Steam-Hydraulic Turbines Load Frequency Controller Based on Fuzzy Logic Control

1,4Ali M. Yousef, 2Jabril A. Khamaj and 3,4Ahmad Said Oshaba

1Electrical Engineering Department Faculty of Engineering, Assiut University, Egypt, 71516,
2Mechanical Engineering Department Faculty of Engineering Jazan University, KSA
3Power Electronics and Energy Conversion Department, Electronics Research Institute, Egypt
4Electrical Engineering Department Faculty of Engineering Jazan University, KSA

Abstract: This study investigates an application of the fuzzy logic technique for designing the load-frequency control system to damp the frequency and tie line power oscillations due to different load disturbances under the governor deadzones and GRC non-linearity. Integral controller are designed and compared with the proposed fuzzy logic controller. To validate the effectiveness of the proposed controller, two-area load frequency power system is simulated over a wide range of operating conditions and system parameter changes. Further, comparative studies between the conventional PID control and proposed efficient fuzzy logic load frequency control are included on the simulation results. Programs Matlab software are developed for simulation. The digital results prove the power of the present fuzzy load-frequency controller over the conventional. PID controller in terms of fast response with less overshoot and small settling time.

Keywords: Fuzzy logic controller, PID controller, steam-hydraulic turbines

INTRODUCTION

Power systems have complex and multi-variable structures. Also they consist of many different controls blocks. Most of them are non-linear. Power systems are divided into control areas connected by tie lines. From the experiments on the power systems, it can be seen that each area need to its system frequency and tie line power flow to be controlled. Frequency control is accomplished by two different control actions in interconnected two area power system: primary speed control and supplementary or secondary speed control actions as in Ertugrul and Ilhan (2005), El-Sherbiny et al. (2001) and El-Sherbiny et al. (2002). The secondary loop takes over the fine adjustment of frequency by resetting the frequency error to zero through integral action. The relationship between the speed and load can be adjusted by changing a load reference set point input.

Load-Frequency Control (LFC) is important in electric power system design and operation. Moreover, to ensure the quality of the power supply, it is necessary to design a LFC system, which deals with the control of loading of the generator depending on the frequency. The conventional proportional plus integral controller is probably the most commonly used. It is well known that power systems are non-linear and complex, where the parameters are a function of the operating point and the loading in a power system is never constant. Further, the two area power system composed of steam turbines controlled by integral control only, is sufficient for all load disturbances and it does not work well. Also, the non-linear effect due to governor deadzones and Generation Rate Constraint (GRC) complicates the control system design. Further, if the two area power system contains hydro and steam turbines, the design of LFC systems is important. There are different control strategies that have been applied, depending on linear or non-linear control methods as in Saadat (1980), Kothari et al. (2000) and found in Anju and Sharma (2011). With the advent of fuzzy logic theory, various applications for it have been established as in Pan and Liaw (1989), Saravuth et al. (2006) and as in Yusuf and Ahmed (2004). It is considered that the fuzzy logic control system works well with non-linear systems. The present study utilizes the fuzzy logic control technique control to design the LFC system for two area power systems. The proposed technique is added to the integral control LFC system as a supplementary signal to improve the power system stability and response characteristics. Also, the non-linear effect due to governor dead zones or GRC are
considered as in Yousef (2011). The types of turbines employed in the two area power system, steam-hydro, are studied with the proposed fuzzy logic control technique.

**MATERIALS AND METHODS**

The system investigated comprises an interconnection of two areas load frequency control. The model is steam-hydraulic turbines. The linearized mathematical models of the first order system are represented by state variables equations as follows:

