Fuzzy Logic Excitation and Speed Governing Control Systems for Stability Enhancement of Power System

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Abstract: Fuzzy logic excitation and speed governing control systems have been proposed to enhance the overall stability of power systems. The proposed excitation system has two control loops. One is the voltage control loop which achieves the automatic voltage regulator (AVR) function, and the other is the damping control loop which gives the power system stabilizer (PSS) function. The speed governing control system has only one speed control loop which achieves the governor function. The same fuzzy logic control rules are applied to all the control loops. The input signal to the voltage control loop is the terminal voltage, and the input signal to the damping control loop is the real power output. In addition, the input to the speed governing control loop is the speed deviation. Simulation studies show the advantages of the fuzzy logic excitation and speed governing control systems.

Keyword: Fuzzy logic excitation and speed governing control systems, damping control, voltage control, power system stabilizer, real time control, digital control.

1. Introduction

In our previous work, we have proposed a micro-computer based fuzzy logic power system stabilizer (FLPSS) to enhance the overall power system stability through the excitation control using fast-acting thyristor exciters. Through both the simulation studies and the experiments using a 5 kVA laboratory system and an actual 5 MVA hydro unit, the effectiveness of the FLPSS has been demonstrated [1-5]. In addition, the long term evaluation of the FLPSS is now ongoing on a 30.2 and a 23.4 MVA hydro units in the Kyushu Electric Power System [6].

For further improvement of power system stability, we have proposed a fuzzy logic excitation system together with a fuzzy logic speed governing system. The fuzzy logic excitation system has two control loops. One is the voltage control loop which gives the automatic voltage regulator (AVR) function, and the other is the damping control loop which gives the power system stabilizer (PSS) function. The speed governing system has only one speed control loop which achieves the governor function. The same fuzzy logic control rules are utilized to achieve all the functions of AVR, PSS, and governor. The control rules are based on the PD information [7] of the generator terminal voltage for the voltage control loop, and also based on the PI information of the generator output for the damping control loop in the proposed fuzzy logic excitation system. The damping control loop has the same configuration of the fuzzy logic power system stabilizer (FLPSS) in our previous study. In the speed governing control loop, the PD information of the generator speed is utilized to generate the speed control signal. The control rules are the same for all these control loops.

The proposed control scheme is very simple so as not to require heavy computation, therefore, its on-line implementation is readily available. Furthermore, an integrated controller can be set up for both the excitation and the speed governing control systems using only one micro-computer because of the short computation time less than 1 ms for each interval.

Simulation studies have been performed using a one machine infinite bus system. The results show the advantages of the proposed fuzzy logic excitation control system comparing with the conventional excitation control systems, i.e., a conventional AVR with a conventional PSS. The speed governing system has only secondary effects for the stability enhancement. However, the better performance is obtained by the proposed fuzzy logic speed governing system.

2. Fuzzy Logic Excitation System

Fig. 1 gives the block diagram of the fuzzy logic excitation system, which has both the voltage and
damping control loops for the stability enhancement. The proposed excitation control system is considered to be set up by using a micro-computer and AD and DA conversion interfaces. The input signals are the terminal voltage and the real power output for the voltage and the damping control loops, respectively. In the simulation studies shown later, a self-excited fast acting thyristor excitation system is utilized, therefore, the setting of the steady state excitation voltage $E_{fd0}$ is divided by the steady state terminal voltage $V_{to}$. Moreover, the output from the excitation control system is multiplied by the instantaneous terminal voltage $V_t(k)$. When considering the separately excited excitation systems, both these values should be set to 1.0.

![Fig. 1. Fuzzy Logic Excitation System](image)

**Fig. 1. Fuzzy Logic Excitation System**

### 2.2 Configuration of Damping Control Loop

The block diagram of the damping control loop is shown in Fig. 3[1-5]. The damping control loop has the same configuration of the fuzzy logic PSS in our previous studies. The damping control signal $Ud(k)$ is also derived from the PI information of the generator output $P_e(k)$, i.e. $Z_s(k)$ and $Z_a(k)$. These PI information is obtained through the signal conditioning using reset filters and an integrator. Here, $Z_a(k)$ is the deviation of the real power output, which gives the acceleration of the generator, and $Z_s(k)$ is its integral, which gives the speed deviation of the generator.

