Chapter 5

Simulation Results and Analysis -Two Area System

5.1 Introduction

The control strategies i.e. linear quadratic regulator and fuzzy logic based integral control for load frequency control problem of interconnected power system have been discussed in detail in the previous chapter. The results of two area power system with different system conditions when proposed schemes are implemented are presented in this chapter.

For all simulation purpose, MATLAB/ Simulink 7.0 version [136] is used. Fuzzy logic toolbox is used in designing fuzzy logic controller for this problem of power system control. All data taken are IEEE standard data given in Appendix A. Results in this chapter are arranged in the sequence of control strategy applied to the system. First results of linear quadratic regulator technique are presented with different cases of Q and R matrices. Second part of chapter presents the results obtained when fuzzy logic based integral controller is applied to two area system with different cases (Block diagrams are given in chapter 3) as given below.

- Two area system with non-reheat turbine.
- Two area system with reheat turbine.
- Two area system with non-reheat turbine and GRC.
- Two area system with reheat turbine and GRC.
- Two area system with one non-reheat and one hydro turbine.
- Two area system with one reheat and one hydro turbine.
- Two area system with parallel AC/HVDC link

Robustness of the designed controller is also checked by varying three important parameters i.e. frequency bias constant, tie-line constant, and power system time constant to $\pm 30\%$ of their nominal values.

5.2 Results with LQR Technique

Two area system with non-reheat turbine when subjected to 1% change in load gives variation in frequency of area 1 and area 2 along with variations in tie line power. In this case program, when given the system matrices, checks for controllability and observability, and if the conditions are satisfied, solves the necessary conditions for the optimal control matrix on the basis of algorithm in previous chapter. The system was simulated on computer for the optimal gains. Four cases were tried and all through A and B matrix did not change throughout. The Q and R matrices were varied to show their effect on the system response. Matrices Q and R are given in chapter 4.

The figures 5.1 to figure 5.4 illustrate the improvement in damping of the system given by the optimal controller. The controller for each area is a function of the states of both areas. It is observed that the controller of area 1 depends weakly on information received from area 2 and vice-versa. The control system is essentially non-interacting. Figure 5.5 shows the best response obtainable in the sense of minimizing the tie-line deviation using the control strategy employed since only x_1, x_2 and x_6 states are taken in to consideration. Obtained feedback gain matrix K and eigen values for all cases are listed below each figure. On inspection, it is inferred that with optimal linear quadratic regulator designed in present study, the system stability is ensured in all cases as eigen value in each case has negative real part. In figure 5.5 the dynamic response parameters obtained are: peakovershoot as -0.0171 Hz and settling time as 10.20 seconds.

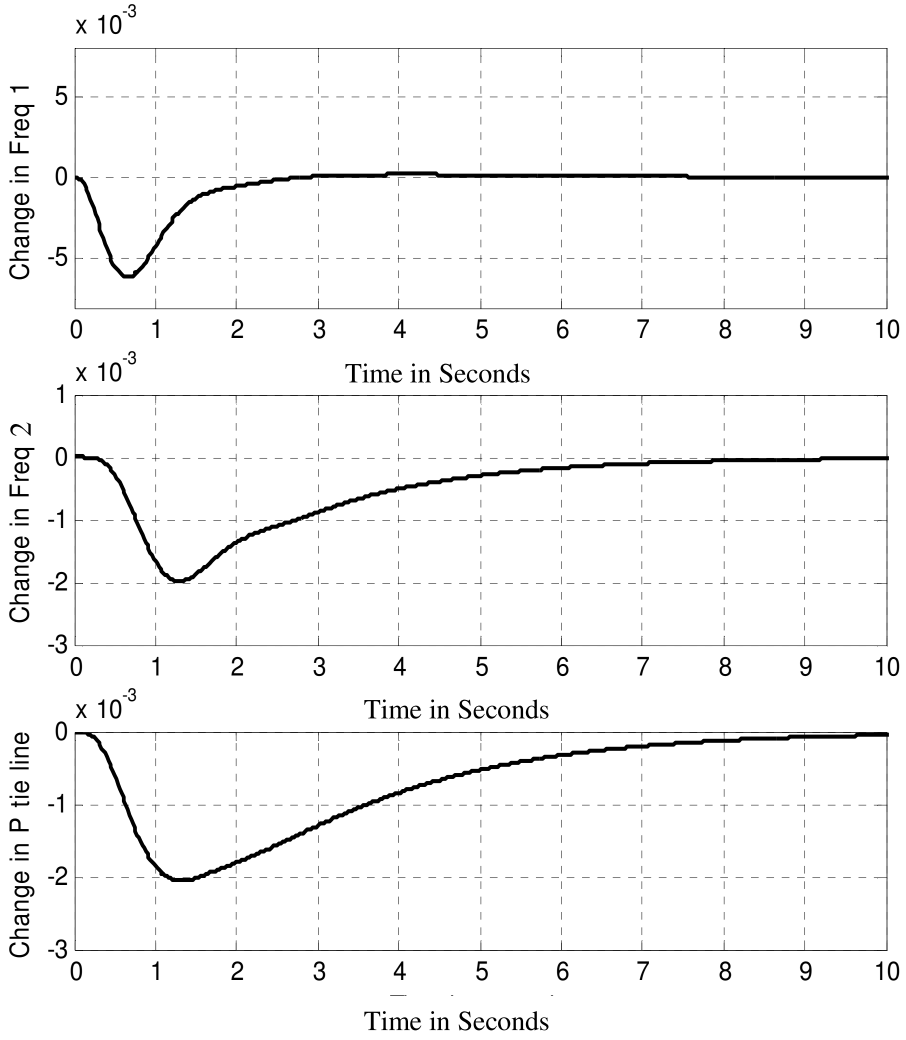

Figure 5.1: System dynamic responses for LQR (when Q and R as defined)

First Case (Figure 5.1):

```
K =       0.7071    0.2991    0.9324    1.2762    0.2964    0.7009    0.0639    0.0305    0.0063
         -0.7071    0.7009    0.0639    0.0305    0.0063    0.2991    0.9324    1.2762    0.2964

E =
         -13.3307
         -13.3596
         -2.1812 + 4.1796i
         -2.1812 - 4.1796i
         -2.6976 + 3.6402i
         -2.6976 - 3.6402i
         -1.3265
         -0.4902
         -0.9116
```

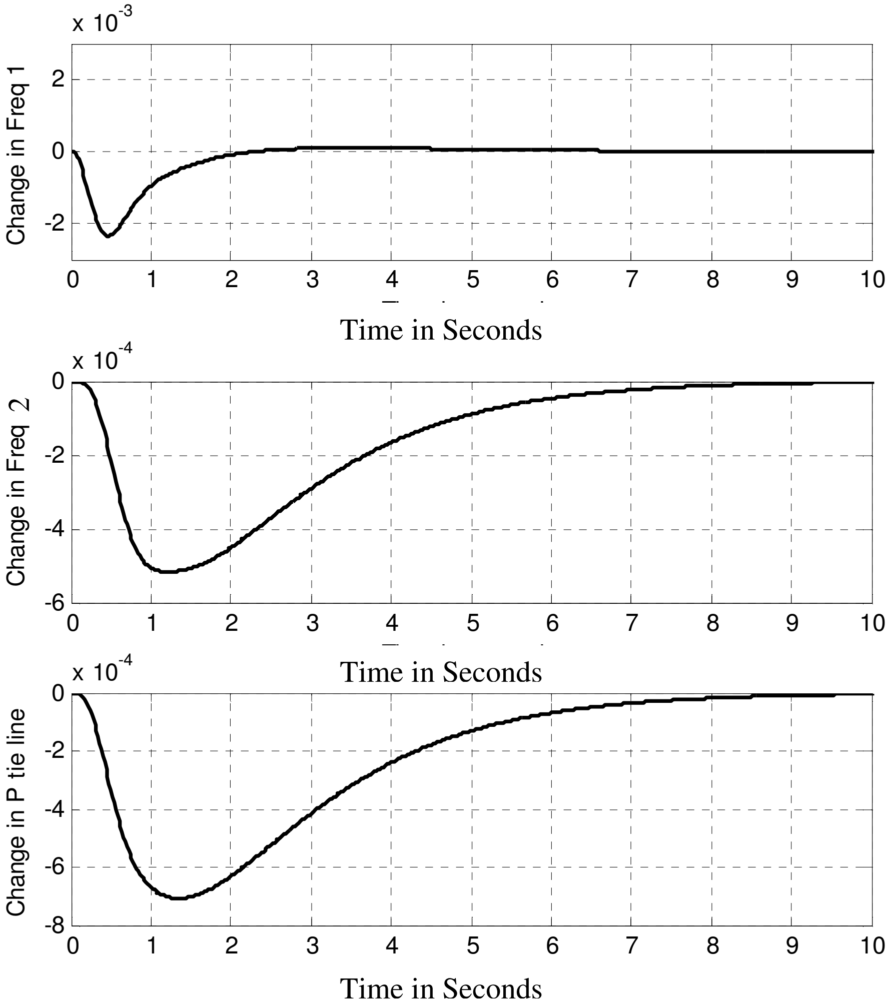

Figure 5.2: System dynamic response for LQR, (Q multiplied by 10, R as defined)

