CHAPTER 4

LOAD FREQUENCY CONTROL OF INTERCONNECTED
HYDRO-THERMAL SYSTEM

4.1 INTRODUCTION

Reliable power delivery can be achieved through interconnection of hydro and thermal system. In recent years, major hike in power demand has been seen from the industrial and domestic side all around the world. To surpass this demand major changes have been made in power station to improve the efficiency and to increase the generating power. Besides the interconnected thermal system, this hydro-thermal system can deliver its full capacity.

Seeing the omission of non-linearities in hydro-thermal system, the research interest is focused towards the incorporation of non-linearities and boiler dynamics in thermal area and to design a reliable fuzzy logic based load frequency controller. Bhise et al (1993) presented optimum selection of hydro governor parameters for AGC of a hydro thermal system.

This method provides both the areas controlled by separate FLCs in order to improve the reliability of power supply in power system control operations. The main contribution is that FLC is responsible to suppress frequency oscillations and tie-line power deviations. According to this, FLC controls not only thermal area but also hydro area. In thermal interconnections, both the areas have same non-linearities and BD. In hydro-
thermal system, hydro area does not having boiler dynamic character. But there is a necessary to incorporate governor dead band and generation rate constraint.

The proposed strategy is that in FLC, the Area Control Error (ACE) parameter is also optimized. Furthermore, this control mechanism needs no other parameters to check.

The rest of the chapter is organized as follows. Section 4.2 presents the open loop responses of interconnected hydro-thermal system. Section 4.3 discusses in detail about optimum design of PI gains. Section 4.4 and 4.5 presents the model of hydro-thermal system with PI controller and its responses respectively. Section 4.6 enumerates the implementation of fuzzy logic controller. Section 4.7 presents the model of hydro-thermal system FL controller. Section 4.8 presents responses with PI and FL controller, also discusses the performance analysis of both controllers. Finally, section 4.9 concludes this chapter by summarizing remarks.

4.2 OPEN LOOP RESPONSES

To study the performance of interconnected hydro-thermal system, the transfer function model which is developed in chapter 2, Figure 2.5 is simulated for 200s and the details of system parameters are enumerated in Appendix 1. The 1% step load disturbance is given in hydro area due to the reason that, as said by Nanda et al (2006), the settling time and steady state error parameters are taken more time to settle down than in thermal area.

Figure 4.1 to 4.3 shows the open loop responses of interconnected hydro-thermal system when a step load disturbance is given in hydro area.
Figure 4.1 Open Loop Frequency Deviation in Thermal Area

Figure 4.2 Open Loop Frequency Deviation in Hydro Area
4.2.1 Inference

It is learnt from the Figures 4.1 to 4.3 that, obviously the system parameters are not settled. In other words, frequency peak in Figures 4.1 and 4.2 are quite high and steady state error and settling time in Figures 4.1 to 4.3 are large. It is not advisable to have such situation prolonged. The above said three parameters are enough to judge the system performance. Moreover, the following table clearly depicts the facts.

Table 4.1(a) Observations in Open Loop Frequency Deviation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Thermal Area</th>
<th>Hydro Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency peak (Hz)</td>
<td>-0.114</td>
<td>-0.113</td>
</tr>
<tr>
<td>Settling time (s)</td>
<td>200</td>
<td>194</td>
</tr>
<tr>
<td>Steady state error (Hz)</td>
<td>-0.0285</td>
<td>-0.0286</td>
</tr>
</tbody>
</table>
Table 4.1(b) Observation in Open Loop Tie Line Power Deviation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Hydro Area, Area 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power (pu MW)</td>
<td>-0.0118</td>
</tr>
<tr>
<td>Settling time (s)</td>
<td>200</td>
</tr>
<tr>
<td>Steady state error (pu MW)</td>
<td>-3.4x10^{-3}</td>
</tr>
</tbody>
</table>

By analyzing the Tables 4.1(a) and (b), the frequencies and tie line power are out of the range, in other words, up to 200s these parameters are oscillating. Similarly the peak power and steady state error are quite high. In this scenario, it is necessary to employ conventional controller scheme to suppress the oscillations, thereby avoiding the unstable condition to the power system.

4.3 OPTIMUM DESIGN OF PI GAINS

To achieve better dynamic performance and to provide accuracy, Proportional Integral (PI) controller is adopted. The main idea of implementing PI controller is to actuate the load reference point until the frequency deviation becomes zero. Integral controller provides zero steady state frequency deviation and proportional controller reduce the overshoot. The load frequency controller is based upon tie line bias control where each area tends to reduce the Area Control Error (ACE) to zero. As described in section 3.5, here also Integral Square Error (ISE) technique is used to get optimum PI gains. Figure 4.4 illustrates the performance index curve.