![Fig. 3. Configuration of Damping Control Loop](image)

### 3. Fuzzy Logic Speed Governing System

The configuration of the speed governing system is shown in Fig. 4. The Figure also includes the valve servo system. The speed control signal $Ug(k)$ from the speed control loop is added to the valve servo system. As shown in Fig. 4, there are several restrictions in the valve servo system. The valve opening speed is restricted by $U_1$ and the closing speed is restricted by $L_1$. The fast valve closing speed is available compared with the valve opening speed. The range of turbine output regulation is up to $1.1P_{to}$, where $P_{to}$ is the setting of the turbine output.

![Fig. 4. Configuration of Speed Governing System](image)

Australian Journal of Intelligent Information Processing Systems

Autumn 1996
4. Fuzzy Logic Control Rules

The same fuzzy logic control rules are applied to all the control loops for the fuzzy logic excitation and speed governing systems. The generator state is given by the point \( p(k) \) in the phase plane shown in Fig. 6 for each control loop.

\[
p(k) = [X(k), Y(k)]
\]

Here, \( As \), which gives the scaling factor for \( Y(k) \), is one of the adjustable control parameters. The origin \( O \) is the equilibrium, therefore, all the control action should be directed to shift the point \( p(k) \) to the origin.

Switching Line

\[
\text{Sector B}
\]

Switching Line

\[
\text{Sector A}
\]

In this study, the generator state is given by the polar information instead of the rectangular information, i.e., the radius \( D(k) \) and the phase \( \theta(k) \) to simplify the control rules.

\[
D(k) = \sqrt{X(k)^2 + (A_2 \cdot Y(k))^2}
\]

\[
\theta(k) = \tan^{-1}(A_2 \cdot Y(k)/X(k))
\]

To derive the control scheme, the phase plane is divided into two Sectors, i.e., Sector A and Sector B. Here, \( \alpha \) is the overlap angle between these two sectors. When considering the excitation control, Sector A, especially the first quadrant, gives the region where the excitation should be increased to rise the terminal voltage, and also to achieve the deceleration control for the damping of oscillations. On the contrary, Sector B, especially the third quadrant, gives the region where the excitation should be decreased to reduce the terminal voltage, and also to achieve the acceleration control. When considering the speed governing system, Sector A gives the region where the increase of the turbine output is required for the acceleration of the generator speed, and Sector B gives the region where the decrease of the turbine output is required for the deceleration of the generator speed.

These two sectors are defined by using the two polar membership functions \( N(\theta(k)) \) and \( P(\theta(k)) \) as shown in the Appendix 1. For the excitation control system, the function \( N(\theta(k)) \) gives the grade of increasing the excitation voltage, and \( P(\theta(k)) \) gives the grade of decreasing the excitation voltage. In addition, these functions also give the grade to increase or to decrease the turbine output for the speed governing control. By using these two membership functions, the control signal \( U(k) \) from each control loop is given by

\[
U(k) = \frac{P(\theta(k)) - N(\theta(k))}{P(k) + N(k)} \cdot G(k) \cdot U_{\text{max}}
\]

(9)

\[
= (1 - 2P(\theta(k))) \cdot U_{\text{max}} \cdot G(k)
\]

(10)

\[
G(k) = \begin{cases} 
D(k)/Dr & \text{for } D(k) < Dr \\
1.0 & \text{for } D(k) > Dr 
\end{cases}
\]

(11)

(12)

where \( G(k) \) gives the gain factor, which is determined by the radius \( D(k) \) and the distance parameter \( Dr \). \( U_{\text{max}} \) gives the maximum size of the output signal \( U(k) \) from the fuzzy logic control loop. By using these equations, the control signals from all the control loops are determined as follows:

**Excitation Control System**

Voltage Control Loop:

\[
Uv(k) = U(k) \quad \text{from } X(k) = e(k) \text{ and } Y(k) = e_0(k)
\]

Damping Control Loop:

\[
Ud(k) = U(k) \quad \text{from } X(k) = Zs(k) \text{ and } Y(k) = Za(k)
\]

In the voltage control loop of the excitation system, the voltage control signal \( Uv(k) \) is derived through the PI control loop from the control signal \( Uv(k) \) as shown in Fig. 2.