Second Case (Figure 5.2):

```
K =       2.2361   1.9259   3.4795   3.4085   0.6786   1.2364   0.0027  -0.0353  -0.0056
         -2.2361   1.2364   0.0027  -0.0353  -0.0056   1.9259   3.4795   3.4085   0.6786

E =
         -13.8261
         -4.4154 + 6.2259i
         -4.4154 - 6.2259i
         -13.8779
         -4.7143 + 5.9439i
         -4.7143 - 5.9439i
         -0.7023
         -1.0772
         -0.9898
```

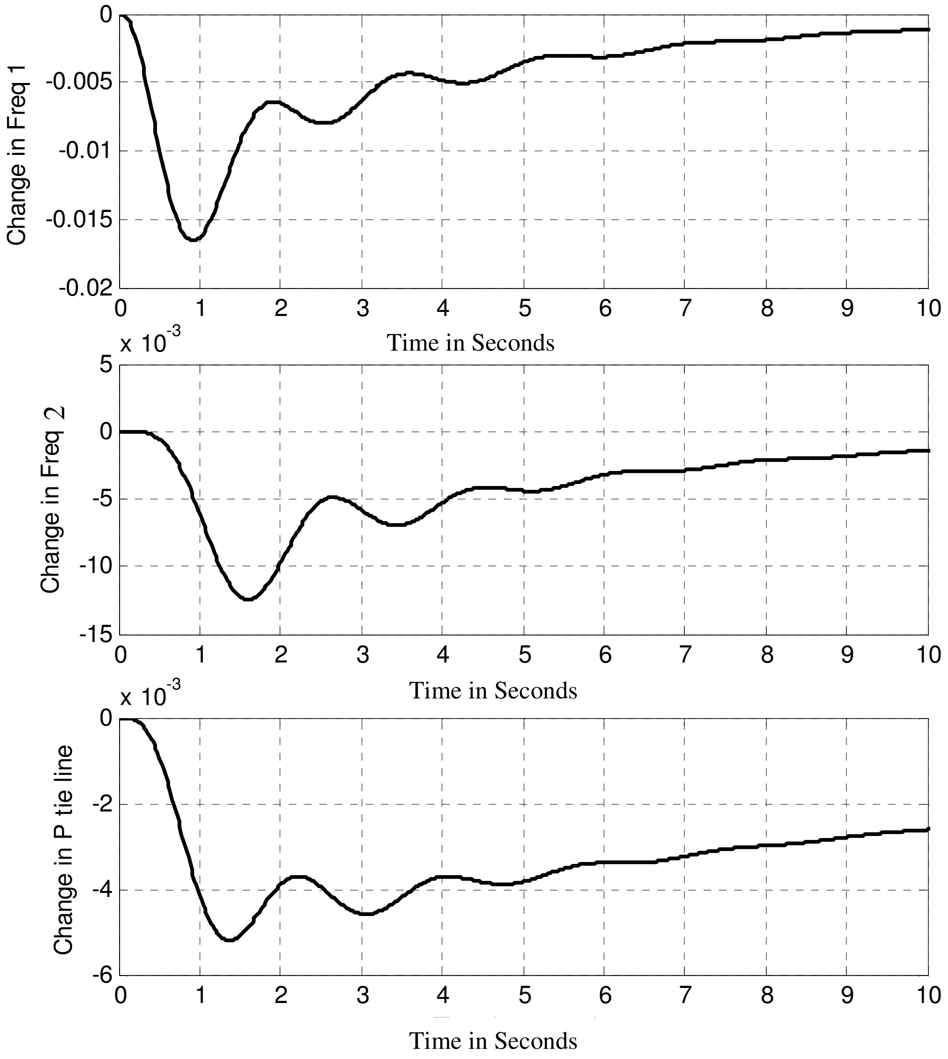

Figure 5.3: System dynamic responses for LQR (Q as defined and R multiplied by 100).

Third Case (Figure 5.3):

```
K =       0.0707   0.0457   0.0389   0.0743   0.0196   0.0543   0.0132   0.0196   0.0051
         -0.0707   0.0543   0.0132   0.0196   0.0051   0.0457   0.0389   0.0743   0.0196
E =
          -13.2658
          -13.2909
           -0.5554 + 3.5310i
           -0.5554 - 3.5310i
           -1.6176
           -0.0703
           -1.3366 + 2.5405i
           -1.3366 - 2.5405i
           -0.2283
```

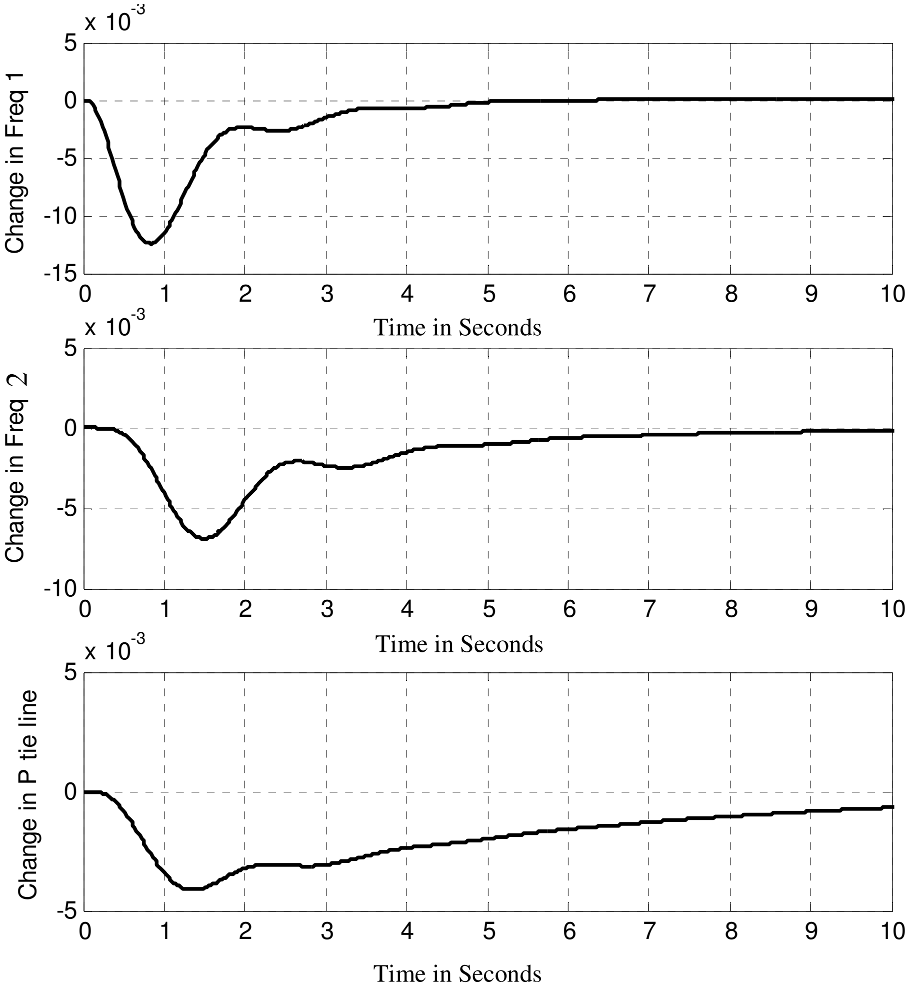

Figure 5.4: System dynamic response for LQR, (Q multiplied by 10 and R by 100).

__Fourth Case (Figure 5.4):__

```
K =      0.2236   0.0797   0.1962   0.3496   0.0892   0.2366   0.0377   0.0383   0.0094
        -0.2236   0.2366   0.0377   0.0383   0.0094   0.0797   0.1962   0.3496   0.0892

E =
          -13.2718
          -13.2972
          -0.9149 + 3.6080i
          -0.9149 - 3.6080i
          -1.5683
          -0.2113
          -1.6154 + 2.7402i
          -1.6154 - 2.7402i
          -0.5876
```

