the rank one specification of the uncertainty matrices A_1 and A_2 we can decompose these matrices as follows:

$$A_1 = d_1 e_1^T = [0 \ 1.5732 \ 0.2503 \ -0.4868 \ 0 \ 0 \ 0]^T [1 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0]^T$$

$$A_2 = d_2 e_2^T = [0 \ 0.1796 \ 0.0339 \ -0.1172 \ 0 \ 0 \ 0]^T [0 \ 0 \ 1 \ 0 \ 0 \ 0 \ 0]^T$$

T and U can be obtained as below:

$$T = d_1 d_1^T + d_2 d_2^T =$$

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 2.5072 & 0.3999 & -0.7869 & 0 & 0 & 0 \\ 0 & 0.3999 & 0.0638 & -0.1258 & 0 & 0 & 0 \\ 0 & -0.7869 & -0.1258 & 0.2507 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$U = e_1 e_1^T + e_2 e_2^T = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Here because we consider only fault uncertainties we assume that $\Delta B = 0$.

The uncertainty in the output matrix C is considered to be $\Delta C = [0 \ 0.2 \ 0 \ 0 \ 0 \ 0 \ 0]$ for designing. Following the same procedure for ΔA , for the portion of ΔC we have $h = [0.2]$, $w = [0 \ 1 \ 0 \ 0 \ 0 \ 0 \ 0]$, $X = h h^T = 0.04$ and

$$Y = w w^T = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

For weighting matrices we used $Q_1 = \text{diag}[10 \ 10 \ 1 \ 1 \ 1 \ 1 \ 1]$, $Q_2 = \text{diag}[10 \ 10 \ 1 \ 1 \ 1 \ 1 \ 1]$, $R_1 = \text{diag}[1 \ 1]$, $R_2 = 1$ and positive constants $(\varepsilon_1, \varepsilon_2) = (1, 1)$. With these values the Riccati equations (A-2) and (A-3) had no positive definite solutions. Then ε_1 was replaced by a smaller ε_1 , and ε_2 was replaced by a larger ε_2 until the Riccati equations (A-2) and (A-3) had positive definite solutions satisfying inequality (A-4), as follows: $(\varepsilon_1, \varepsilon_2) = (1, 1) \rightarrow (0.1, 1) \rightarrow (0.1, 10) \rightarrow (0.01, 10) \rightarrow (0.01, 100) \rightarrow (0.001, 100)$. The number of the required iterations was 5 and the required computing time was 1.14 seconds using MATLAB Ver.4.2 on a Pentium-120MHz PC. A suggested procedure would be to choose starting values of $Q_1 = Q_2 = I$, $R_1 = R_2 = I$, $\varepsilon_1 = \varepsilon_2 = 1$ and solve the Riccati equations (A-2) and (A-3). If no positive solutions satisfying inequality (A-4) are found replace ε_1 by a smaller ε_1 and ε_2 by a larger ε_2 and repeat the process. If it does not succeed repeat the process for other choices of Q_1 , Q_2 , R_1 and R_2 .

Using the gain matrices, we can construct the observer based robust feedback controller. To show the effectiveness of the proposed observer based robust controller at first the simulations were carried out for four different cases and were compared with LQG. For all simulation cases the original nonlinear equations were used and a time varying uncertainty of the sinusoidal form such as $\alpha = \cos(78.5)t$ is considered in the output matrix C , i.e., $C = C_0 + \alpha \Delta C$. The observer and feedback gains of LQG are calculated using equations (A-5) to (A-8).

The following cases have been investigated:

Case 1: First the simulation is run with one circuit line opening. Before applying any controller the system was oscillatory and the eigen values of the system were: $-0.04 + 190i$, $-0.04 - 190i$, -0.43 , $-0.57 + 0.84i$, $-0.57 - 0.84i$, -0.200 , -100.00 . Fig. 3 shows the behavior of the system with the proposed robust control and LQG. From Fig. 3 it is seen that while the LQG case becomes unstable the proposed robust control keeps the system stable. This is because the effect of one circuit line opening is considered in the design of the proposed method.