**For steam area as:**

\[
\Delta f_1 = -1/T_{p1}\Delta f_1 + k_{p1}/T_{p1}\Delta P_{g1} - k_{p1}/T_{p1}\Delta P_{tie}
\]

\[
\Delta \dot{P}_{g1} = -1/T_{i1}\Delta P_{g1} + \Delta P_{tie}[1/T_{i1} - K_{ii}/T_{i1}]
\]

\[
\Delta \dot{P}_{t1} = 1/T_{i1}\Delta X_{E1} - 1/T_{i1}\Delta P_{tie}
\]

\[
\Delta \dot{X}_{E1} = -1/R_{i1}T_{g1}\Delta f_1 - 1/T_{g1}\Delta X_{E1} + 1/T_{g1}\Delta E_{x1}
\]

\[
\Delta \dot{E}_{x1} = -K_{E1}[B_1\Delta f_1 + \Delta P_{tie}]
\]

**For hydraulic area as:**

\[
\Delta f_2 = -1/T_{p2}\Delta f_2 + k_{p2}/T_{p2}\Delta P_{g2} - k_{p2}/T_{p2}\Delta P_{tie}
\]

\[
\Delta \dot{P}_{g2} = - \Delta P_{tie}[1/S_{T_i} + (1/S_{T_2} - T_p/S_{T_2}T_i)]
\]

\[
+ \Delta X_{E2}[1/S_{T_i} + 1/S_{T_2} - T_p/S_{T_2}T_i]R_2\Delta f_2
\]

\[
\Delta \dot{E}_{x2} = -K_{E2}[B_2\Delta f_2 + a12*\Delta P_{tie}]
\]

The tie line power as:

\[
\Delta P_{tie} = 2\pi T_2[\Delta f_1 - \Delta f_2]
\]

The overall system can be modeled as a multi-variable system in the form of:

\[
x = A(t)x(t) + B(t)u(t) + L(t)d(t)
\]

where A is system matrix, B and L are the input and disturbance distribution matrices.

\[
x(t), u(t) \text{ and } d(t) \text{ are system state, control signal and load changes disturbance vectors, respectively:}
\]

\[
x(t) = [x_1(x_2)]^T
\]

\[
u(t) = [u_1 u_2]^T
\]

\[
d(t) = [d_1 d_2]^T
\]

\[
ACE_i = \Delta p_{tie,i} + b_i \Delta f_i
\]

\[
y(t) = C(t)x(t)
\]

\[
\Delta p_{tie}(t) = \Delta p_{tie,1}(t) - \Delta p_{tie,2}(t)
\]

\[
A = \begin{bmatrix}
\frac{-1}{T_{i1}} & \frac{k_{i1}}{T_{i1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{k_{i2}}{T_{i2}}
0 & \frac{-1}{T_{i2}} & \frac{k_{i2}}{T_{i2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
0 & 0 & \frac{-1}{T_{i1}} & \frac{k_{i1}}{T_{i1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\frac{-1}{R_{i1}T_{i1}} & 0 & 0 & \frac{-1}{T_{p1}} & \frac{1}{T_{p1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\frac{1}{T_{i1}} & 0 & 0 & \frac{-1}{T_{p2}} & \frac{1}{T_{p2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\frac{1}{T_{i2}} & 0 & 0 & \frac{-1}{T_{p1}} & \frac{1}{T_{p1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\frac{1}{R_{i2}T_{i2}} & 0 & 0 & \frac{-1}{T_{p2}} & \frac{1}{T_{p2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\frac{1}{T_{i2}} & 0 & 0 & \frac{-1}{T_{p1}} & \frac{1}{T_{p1}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\frac{1}{R_{i2}T_{i2}} & 0 & 0 & \frac{-1}{T_{p2}} & \frac{1}{T_{p2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\frac{1}{T_{i1}} & 0 & 0 & \frac{-1}{T_{p2}} & \frac{1}{T_{p2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\frac{1}{R_{i2}T_{i2}} & 0 & 0 & \frac{-1}{T_{p2}} & \frac{1}{T_{p2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\frac{1}{T_{i1}} & 0 & 0 & \frac{-1}{T_{p2}} & \frac{1}{T_{p2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\frac{1}{R_{i2}T_{i2}} & 0 & 0 & \frac{-1}{T_{p2}} & \frac{1}{T_{p2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\frac{1}{T_{i1}} & 0 & 0 & \frac{-1}{T_{p2}} & \frac{1}{T_{p2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\frac{1}{R_{i2}T_{i2}} & 0 & 0 & \frac{-1}{T_{p2}} & \frac{1}{T_{p2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\frac{1}{T_{i1}} & 0 & 0 & \frac{-1}{T_{p2}} & \frac{1}{T_{p2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\frac{1}{R_{i2}T_{i2}} & 0 & 0 & \frac{-1}{T_{p2}} & \frac{1}{T_{p2}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]
\[
B = \begin{bmatrix}
0 & 0 & 0 & \frac{1}{T_g} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{T_i} & 0 & 0 & 0 & 0 & 0
\end{bmatrix}^T
\]