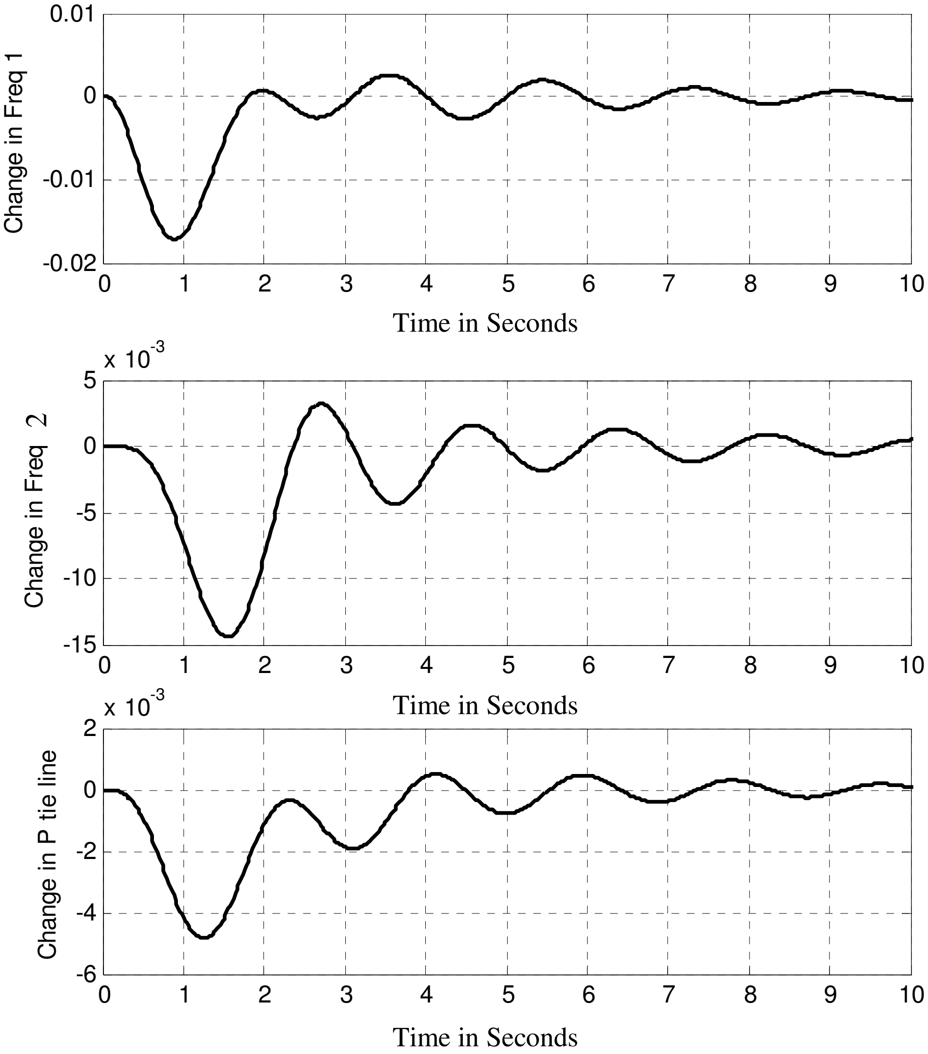

Figure 5.5: Best response using LQR control strategy in the sense of minimizing the tie-line deviation.

```
K=
                 0.7071   0.2991   0   0   0   0          0    0  0
                -0.7071   0        0   0   0   .2991      0    0  0
```

5.3 Results with Fuzzy Logic Based Integral Controller

5.3.1 Two area system with non-reheat turbine

In this case fuzzy logic based integral controller is applied to a two area power system. The same values of the system parameters, given in appendix A, are used for controller for a comparative study.

The frequency deviations of area 1, area 2 and tie-line after step load change of 1% i.e. 0.01 p.u. in area 1 are shown in figure 5.6. Settling time for 5 % tolerance band of the step change and peakovershoot are calculated. The performance comparison of the proposed controller versus some other controllers indicates that the system response with the proposed controller has much shorter peakovershoot and settling time. Simulations have been repeated with various instantaneous load changes, and success has been obtained for all. Table 5.1 shows dynamic parameters obtained with proposed controller for frequency deviation of area 1 with respect to other studies.

Table 5.1: Frequency deviations with proposed controller with respect to others in two area system

	Settling Time (s) (for 5 % tolerance band of the step change)	Peakovershoot (Hz)
Proposed study	**3.53**	**-0.0202**
Akalin's study [96]	6.35	-0.025
Convention PI [96]	6.92	-0.028
Chang's study [88]	7.20	-0.022
E Cam's study [96]	4.26	-0.027

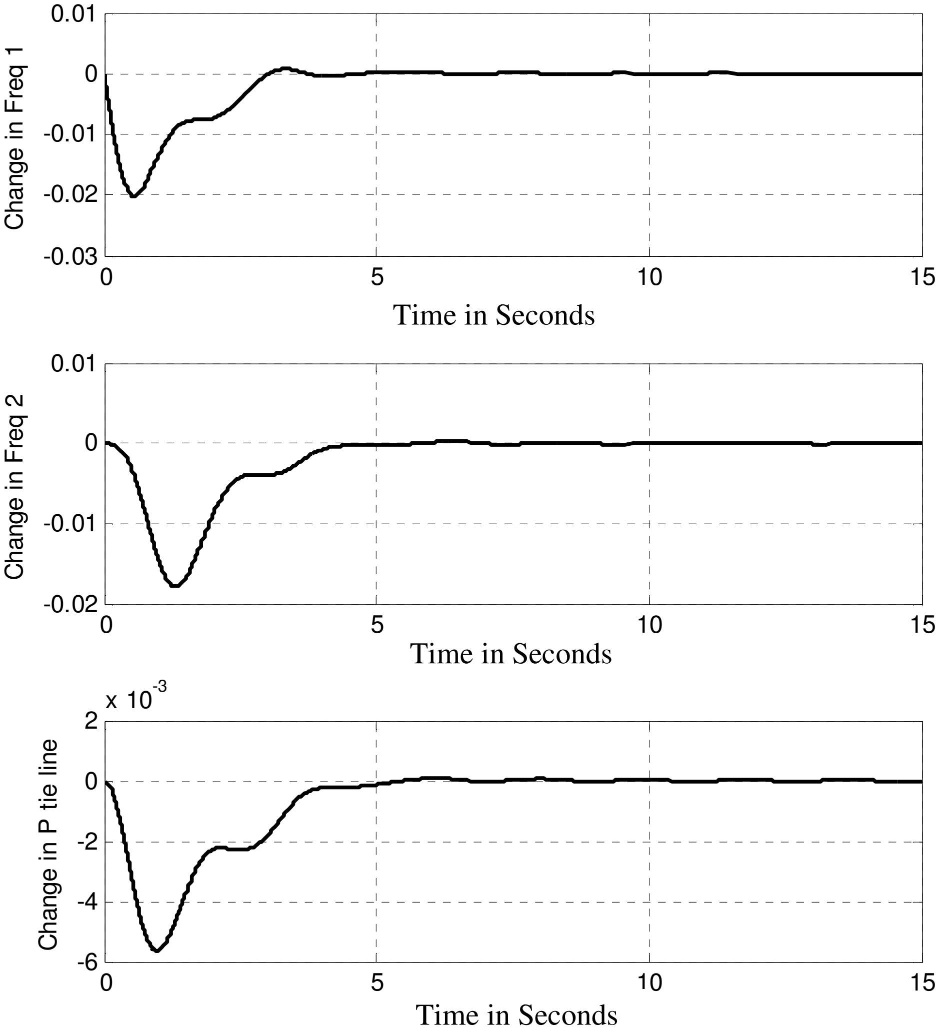

Figure 5.6: Deviations of frequency for area 1, area 2 and tie line power.

For the same system, three important parameters power system time constant T_P, tie-line constant T_{12} and frequency bias constant B are varied to +/- 30 % of their defined value to check the robustness of the designed controller.

The dynamic response of system with + 30 % change in mentioned parameters is shown in figure 5.7 and with -30 % in figure 5.8. It is observed that in both the cases dynamic parameters obtained are with in limits. Settling time in + 30 % case for area 1 is 7.1578 seconds and peakovershoot is -0.0166 Hz while for -30 % is 10.22 seconds and -0.0260 Hz.