The objective function used for hydro-thermal system to optimize PI gains:

\[ J = \int_0^1 (\Delta F_1^2 + \Delta F_2^2 + \Delta P_{\text{tie}}^2) \, dt \] (4.1)
Equations (3.2) and (3.3) deliver the controlled output to the system. By using equation (4.1), the tuning values of optimum proportional-integral controller gains are found to be $K_p = 0.3$ and $K_i = 0.12$. In other words, first find optimum integral controller gain. Then fix $K_i$ as constant then tune $K_p$.

![Figure 4.4 Performance Index Curve for Hydro-Thermal System](image)

4.4 HYDRO-THERMAL SYSTEM WITH PI CONTROLLER

A scenario of thermal system in area 1 and hydro system in area 2 in the interconnected group share the load disturbance. Figure 4.5 illustrates the interconnected hydro-thermal system with PI controller. When load disturbance occurs in hydro area, that is, power demand, its neighbor thermal area can deliver those demand at this time. In brief, power demand is compensated by neighbor area. The control mechanism of this controller is simple. The other reasons to use that controller are:

- Proportional controller reduces peak overshoot, here in, frequency peak and tie line power peak.
- Integral controller settles the system on set point, thereby nullifying steady state error, here, frequency deviation and tie line power deviation in zero.

- In the combination of both, PI controller reduces peak overshoots and settles the system on set point.

Figure 4.5 Interconnected Hydro-Thermal System with PI Controller

4.5 RESPONSES

In order to validate the PI controller, however, 1% of step load disturbance in simulated in hydro area, the responses are depicted in Figures 4.6 to 4.8. The optimum values of PI gains are obtained as described in section 4.3. Each area in Figure 4.5 is controlled by conventional PI controller.
Figure 4.6 Comparison of Frequency Deviation in Thermal Area

Figure 4.7 Comparison of Frequency Deviation in Hydro Area
4.5.1 Inference

In order to improve the system performance proportional-integral controller is designed and simulated for interconnected hydro system. The responses are shown from Figures 4.6 to 4.8. PI controller gives better performance than open loop responses. In PI controller, the system is settled with larger settling time and frequency peak is considerably reduced. Thereby, this controller makes the improvement at its maximum.
Table 4.2(a) Frequency Deviation Comparison

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Thermal Area</th>
<th>Hydro Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Open Loop</td>
<td>PI</td>
</tr>
<tr>
<td>Frequency peak (Hz)</td>
<td>-0.114</td>
<td>-0.102</td>
</tr>
<tr>
<td>Settling time (s)</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Steady state error (Hz)</td>
<td>-0.0285</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Table 4.2(b) Tie Line Power Deviation Comparison

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Hydro Area, Area 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Open Loop</td>
</tr>
<tr>
<td>Peak power (pu MW)</td>
<td>-0.0118</td>
</tr>
<tr>
<td>Settling time (s)</td>
<td>200</td>
</tr>
<tr>
<td>Steady state error (pu MW)</td>
<td>-3.4x10^{-3}</td>
</tr>
</tbody>
</table>

By referring Tables 4.2 (a) and (b), the responses are not settled up to full length of simulations (200s), due to the reason that, the fixed PI gains. In brief, if the time varies, the error on frequency and tie line changes. In order to deliver good control strategy, the corresponding controller value should change. When the error is maximum, controller value should also be maximum and vice versa. In this way, the controller values are repeated until the error found zero.

In this situation, a fuzzy logic based load frequency controller is the suitable to provide adequate control performance.
4.6 IMPLEMENTATION OF FLC

Fuzzy logic controller is implemented to improve the dynamic performance of interconnected system. It is clear that from the Tables 4.1(a) and 4.1(b), conventional PI controller does not provide adequate control performance with the consideration of non-linearities and boiler dynamics. This is because of the reason that, the fixed value of PI gains.

In order to ratify the decentralized nature of gains, FLC is proposed. Figure 3.13 demonstrates the fuzzy logic controller, which includes the inputs of ACE and $\dot{\text{ACE}}$. The simulation environment is identical to that of section 3.8 as in thermal system.