Case 2: In this case the simulation is carried out for a three phase to ground fault near the generator terminal for which the duration of the fault is 100 ms. The post-fault initial conditions are calculated as $x_0 = [0.0173, 0.3458, -0.2060, 0.9811, 0, -0.0005, 0]$. Fig. 4 shows the behavior of the system with the proposed control and LQG. From the figure it is observed that the proposed method gives superior control over the LQG, but u_g of the proposed method is overshooted compared with the LQG case.

Case 3: In this case the simulation is carried out for a three phase line to ground fault near the generator terminal followed by one circuit line opening. And it is assumed that the duration of fault is 100 ms. Fig. 5 shows the behavior of the system with the proposed method and LQG. As expected from Case 1 the LQG can not stabilize the system but the proposed method is robust even for this case.

Case 4: In this case the condition is the same as Case 3, but the control u_g is limited by a limiter with a maximum limit of 5 pu. Fig. 6 shows the behavior of the system with the limiter consideration. From the figure it is observed that even when a limiter is installed the robust controller does not degrade and gives good quality of control.

Although in the simulations above all the data were taken from reference [11], we also ran simulations for other typical values such as $\mu_e = 25$, $T_s = 0.1$ [17]. And for these typical values also the proposed control performed well and gave good quality of control, as shown in Fig. 7 which corresponds to Fig. 4.

Fig. 3 Comparison of proposed control with LQG for one circuit line opening. (— proposed control, LQG)

Fig. 4 Comparison of proposed control with LQG for a 100 ms three phase to ground fault. (— proposed control, LQG)

Fig. 5 Comparison of proposed control with LQG for a 100 ms three phase to ground fault followed by one circuit line opening. (— proposed control, LQG)

Fig. 6 Comparison of proposed control with LQG for a 100 ms three phase to ground fault followed by one circuit line opening and with limiter. (— proposed control, LQG)

Fig.7 Comparison of proposed control with LQG for a 100 ms three phase to ground fault. (— proposed control,LQG) ($\mu_e=25$ and $T_s=0.1$)

As a whole it has been observed that the proposed robust controller is very effective for the two typical power system abnormal conditions, which will be very useful for power system operations. It should be noted that the consideration of time varying uncertainty in matrix C did not affect the simulation results much compared to the uncertainties in A matrix.

5 Conclusions

In order to take into account the one circuit line opening and three phase to ground fault in generator control design, this paper has introduced the idea of robust quadratic stability to power system control. We have dealt with the one machine to infinite bus system. The effect of the proposed controller on a three phase to ground fault followed by one circuit line opening in the presence of time varying uncertainties in the output matrix and limiter consideration has been investigated, while the possibility to multi-machine application is still under investigation. Detailed procedures are given and the results are compared with those of LQG. It is shown that the proposed control is effective for different fault scenarios. Since the controller is observer based there is no need for all the states to be measured or to be available for measurements. Furthermore it is expected that upon the application of the robust controllers, the safety margins of the existing power systems can be increased and in this way some part of the electrical energy demand can be covered.

(Manuscript received Apr. 26, 1995, revised Oct. 24, 1995)

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APPENDIX I

The example system is taken from [11]. The original system has h (water head) and line charging capacitance, which are not considered here for simplicity. In the following, definitions and necessary parameters are shown. See [11] for more details.

System equations:

$$\begin{aligned}\frac{d\delta}{dt} &= \omega' \\ \frac{d\omega'}{dt} &= \frac{1}{M}(P_i' - D\omega' - P_e') \\ \frac{d\psi_F}{dt} &= v_F + v_{F0} - \frac{X_d\psi_F}{X_d' T_{d0}} + \frac{(x_d - x_d')v_0 \cos \delta}{X_d'} \\ \frac{dv_F}{dt} &= -\frac{v_F}{T_e} + \frac{\mu_e}{T_e}(-v_i' - v_s) \\ \frac{dv_s}{dt} &= -\frac{v_s}{T_s} + \frac{\mu_s}{T_s}u_1 \\ \frac{dP_i'}{dt} &= -\frac{\sigma P_i'}{T_k} + \frac{1}{T_s}(-\frac{\omega'}{\omega_0} - g_r) \\ \frac{dg_r}{dt} &= -\frac{g_r}{T_a} + \frac{\mu_a}{T_a}u_2 \\ \omega' &= \omega - \omega_0 \\ P_e' &= \frac{v_0 \sin \delta \psi_F}{X_d' T_{d0}'} + \frac{(x_d' - x_q)v_0^2}{2X_d' X_q} \sin 2\delta - P_0 \\ v_i' &= (v_d^2 + v_q^2)^{\frac{1}{2}} - v_{i0} \\ v_d &= \frac{x_q v_0 \sin \delta}{X_q} \\ v_q &= \frac{x_e \psi_F}{X_d' T_{d0}'} + \frac{x_d' v_0 \cos \delta}{X_d'} \\ i_q &= \frac{v_0 \sin \delta}{X_q} \\ i_d &= \frac{\psi_F}{X_d' T_{d0}'} - \frac{v_0 \cos \delta}{X_d'} \\ X_d &= x_d + x_e \\ X_d' &= x_d' + x_e \\ X_q &= x_q + x_e\end{aligned}$$

Nomenclature:

δ : torque angle (radian)
 x_d : synchronous reactance d axis
 ω : speed (radian)
 x_d' : transient reactance d axis

v_s	: stator voltage
T'_{d0}	: open circuit time constant of the field
P_i	: mechanical power input
T_e	: exciter time constant
g_f	: governor feedback loop signal
T_s	: voltage control feedback loop time constant
P_e	: electrical output
T_g	: gate time constant
v_t	: generator terminal voltage
T_a	: governor actuator time constant
v_d	: d component of v_t
μ_e	: AVR gain
v_q	: q component of v_t
μ_s	: voltage control feedback loop gain
i	: armature current
i_d	: d component of i
μ_a	: governor gain
i_q	: q component of i
σ	: permanent droop
D	: damping coefficient
v_0	: infinite bus voltage
M	: inertia constant
$'$	: deviation from the initial value
0	: 'initial value' of a variable(subscript)
ω_0	: synchronous speed (377 rad/s)
u_v	: excitation control
u_g	: governor control
x_e	: transmission line reactance

System data:

x_d	: 1.000	σ	: 0.045
x'_d	: 0.270	T_g	: 0.100
x_q	: 0.600	T_a	: 0.010
x_e	: 0.7417	P_0	: 0.735
M	: 0.2122	T_e	: 1.000
D	: 0.0053	v_{t0}	: 1.031
T'_{d0}	: 9.000	μ_e	: 10.00
T_s	: 0.500		

The numerical values of μ_a and μ_s are not given since they are included in u_v and u_g [11].

APPENDIX II

Design procedure: The design procedure is explained

below. Rewriting (1), we have

$$\begin{aligned} \dot{x}(t) &= [A_0 + \Delta A(r(t))]x(t) + [B_0 + \Delta B(s(t))]u(t) \quad \text{.....(A-1)} \\ y(t) &= [C_0 + \Delta C(v(t))]x(t) \end{aligned}$$

Here we use the following theorem.

Theorem: For the considered uncertain system (A-1) if there exist positive constants $\varepsilon_1 > 0, \varepsilon_2 > 0$ and positive definite weighting matrices $Q_1 > 0, R_1 > 0, Q_2 > 0$ and $R_2 > 0$ such that the following conditions hold:

(a) there exists positive-definite symmetric matrix P_c satisfying the algebraic Riccati equation (A-2)

$$\begin{aligned} A_0^T P_c + P_c A_0 - P_c \left[\frac{1}{\varepsilon_1} \left\{ B_0 \left[R_1^{-1} - 2 R_1^{-1} V R_1^{-1} \right] B_0^T - 2 W \right\} - T \right] P_c \\ + 2 U + \frac{1}{\varepsilon_2} Y + \varepsilon_1 Q_1 = 0 \end{aligned} \quad \text{.....(A-2)}$$