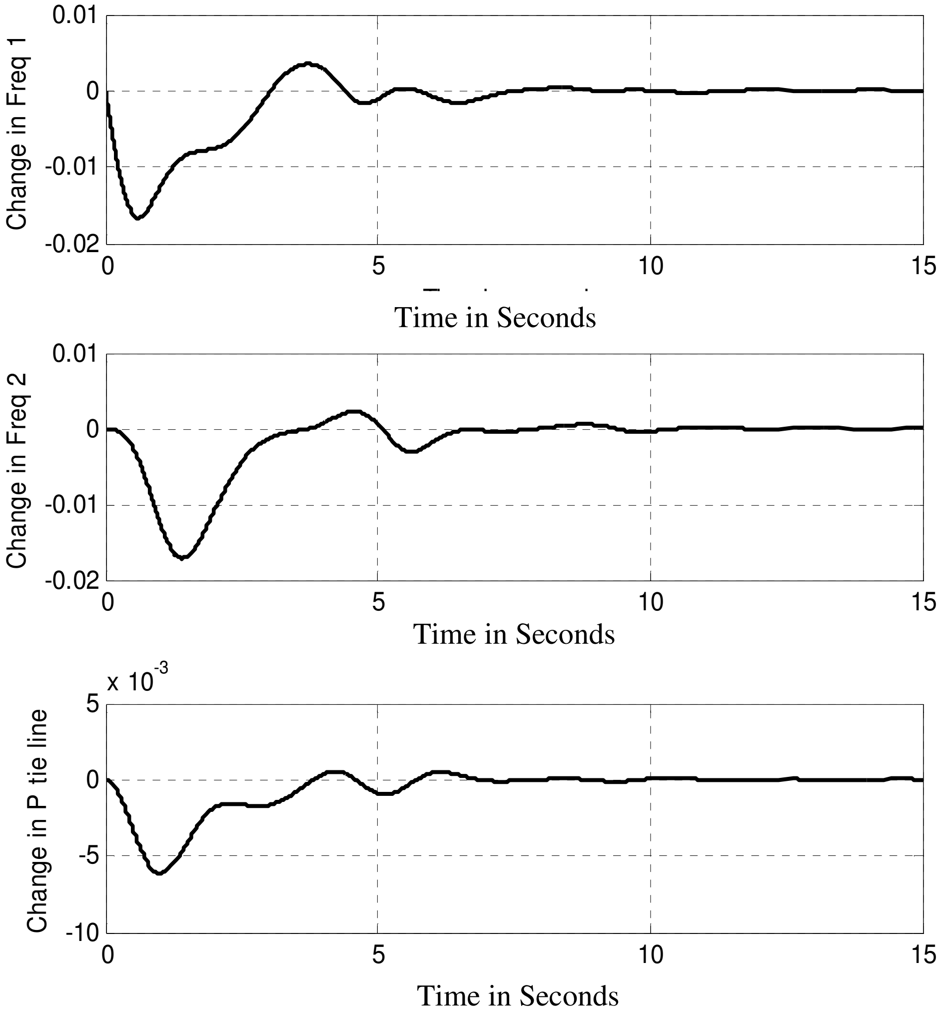

Figure 5.7: Deviations of frequency for area 1, area 2 and tie line power (+30 %)

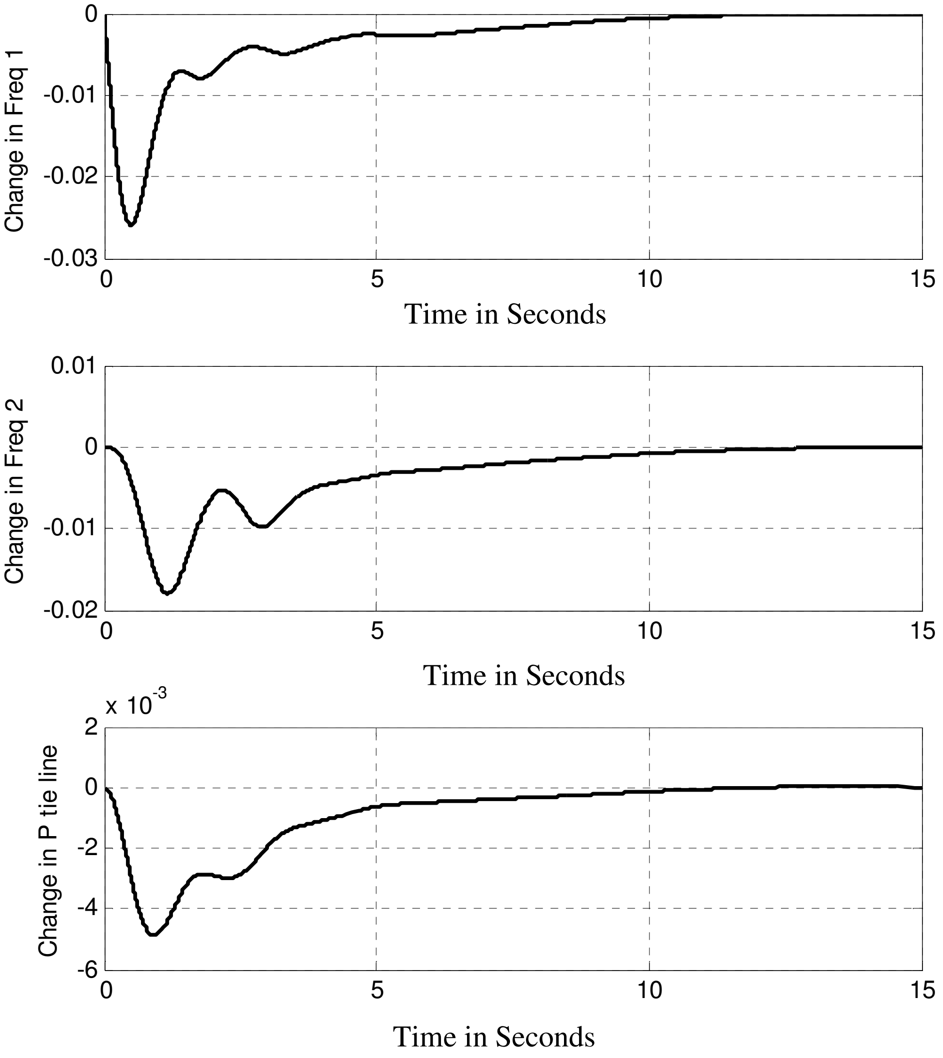

Figure 5.8: Deviations of frequency for area 1, area 2 and tie line power (-30 %)

5.3.2 Two area system with reheat turbine

Now the change in frequency of both areas and tie line deviation are plotted, when a two area with reheat steam turbine is given a disturbance of same amount as in previous case i.e. 1 %. It is observed that reference [92] has more oscillations before reaching the steady state value. Settling time and peakovershoot are also more as compared to proposed study. The figure 5.9 shows the variations in frequency and tie-line power and in figure 5.10 and 5.11 are shown with +/- 30 % change in system parameters as mentioned in previous case.

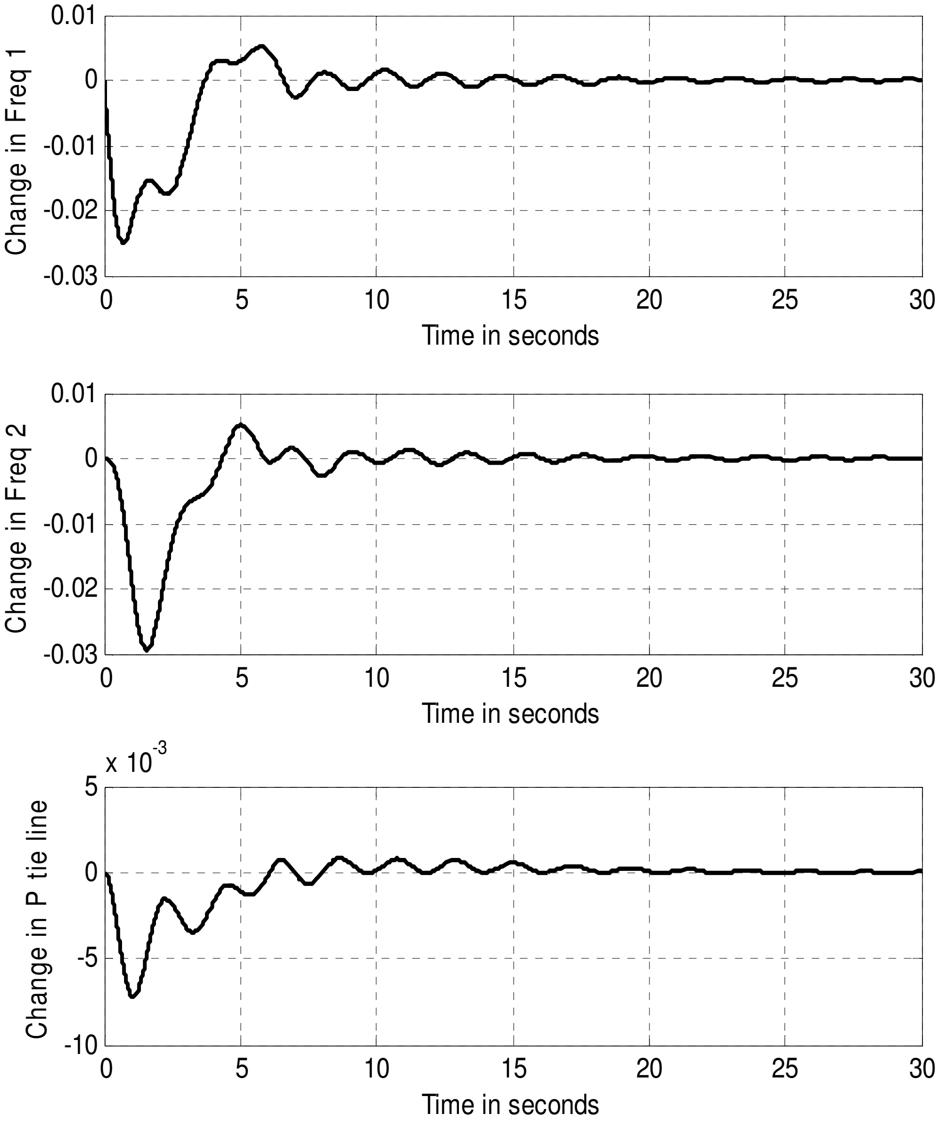

Figure 5.9: System responses with reheat steam turbine at nominal values of parameters