\[
L = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -\frac{K_{r1}}{T_{r1}} & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}^T
\]

where,

\[\Delta f_1, \Delta f_2 = \text{The frequency deviation (HZ) of area No. 1 and area No. 2}\]

\[\Delta P_{g1}, \Delta P_{g2} = \text{The change in generator output (p.u. MW) of area No. 1 and area No. 2}\]

\[\Delta X_{e1}, \Delta X_{e2} = \text{The change in governor value position (p.u. MW) of area No. 1 and area No. 2}\]

\[\Delta P_{d1}, \Delta P_{d2} = \text{The change in turbine values (p.u. MW) of area No. 1 and area No. 2}\]

\[\Delta E_{X1}, \Delta E_{X2} = \text{The change in integral control of area No. 1 and area No. 2}\]

\[\Delta P_{d1}, \Delta P_{d2} = \text{Load disturbance (p.u. MW) of area No. 1 and area No. 2}\]

\[T_{g1}, T_{g2} = \text{Governor time constant (s) of area No. 1 and area No. 2}\]

\[T_{r1}, T_{r2} = \text{Turbine time constant (s) of area No. 1 and area No. 2}\]

\[T_p = \text{Plant model time constant (s)}\]

\[K_p = \text{Plant gain}\]

\[R = \text{Speed regulation due to governor action (HZ/p.u. MW)}\]

\[K_{i1} = \text{The integral control gain}\]

**Effect of governor dead zones non-linearity:** Figure 1 shows the power system block diagram with governor dead zones. The described of governor dead zones \(D(v)\) by the following function:

\[m(v-d), \text{if } v \geq d\]

\[D[v] = 0, \{\text{if } d \leq v \leq d\}\]

\[\{m(v+d) \text{ if } v \leq d\}\]

**Effect of GRC non-linearity:** The block diagram of the plant model with Generation Rate Constraint (GRC) given by \(\Delta P_g \leq 0.0017\) p.u. MW/s is shown in Fig. 1

**Fuzzy logic control:** Fuzzy logic has an advantage over other control methods due to the fact that it does not sense to plant parameter variations. The fuzzy logic control approach consists of three stages, namely fuzzification, fuzzy control rules engine and defuzzification. To design the fuzzy logic load frequency control, the input signals is the frequency deviation at sampling time and its change. While, its output signal is the change of control signal \(\Delta U(k)\). When the value of

![Fig. 1: Two-Area (Steam-Hydraulic Turbines) load frequency control with governor deadzone and GRC nonlinearity](image-url)
Fig. 2: Three-stage of fuzzy logic controller: u, membership degree