**Speed Governing Control System**

Speed Control Loop:

\[
Ug(k) = U(k) \quad \text{from } X(k) = \Delta \omega(k) \text{ and } Y(k) = \Delta \omega_d(k)
\]

Here, it must be noted that the all the control parameters \( As, Dr, \) and \( \alpha \) should be tuned separately for each control loop. Namely, the setting of these adjustable control parameters depends on the control loops.
5. Simulation studies

5.1 One Machine Infinite Bus System

A one machine infinite bus system, shown in Fig. 7, is used as a model system for the simulation studies. A reheat type thermal generator is selected as the generator model. The proposed fuzzy logic excitation and speed governing control systems are set to the generator to demonstrate the effectiveness of the proposed control scheme. The generator constants are also shown in the Figure. For the comparison studies, the following conventional excitation and speed governing systems are also considered. The block diagram of the conventional excitation system is shown in Fig. 8. A self-excited fast acting thyristor exciter is considered together with a conventional PSS, shown in Fig. 9. A conventional speed governing system shown in Fig. 10. The block diagram of the reheat type turbine system is shown in Fig. 11.

The simulations have been performed subject to the following disturbance:
(a) a 5% step change of the reference voltage $V_r$
(b) a three-phase to ground fault at the point A following the isolation of the faulted line after 0.07 s.

![Fig. 7. One Machine Infinite Bus System](image)

![Fig. 8. Conventional Excitation System](image)

![Fig. 9. Conventional PSS](image)

![Fig. 10. Conventional Speed Governing System](image)

![Fig. 11. Reheat Type Turbine System](image)

5.2 Tuning of Control Parameters

The proposed fuzzy logic excitation and speed governing systems have three adjustable parameters $\alpha_s$, $\alpha_r$, and $\alpha$ for the voltage and the damping control loops in the excitation system, and also for the speed control loop of the speed governing system. Through a sequential optimization technique[4], optimal parameters have been determined for the proposed fuzzy logic excitation system.

The control parameters for the voltage control loop are determined subject to the above disturbance (a) at the operating point of the real power output $P_e = 1.0$ pu. In the sequential optimization, the parameters have been optimized on a one by one basis. The following discrete-type quadratic performance index $J_v$ is defined for the voltage control loop.

$$J_v = \sum_{k} (\Delta V(k) \cdot k \cdot \Delta T)^2$$

Here, $k$ is set to 0 at the instance when the disturbance is added to the system, and $\Delta T$ is the sampling interval.

The parameters for both the damping and the speed control loops are also optimized subject to the disturbance (b). The conventional PSS is also optimized at the same operating point subject to the same disturbance for the comparison studies. In the case of the conventional PSS, the gain $G_{pss}$ is set to 10.0, and the time constants $T_2$ and $T_3$ are tuned, and all the other parameters are fixed to the values shown in Fig. 8. The discrete type quadratic
performance index \( J_d \) is defined by the following for the damping control loop.

\[
J_d = \sum_{k} (\Delta \omega(k) \cdot k \cdot \Delta T)^2
\]  

(15)

Here, \( \Delta \omega(k) \) is the speed deviation of the study unit.

The optimal parameters are shown in Table 1. For the fuzzy logic excitation system, the maximum sizes of the voltage and the damping control signals \( U_{v_{\text{max}}} \) and \( U_{d_{\text{max}}} \) is set to 1.0 pu considering the maximum size of the conventional PSS signal \( U_{\text{max}} \) of 1.0 pu. The maximum size of the speed control signal \( U_{g_{\text{max}}} \) is set to 1.0. The adjustable parameter \( D_r \) is set to \( \omega_0 R \) considering the speed regulation of the conventional governor.

Throughout all the simulations, the sampling interval \( \Delta T \) is set to 10 ms. for the fuzzy logic excitation and speed governing control systems.

### Table 1. Optimal Settings of Control Parameters

<table>
<thead>
<tr>
<th>Fuzzy Logic Excitation System</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Control Loop:</td>
<td>( A_s = 0.001 ), ( D_r = 0.1 ), ( \alpha = 90.0 ), ( U_{v_{\text{max}}} = 1.0 ) pu</td>
<td></td>
</tr>
<tr>
<td>Damping Control Loop:</td>
<td>( A_s = 0.01 ), ( D_r = 0.05 ), ( \alpha = 90.0 ), ( U_{d_{\text{max}}} = 1.0 ) pu</td>
<td></td>
</tr>
</tbody>
</table>

| Fuzzy Logic Speed Governing System | \( A_s = 0.5 \), \( D_r = 12.56 \), \( \alpha = 90.0 \), \( U_{g_{\text{max}}} = 1.0 \) pu |       |

| Conventional PSS | \( G_{\text{PSS}} = 10.0 \), \( T_2 = 0.16 \) s, \( T_d = 0.11 \) s, \( U_{\text{max}} = 1.0 \) pu |       |