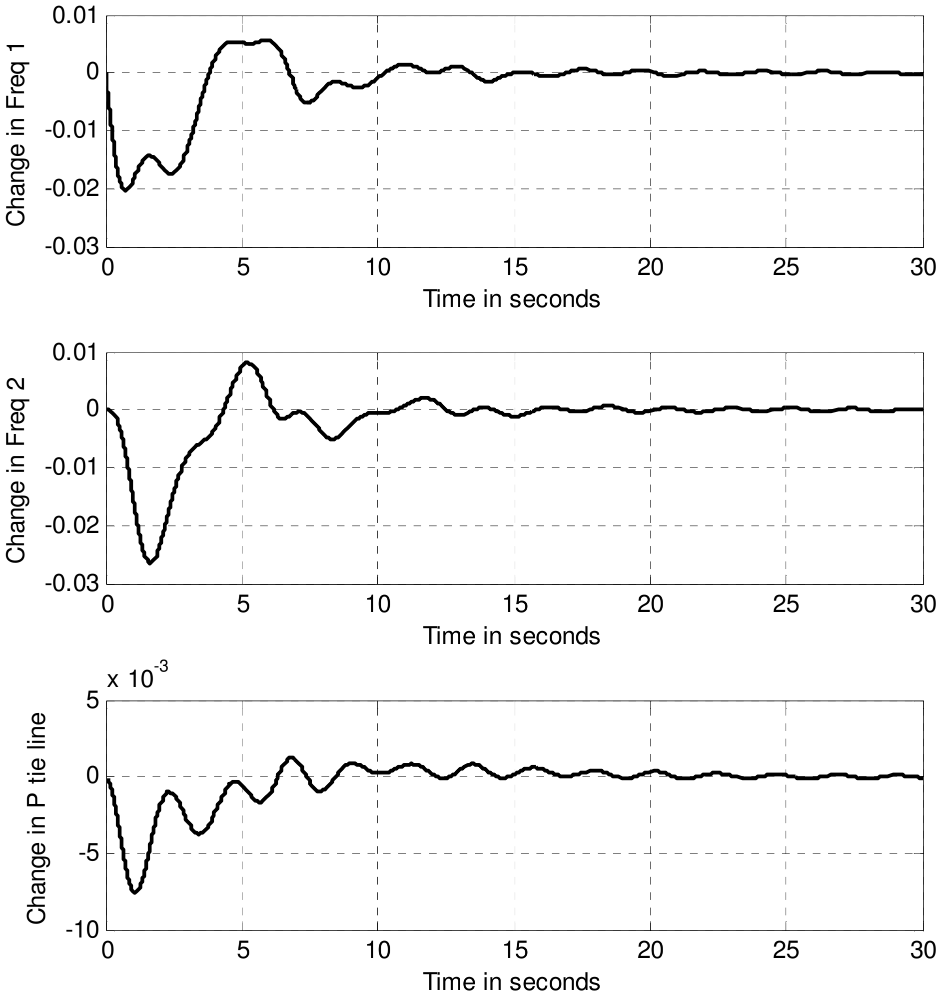

Figure 5.10: System responses with reheat steam turbine at +30 % of nominal values of parameters

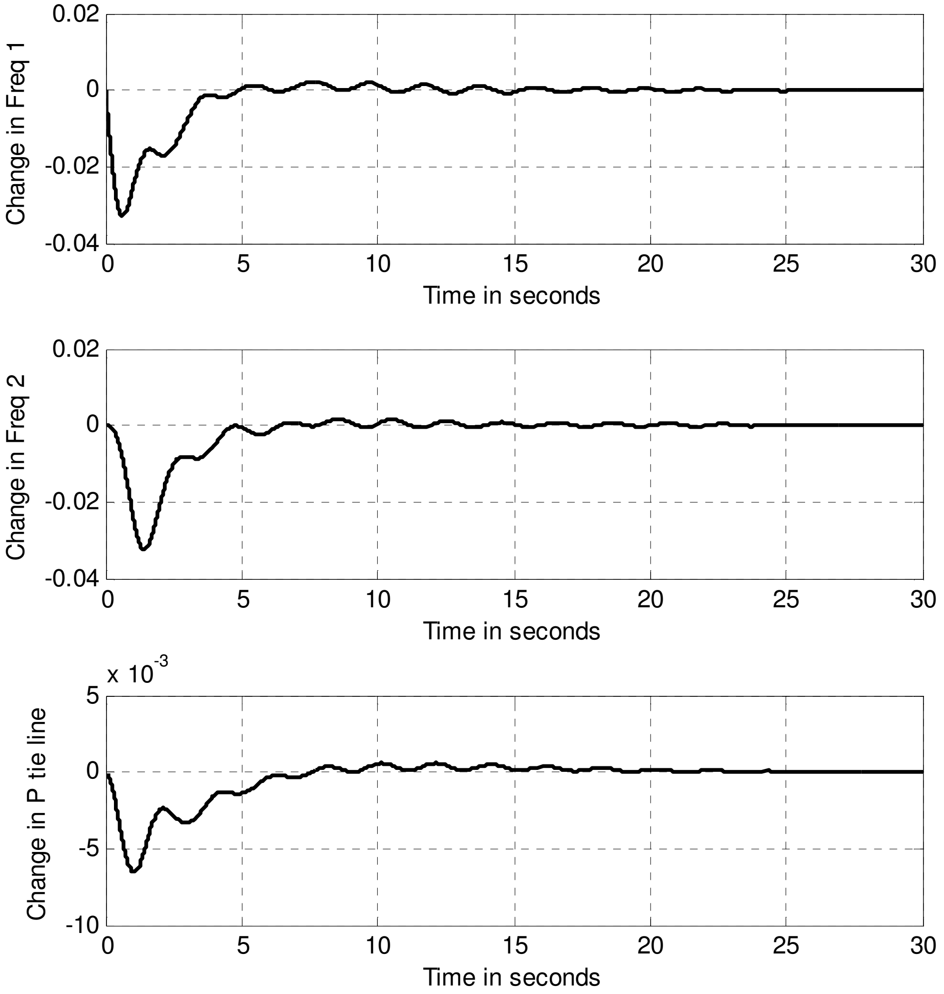

Figure 5.11: System responses with reheat steam turbine at -30 % of nominal values of parameters

5.3.3 Two area system with non-reheat turbine with GRC

The linear model of a non-reheating turbine which was used in the first case is replaced by the non-linear model as shown in figure 3.10 with d= 0.015. This replacement is done to take into account the generation rate constraint (GRC) that emulates the practical limit on the response of a turbine [81]. The simulations were done by applying a single step disturbance of 1 % $(\Delta P_{d1} = 0.01\,\text{p.u.})$ to the first area.

Results obtained are shown in figure 5.12 to figure 5.14. Figure 5.13 and 5.14 are with +/- 30 % parameter changes.