**Figure 4.9(a) Input (ACE)**

![Figure 4.9(a) Input (ACE)](image)

**Figure 4.9(b) Input ($\dot{\text{ACE}}$)**

![Figure 4.9(b) Input ($\dot{\text{ACE}}$)](image)
As far as the design of FLC is considered, membership function of input (ACE), change in input (ACE) and output are shown in Figure 4.9 (a), (b) and (c) respectively. Each function is partitioned into seven variables. The linguistic variables are:

- Negative Big (NB)
- Negative Medium (NM)
- Negative Small (NS)
- Zero (ZO)
- Positive Small (PS)
- Positive Medium (PM) and
- Positive Big (PB).

As far as fuzzy based controller for hydro-thermal system is considered, the simulation time is increased to 200s.
4.7 HYDRO-THERMAL SYSTEM WITH FLC

In order to validate the proposed FLC for interconnected hydrothermal system, the existing PI controller is replaced by FLC. Two separate controllers are provided. As defined by equation (3.4), the inputs are given to the fuzzy logic controller.

![Diagram of Interconnected Hydro-Thermal System with FLC](image)

Figure 4.10 Interconnected Hydro-Thermal System with FLC

4.8 RESPONSES WITH PI AND FLC

Figure 4.10 is simulated with 1% step load disturbance in hydro area.
Figure 4.11 Frequency Deviation in Thermal Area with FLC

Figure 4.12 Frequency Deviation in Hydro Area with FLC
4.8.1 Performance Analysis

This section presents the discussion of simulation results obtained for a multi area interconnected hydro-thermal system with fuzzy logic controller. The performance of the FLC with non-linearities is tested with conventional PI controller.

Table 4.3(a) Comparison of Frequency Deviation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Thermal Area</th>
<th>Hydro Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PI</td>
<td>FLC</td>
</tr>
<tr>
<td>Frequency peak (Hz)</td>
<td>-0.102</td>
<td>-0.11</td>
</tr>
<tr>
<td>Settling time (s)</td>
<td>200</td>
<td>170</td>
</tr>
<tr>
<td>Steady state error (Hz)</td>
<td>0.002</td>
<td>0</td>
</tr>
</tbody>
</table>
By seeing the Table 4.3 (a), it shows clearly that the performance of fuzzy logic controller is superior to conventional PI controller. As far as the settling time is concerned, with PI the system would not settle until 200s. But fuzzy logic controller settles down the parameter at 170s and 180s. Similar action is obtained in steady state error.

### Table 4.3(b) Comparison of Tie Line Power Deviation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Hydro Area, Area 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PI</td>
</tr>
<tr>
<td>Peak power (pu MW)</td>
<td>-0.0132</td>
</tr>
<tr>
<td>Settling time (s)</td>
<td>200</td>
</tr>
<tr>
<td>Steady state error (pu MW)</td>
<td>$1 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Fuzzy logic controller acts swiftly in tie line power deviation parameter also. The peak power is reduced and steady state error is zero, on the other hand, PI controller unable to bring the system stable.

By analyzing the above circumstances, fuzzy logic controller delivers good control performance with GRC, GDB and BD. In addition that, this proposed controller performance is justified through area control error. ACE determines the amount of error in the control area. If the ACE parameter is controlled better than PI controller, then the proposed controller, it is also said to be superior to conventional controller. This justification is shown in Figure 4.14 and 4.15.
Figure 4.14 Area Control Error 1

Figure 4.15 Area Control Error 2
4.9 CONCLUSION

The new technique of fuzzy logic based load frequency controller for interconnected hydro thermal system considering non-linearities and boiler dynamics is presented in this chapter. The robustness of the controller is a function of both the area size and non-linearities presented on each area (Anand and Ebenezer Jeyakumar (2011)). The properties of fuzzy based load frequency controllers such as rule base design, membership function shapes and method of defuzzification.

In order to reduce area control error and achieve quality of power supply, FL controller extends the application to interconnected hydro-thermal system. When a step load disturbance of 1% is given in hydro area, to check the reliability, FL controller performs fine over PI controller.

Seven linguistic variables in two inputs and output improve quality of the controller, in other words, it can accommodate a wide range of errors. The performance evaluations of fuzzy controller for hydro-thermal system with GRC alone in hydro area and GRC, GDB and BD in thermal area, is superior to conventional PI controller (Anand and Ebenezer Jeyakumar (2008e)). FL controller for interconnected hydro-thermal system with non-linearities in both the areas gives good results, is advocated by the control of area control error parameter (Anand and Ebenezer Jeyakumar (2009b)).

FL based LF Controller focuses on optimization scheme of area control error by fuzzy rules. However the non-linear characteristics control is also a key issue in providing reliable power supply. The validity of this technique for these useful applications gets confirmed with its repeatability and agreement with literature.