### 5.3 Simulation Results

The critical power output is investigated following the disturbance (b) for the various combinations of the generator controllers as shown in Fig. 12. Table 2 also indicates the values of the performance index \( J_d \). As shown in Fig. 12 and Table 2, the widest stable region is achieved by the implementation of the proposed fuzzy logic excitation and speed governing control systems. The speed governing system has only the secondary effects for the stabilization because of the several restrictions for the valve opening and closing speed, the range of the turbine output regulation, and so on. When neglecting these constraints, drastic stabilizing effects are observed through the speed governing control, however, those effects are not realistic under actual operation because of the existence of the restrictions. In addition, the fuzzy logic speed governing system has the better performance comparing with the conventional governor.

Fig. 13 and Fig. 14 illustrate typical simulation results following the disturbance (b). The variations of the speed, the real power output, the turbine output, the excitation voltage, the terminal voltage, and the excitation control signal \( U_eo \), are illustrated.

![Fig. 12. Critical Power Output](image)

### Table 2. Values of Performance Index \( J_d \)

<table>
<thead>
<tr>
<th>( P_e [\text{pu}] )</th>
<th>CPSS</th>
<th>CPSS + CGOV</th>
<th>FEX</th>
<th>FEX + CGOV</th>
<th>FEX + FG0V</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.08</td>
<td>27.80</td>
<td>31.36</td>
<td>1.08</td>
<td>1.24</td>
<td>1.26</td>
</tr>
<tr>
<td>1.09</td>
<td>unstable</td>
<td>85.53</td>
<td>1.15</td>
<td>1.32</td>
<td>1.44</td>
</tr>
<tr>
<td>1.215</td>
<td>15.84</td>
<td>11.24</td>
<td>9.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.22</td>
<td>unstable</td>
<td>16.17</td>
<td>8.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.23</td>
<td>unstable</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.26</td>
<td>30.41</td>
<td>unstable</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CPSS: Conventional PSS, CGOV: Conventional Governor
FEX : Fuzzy Logic Excitation System
FGOV: Fuzzy Logic Speed Governing System
Fig. 13. Typical Simulation Results(I) with CPSS and CGOV ($P_{eo} = 1.08$ pu)

Fig. 14. Typical Simulation Results(II) with FEX and FGOV ($P_{eo} = 1.08$ pu)
6. Conclusions

The effectiveness of the proposed fuzzy logic excitation and speed governing systems have been investigated through the simulation studies. The fuzzy logic excitation system has better performance for both the voltage and the damping control, and a wider stable region is obtained by its implementation. The speed governing system has only secondary effects for the stabilization because of its various restrictions. The proposed excitation and speed governing systems do not require heavy computation, therefore, the implementation is readily available. In addition, required computation time is less than 1ms for each control loop, therefore, the integration of the control loops is also available by using only one micro-computer.

References


Appendix Polar Membership Functions

Two polar membership functions $N(\theta(k))$ and $P(\theta(k))$ are defined as shown in Fig. A to represent Sector A and Sector B, respectively. The values of $N(\theta(k))$ and $P(\theta(k))$ give the grades of increasing and decreasing control of the excitation voltage, respectively, for both the voltage and the damping controls in the excitation system. In addition, these two membership functions also give the grades of increasing and decreasing the turbine output for the speed control.

```
grade
N(\theta(k)) \alpha = 90^\circ \quad P(\theta(k))
```

\[
\begin{array}{cccccc}
0 & 90 & 135 & 180 & 270 & 315 & 360 \\
\theta [\text{degrees}] \\
\end{array}
\]

Fig. A. Two Polar Membership Functions

Biographies

Takashi Hiyama received his B.E., M.S., Ph.D. degrees all in Electrical Engineering from Kyoto University, Japan in 1969, 1971, and 1980, respectively. He joined Kumamoto University in 1971, and he has been a Professor since 1989 at the Department of Electrical Engineering and Computer Science. During the period of June 1985 through 1986, he was at Clarkson University, and was involved with power system harmonics project. His current interests include stabilizing control of power systems using fuzzy logic, and control and operation of photovoltaic systems. He is a Senior Member of IEEE, a Member of IEE of Japan, SICE of Japan, and Japan Solar Energy Society.

Yoshiteru Ueki received his M.S. degree from Department of Engineering Science Research, Osaka University in 1977. He has been in Fuji Electric Co. Ltd. since April 1977. He is engaged in analysis and control of power systems and development of intelligent systems.

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