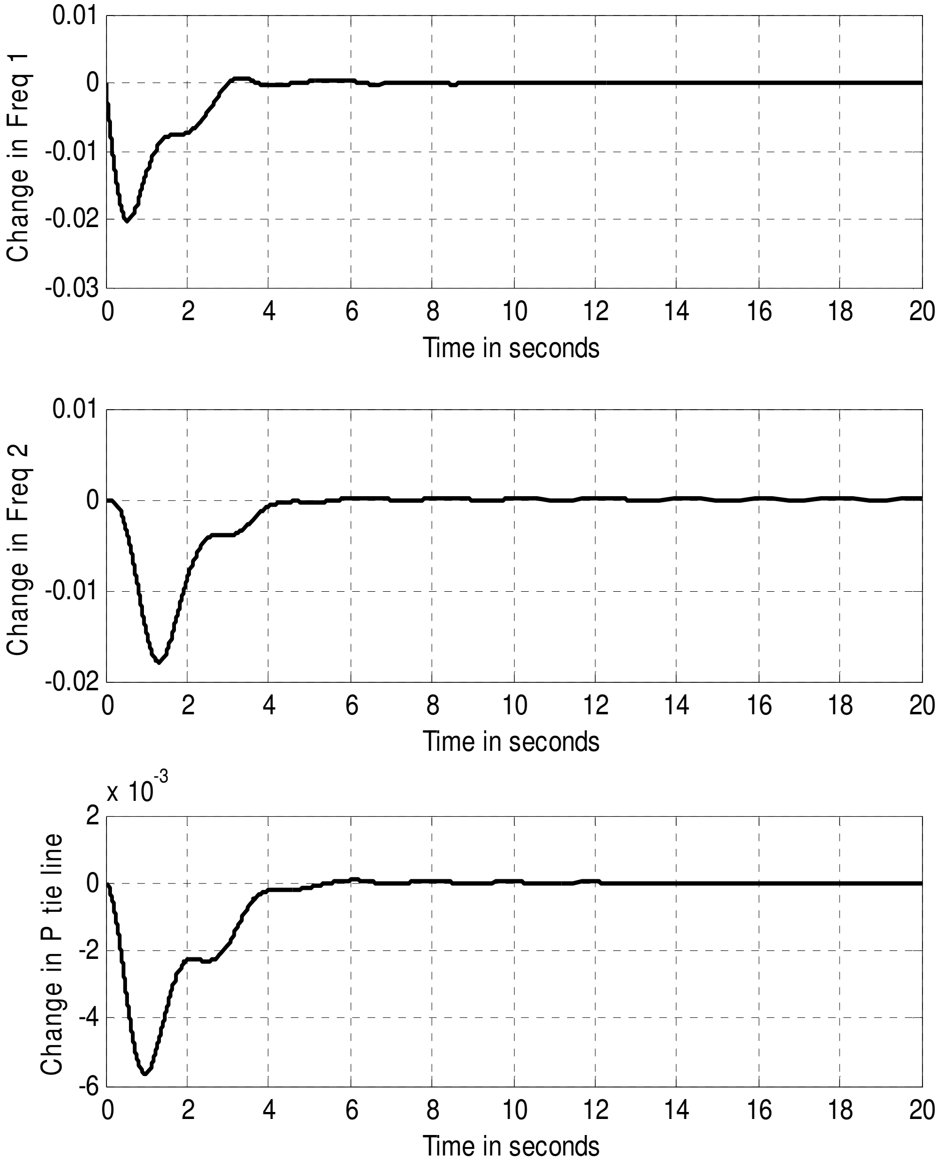

Figure 5.12: System responses with non-reheat turbine with GRC at nominal values of parameters

The comparison criteria to be considered are the maximum overshoot and the settling time. Settling times for the 5 % band of step change and maximum overshoots for various controllers, including the proposed one, are shown in Table 5.2. It is seen that the proposed controller has least settling time than others. As far as the overshoots are concerned, the reference [81] gives better results.

Table 5.2: Deviations with proposed controller with respect to other studies in non-linear case in two area system.

	Settling Time (s)	Peakovershoot (Hz)
Proposed study	**3.54**	**-0.0200**
CIC*	8.13	.0219
DFN*	3.92	.0163
DNN*	6.81	.0149
DWN*	4.26	.0150

* CIC= Conventional Integral Controller, DFN= Dynamic Fuzzy Network, DNN= Dynamic Neural Network, DWN=Dynamic Wavelet Network. [81]

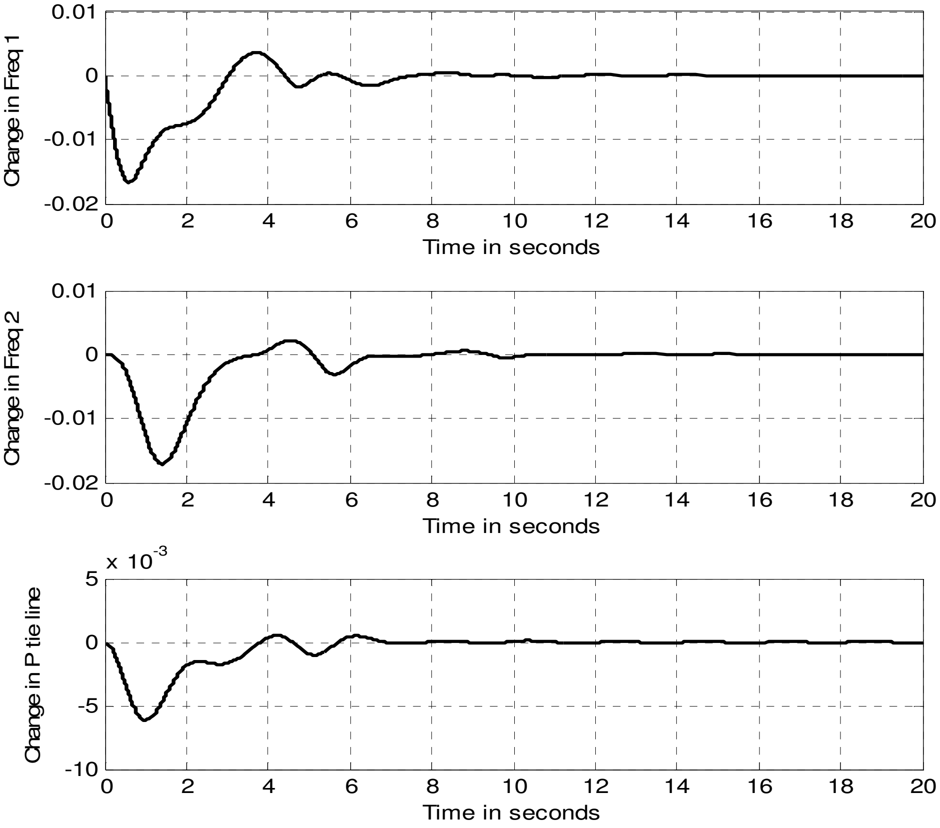

Figure 5.13: System responses with non-reheat turbine with GRC at +30 % of nominal values of parameters

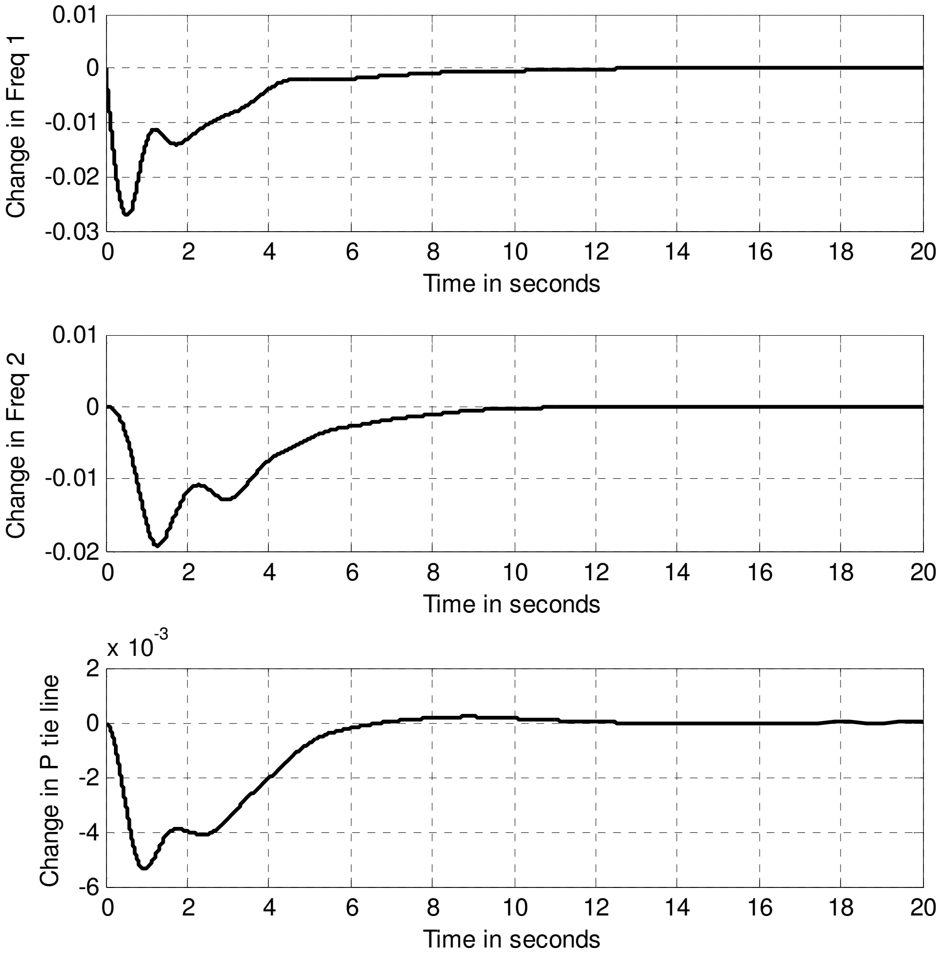

Figure 5.14: System responses with non-reheat turbine with GRC at -30 % of nominal values of parameters

5.3.4 Two area system with reheat turbine with GRC

The earlier studies in this field adopted too strict GRC such as $\leq 0.1 p.u./\min$ to achieve adequate performance from the valve position control. In the real situation, the boiler can afford to keep its steam pressure to be constant for a while, and thus it is possible to increase generation power up to about 1.2 p.u. of normal power during the first tens of seconds**.** The two area power system with GRC 0.0017 p.u. /sec. is considered for the study and responses are noted and analyzed which are shown in figure 5.15 to figure 5.17.