Fig. 3: Fuzzy logic power system stabilizer

Table 1: Fuzzy logic control rules

<table>
<thead>
<tr>
<th>Δf</th>
<th>LN</th>
<th>MN</th>
<th>SN</th>
<th>Z</th>
<th>SP</th>
<th>MP</th>
<th>LP</th>
</tr>
</thead>
<tbody>
<tr>
<td>LN</td>
<td>LP</td>
<td>LP</td>
<td>LP</td>
<td>MP</td>
<td>MP</td>
<td>SP</td>
<td>Z</td>
</tr>
<tr>
<td>MN</td>
<td>LP</td>
<td>MP</td>
<td>MP</td>
<td>MP</td>
<td>SP</td>
<td>Z</td>
<td>SN</td>
</tr>
<tr>
<td>SN</td>
<td>LP</td>
<td>MP</td>
<td>SP</td>
<td>SP</td>
<td>Z</td>
<td>SN</td>
<td>MN</td>
</tr>
<tr>
<td>Z</td>
<td>MP</td>
<td>MP</td>
<td>SP</td>
<td>Z</td>
<td>SN</td>
<td>MN</td>
<td>MN</td>
</tr>
<tr>
<td>SP</td>
<td>MP</td>
<td>SP</td>
<td>Z</td>
<td>SN</td>
<td>SN</td>
<td>MN</td>
<td>LN</td>
</tr>
<tr>
<td>MP</td>
<td>SP</td>
<td>Z</td>
<td>SN</td>
<td>MN</td>
<td>MN</td>
<td>MN</td>
<td>LN</td>
</tr>
<tr>
<td>LP</td>
<td>Z</td>
<td>SN</td>
<td>MN</td>
<td>MN</td>
<td>LN</td>
<td>LN</td>
<td>LN</td>
</tr>
</tbody>
</table>

Fig. 4: Membership functions of the fuzzy regulator

The control signal at sampling time [k-1] (U(k-1)) is added to the output signal of fuzzy logic controller, the required control signal U(k) is obtained. Figure 2 shows the three-stage of fuzzy logic controller. While the fuzzy logic control system is described in Fig. 3. The fuzzy control rules are illustrated in Table 1. The membership function shapes of error and derivative error and the gains are chosen to be identical with triangular function for fuzzy logic control. However, this horizontal axis range is taken different values because of optimizing controller. The membership function sets of FLC for two areas are shown in Fig. 4 where,

- LN : Large negative membership function
- MN : Medium negative
- SN : Small negative
- Z  : Zero
- SP : Small positive
- MP : Medium positive
- LP : Large positive

**PID power system stabilizer:** PID controllers are dominant and popular and, have been widely used because one can obtain the desired system responses and it can control a wide class of systems. This may lead to the thought that the PID controllers give solutions to all requirements, but unfortunately, this is not always true as in Datta et al. (2000). In this work, the PID optimal tuning method used is found in Kristiansson and Lennartson (2002). In this method, the parameters of PID controller satisfying the constraints correspond to a given domain in a plane. The optimal controller lies on the curve. The design plot enables identification of the PID controller for desired robust conditions and in particular, gives the PID controller for lowest sensitivity. By applying this method, trade-off among high frequency sensor noise, low frequency sensitivity, gain and phase margin constraints are also directly available.

The transfer function of a PID controller is given by:

$$K(s) = K_p(1 + 1/T_1 s + T_D s)$$

where $K_p$, $K_p/T_1$ and $K_p T_D$ represent the proportional, integral and derivative gains of the controller respectively. Define $\omega_n = \frac{1}{\sqrt{T_1 T_D}}$ and $\zeta = \frac{1}{2\sqrt{T_1 T_D}}$ as the controller's natural frequency and the damping coefficient, respectively. Then the PID transfer function can be written as:

$$K(s) = K_p \frac{\omega_n^2 s^2 + 2\zeta \omega_n s + s^2}{2\zeta \omega_n s}$$

(9)

The optimal PID controller parameters values were: $K_p = 2$, $T_1 = 0.6$ and $K_D = 1$

**RESULTS AND DISCUSSION**

To validate the effectiveness of the proposed fuzzy controllers, the power system under study is simulated and subjected to different parameters changes. The power system frequency deviations are obtained. Further a various types of turbines (steam and hydro) are simulated. Also a comparison between the power system responses using the conventional integral and PID control system and the proposed fuzzy logic controller is studied as follows and the system parameters are:

Nominal parameters of the hydro-thermal system investigated:

<table>
<thead>
<tr>
<th>Nominal parameters of the hydro-thermal system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>$\omega_n$</td>
</tr>
<tr>
<td>$\zeta$</td>
</tr>
</tbody>
</table>
\( f = 60 \) HZ \( R_1 = R_2 = 2.4 \) HZ/per unit MW  
\( T_{g1} = 0.08 \) s \( T_r = 10.0 \) s \( T_t = 0.3 \) s \( K_r1 = K_r2 = 1/3 \)  
\( P_{d1} = 0.05 \) p.u. MW  
\( B_1 = B_2 = 0.425 \)  
\( P_{d2} = 0.0 \)  
\( T_{r1} = T_{r2} = 20 \) s, \( T_{t1} = T_{t2} = 0.0707 \) s  
The integral control gain \( K_i = 1 \) pu

Figure 5 shows the frequency deviation response of area-1 due to 0.5 p.u. load disturbance in area-1 of the two-area power system with and without integral and proposed fuzzy logic control.

Figure 6 shows the frequency deviation response of area-2 due to 0.5 p.u. load disturbance in area-1 of the two-area power system with and without integral and proposed fuzzy logic control.

Figure 7 shows the tie-line power deviation response due to 0.5 p.u. load disturbance in area-1 of the two-area power system with and without integral and proposed fuzzy logic control.

Figure 8 depicts the tie-line power deviation response due to 0.5 p.u. load disturbance in area-1 of the two-area power system with and without integral and proposed fuzzy logic control at increased 20% in \( T_g \).

Figure 9 shows the frequency deviation response of area-1 due to 0.5 p.u. load disturbance in area-1 of the two-area power system with and without integral and proposed fuzzy logic control of model-2 at increased 20% in \( T_g \).
Fig. 10: Frequency deviation response of area-2 due to 0.5 p.u. load disturbance in area-1 of the two-area power system with and without integral and proposed fuzzy logic control at increased 20% in Tg.

Fig. 11: Frequency deviation response of area-1 due to 0.5 p.u. load disturbance in area-1 of the two-area power system with and without integral and proposed fuzzy logic control at change in Tt, Tr.

Fig. 12: Frequency deviation response of area-2 due to 0.5 p.u. load disturbance in area-1 of the two-area power system with and without integral and proposed fuzzy logic control at change in Tt, Tr.

20% in Tg. Figure 9 depicts the frequency deviation response of area-1 due to 0.05 p.u. load disturbance in area-1 of the two-area power system with and without integral and proposed fuzzy logic control at increased 20% in Tg. Moreover, Fig. 10 depicts the frequency deviation response of area-2 due to 0.5 p.u. load disturbance in area-1 of the two-area power system with and without integral and proposed fuzzy logic control at increased 20% in Tg. Figure 11 displays the frequency deviation response of area-1 due to 0.5 p.u. load disturbance in area-1 of the two-area power system with and without integral and proposed fuzzy logic control at increased 20% in Tg. Figure 12 shows the frequency deviation response of area-2 due to 0.5 p.u. load disturbance in area-1 of the two-area power system with and without integral and proposed fuzzy logic control at increased 20% in Tg. Figure 13 depicts the frequency deviation response of area-2 due to 0.5 p.u. load disturbance in area-1 of the two-area power system with and without integral and proposed fuzzy logic control at increased 20% in Tg. Figure 14 shows the frequency deviation response of area-2 due to 0.5 p.u. load disturbance in area-1 of the two-area power system with and without integral and proposed fuzzy logic control at increased 20% in Tg.
CONCLUSION AND RECOMMENDATIONS

The present study designs a load-frequency control system using fuzzy logic controller for enhancing power system dynamic performances after applying several disturbances upon it. The proposed controller is robust and gives good transient as well as steady-state performance. To validate the effectiveness of the proposed controller a comparison among the conventional integral and PID controller and the proposed controller is obtained. The effect of governor non-linear and GRC is included in the simulation. The proposed controller proves that it is robust to variations in dead zones non-linearity. The digital simulation results proved and show the effectiveness of the power of the proposed FLC over the conventional integral and PID controller through a wide range of load disturbances. The superiority of the proposed fuzzy controller is embedded in the sense of fast response with less overshoot and/or undershoot and less settling time.

REFERENCES