(b) there exists positive-definite symmetric matrix P_o satisfying the algebraic Riccati equation (A-3)

$$\begin{aligned} A_0^T P_o + P_o A_0 - \left[\frac{1}{\varepsilon_1} \left\{ C_0^T \left[R_2^{-1} - R_2^{-1} X R_2^{-1} \right] C_0 \right\} - \frac{2}{\varepsilon_1} P_c B_0 R_1^{-1} V R_1^{-1} B_0^T P_c \right] \\ + P_o \left[T + \frac{2}{\varepsilon_1} W + \varepsilon_2 Q_2 \right] P_o = 0. \end{aligned} \quad \text{.....(A-3)}$$

(c) the matrices P_c and P_o satisfy the inequality (A-4)

$$\begin{aligned} \varepsilon_2 (P_o Q_2 P_o + \frac{1}{\varepsilon_1^2} C_0^T R_2^{-1} C_0) - \frac{1}{\varepsilon_1^3} P_c B_0 R_1^{-1} B_0^T P_c \\ \times \left(Q_1 + \frac{1}{\varepsilon_1^2} P_c B_0 R_1^{-1} B_0^T P_c \right) \times P_c B_0 R_1^{-1} B_0^T P_c > 0 \end{aligned} \quad \text{.....(A-4)}$$

Then the resulting closed loop system (A-1) is guaranteed to be asymptotically stable by the feedback gain matrix K and the observer gain matrix L which can be calculated as follows:

$$K = -\frac{1}{\varepsilon_1} R_1^{-1} B_0^T P_c \quad \text{.....(A-5)}$$

$$L = \frac{1}{\varepsilon_2} P_o^{-1} C_0^T R_2^{-1} \quad \text{.....(A-6)}$$

If system (A-1) contains no uncertain parameters with $\varepsilon_1 = \varepsilon_2 = 1$ equations (A-2) and (A-3) are reduced to

$$A_0^T P_c + P_c A_0 - P_c B_0 R_1^{-1} B_0^T P_c + Q_1 = 0 \quad \text{.....(A-7)}$$

$$A_0^T P_o + P_o A_0 - C_0^T R_2^{-1} C_0 + P_o Q_2 P_o = 0 \quad \text{.....(A-8)}$$

These Riccati equations are equations arising in standard Linear Quadratic Gaussian design [9] [10].

The procedure for the observer based robust control design is summarized in the following flowchart.

Fig. A-1 Flowchart

ALIREZA SANAI SABZEVARY (Member)

Was born in Iran on June 1953. He received the B.E. and M.E. degrees from Tabriz University, Iran, and Waseda University, Tokyo Japan in 1973 and 1993, respectively. He is currently a Ph.D. candidate at Waseda University, Department of Electrical Engineering. His research interest includes power system control and stability. He is a member of IEEJ.

(the late) YASUO TAMURA

Was born in Japan on September 21, 1931. He received the B.E., M.E. and Dr. of Engineering degree in 1953, 1955, 1961, respectively, all from Waseda university, Tokyo, Japan. He was appointed as research assistant in 1955 and professor in 1969 of Engineering School of Waseda University. He was exchange researcher at University of Michigan in 1957-58 period. He led Security Control, Substation Automation and EHV Unmanned Substation Teams to U.S.A. and Europe in 1970, 1973 and 1980. His research interest included power system engineering and application of control theory and computer technology to power systems. Dr. Tamura was a fellow of IEEE and a member of CIGRE, IEEJ and the Society of Instrument and Control of Japan. He died on November 22, 1993.

SHINICHI IWAMOTO (Member)

Was born in 1948. He received his B.E., M.E. and Ph.D. degrees from Waseda University, Tokyo, Japan, in 1971, 1975, and 1978, respectively. From 1972 to 1974, he was at Clarkson University, N.Y. and received a M.S. degree. Presently he is a full professor at Waseda University, Tokyo, Japan. From August 1992 to August 1993 he was at University of Washington as a visiting professor. His research interest includes load flow, stability and AI applications to power system problems.