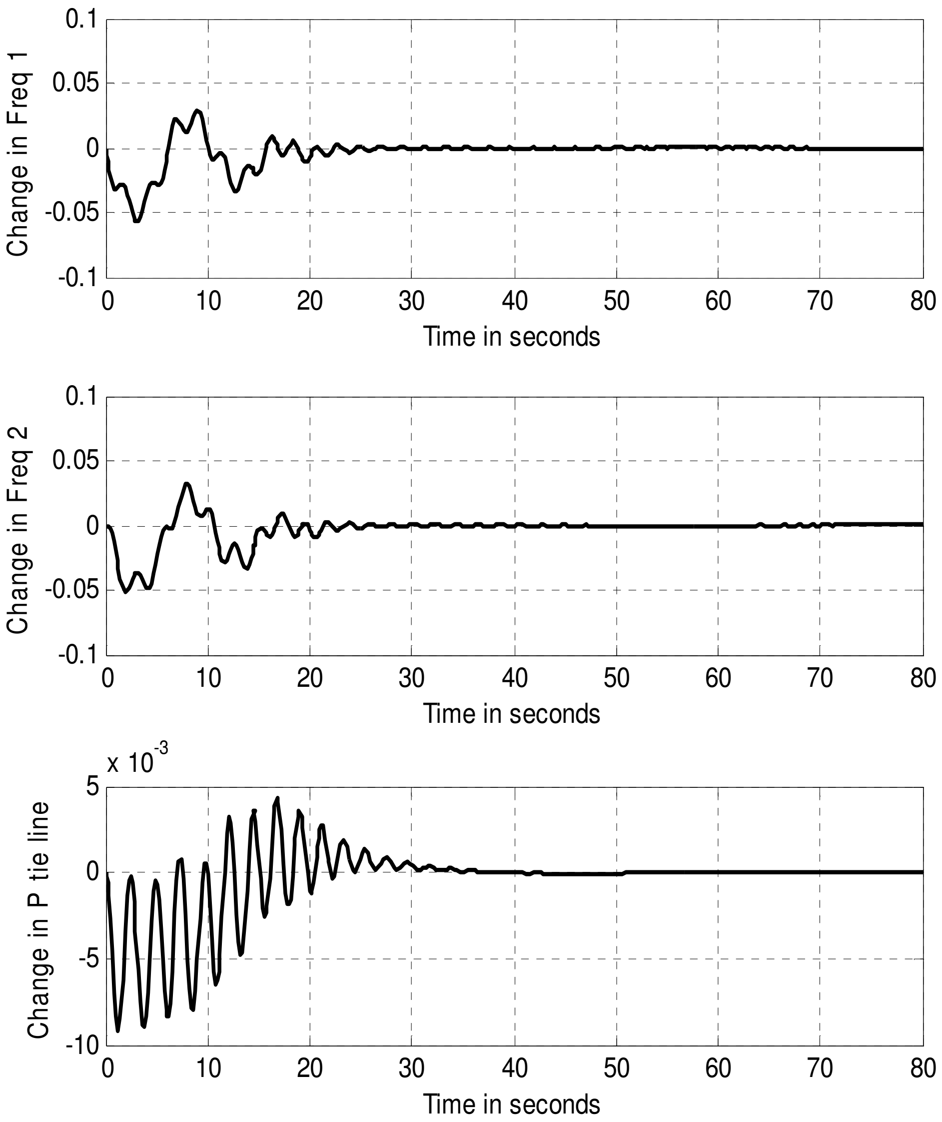

Figure 5.15: System responses with reheat turbine with GRC (0.0017 p.u. /sec.) at nominal values of parameters

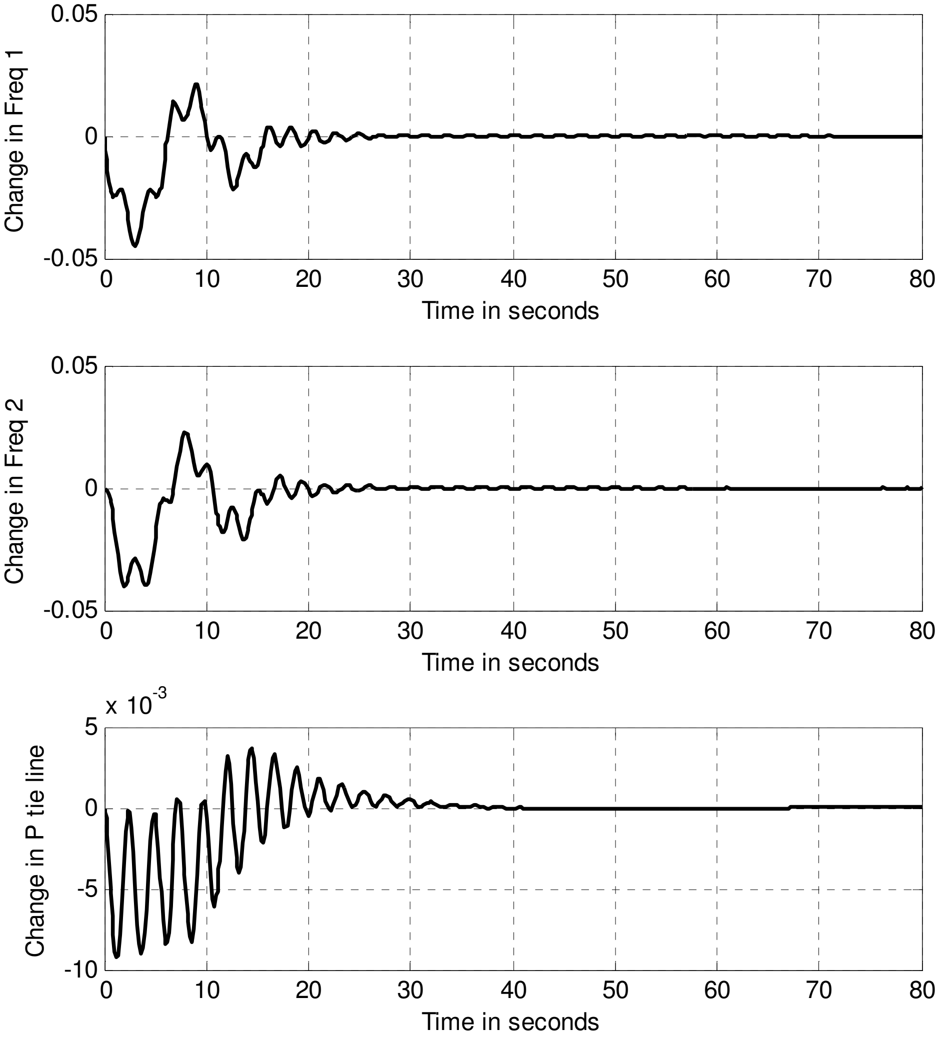

Figure 5.16: System responses with reheat turbine with GRC (0.0017 p.u. /sec.) at +30 % of nominal values of parameters

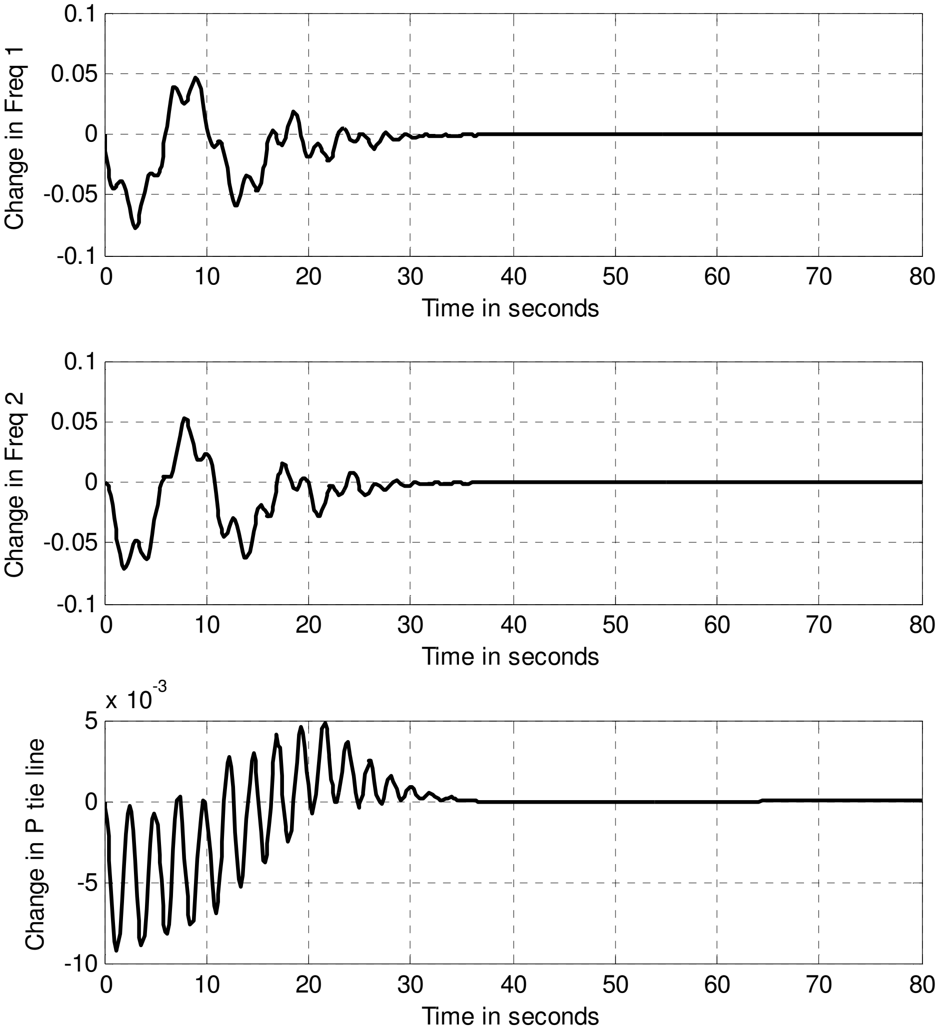

Figure 5.17: System responses with reheat turbine with GRC (0.0017 p.u. /sec.) at -30 % of nominal values of parameters

5.3.5 Two area system with one non-reheat turbine and one hydro turbine

The two area interconnected system of this kind is also studied where thermal system is coupled with a hydro system. The controller settings for both the controllers are kept different since they respond to the disturbance differently because of their inherent properties. Such a system with this combination is not much discussed in literature where thermal system is equipped with non-reheat turbine. The peakovershoot of area 1 is found to be -0.0202 Hz and settling time is 18 seconds when area one is subjected to 1 % load change. Figure 5.18 shows responses of the system.

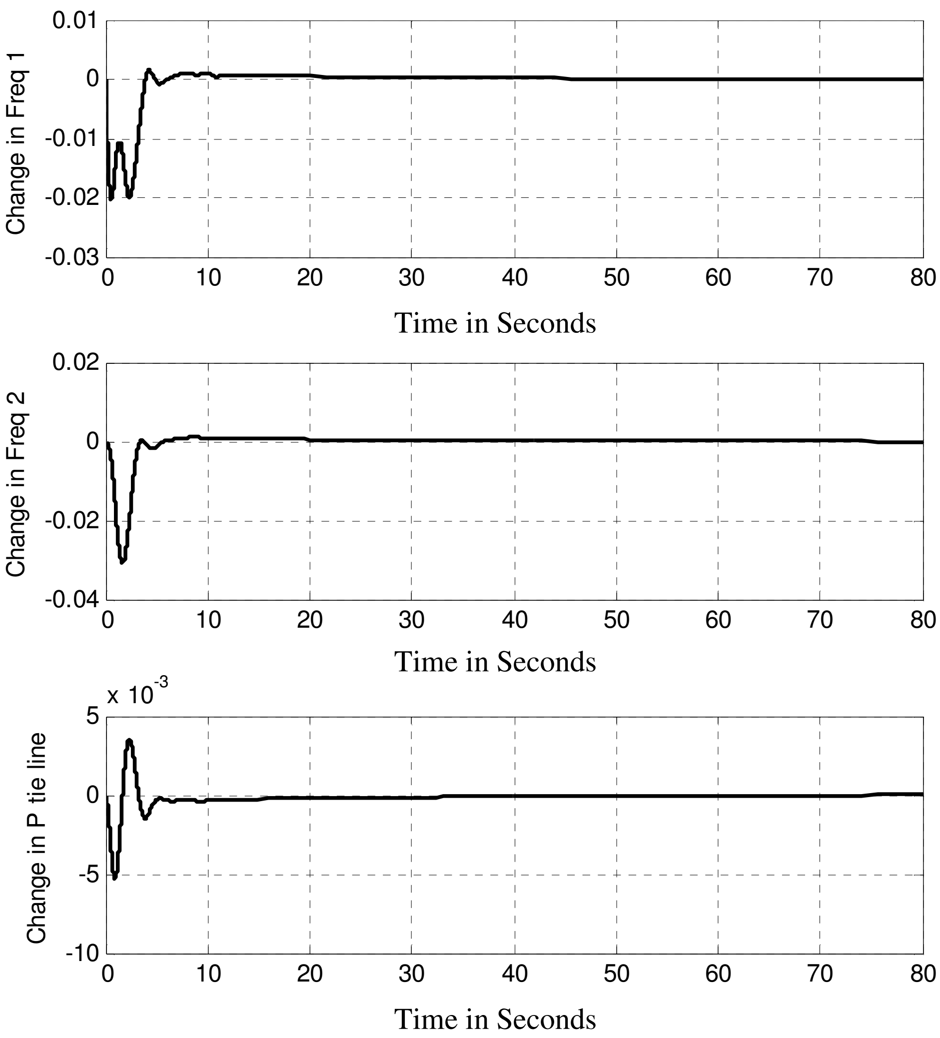

Figure 5.18: Responses with non- reheat and one hydro turbine upon load change in area 1.

5.3.6 Two area system with one reheat turbine and one hydro turbine

This case is studied for another combination in which reheat thermal turbine and one hydro turbine are used. Responses obtained for 1 % disturbance are satisfactory. Results have lesser oscillations as compared with other such systems. Figure 5.19 shows the system responses.

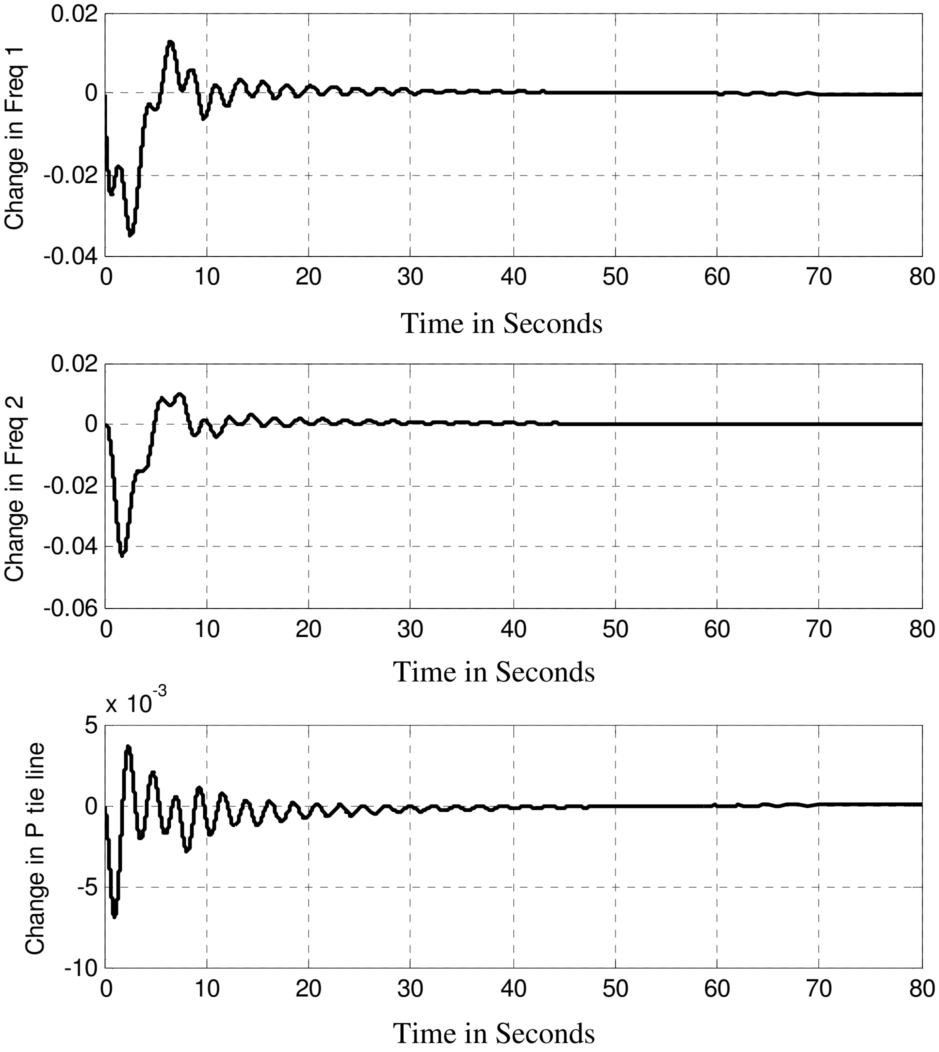

Figure 5.19: Responses with one reheat and one hydro turbine upon load change in area 1.

5.4 Results with Parallel AC/HVDC Transmission Link

This section of the chapter deals with the results of two area interconnected system, whose complete block diagram is discussed in chapter 3, when facilitated with parallel HVDC transmission link to AC link. The dynamic model of incremental power flow through dc transmission link is derived based on frequency deviation at rectifier end. Moreover, the dc link is considered to be operating in constant current control mode. Fuzzy logic based integral control strategy is employed for control action. It has been observed that dynamic performance improves as compared to control strategy employed by [119,120] for same system model with same parameters.

5.4.1 Two area system with reheat turbines

This case study is performed on the dynamic model of two similar areas with reheat turbines. In figure 5.20 is presented the variations in frequency of area 1, area 2 and tie-line power due to load change. Dynamic performance with parameter variations is also studied with this control strategy and compared with the same fuzzy logic based integral control strategy implemented to same model but without HVDC link to analyze the improvement in system performance with HVDC link as shown in figure 5.21 and figure 5.22.

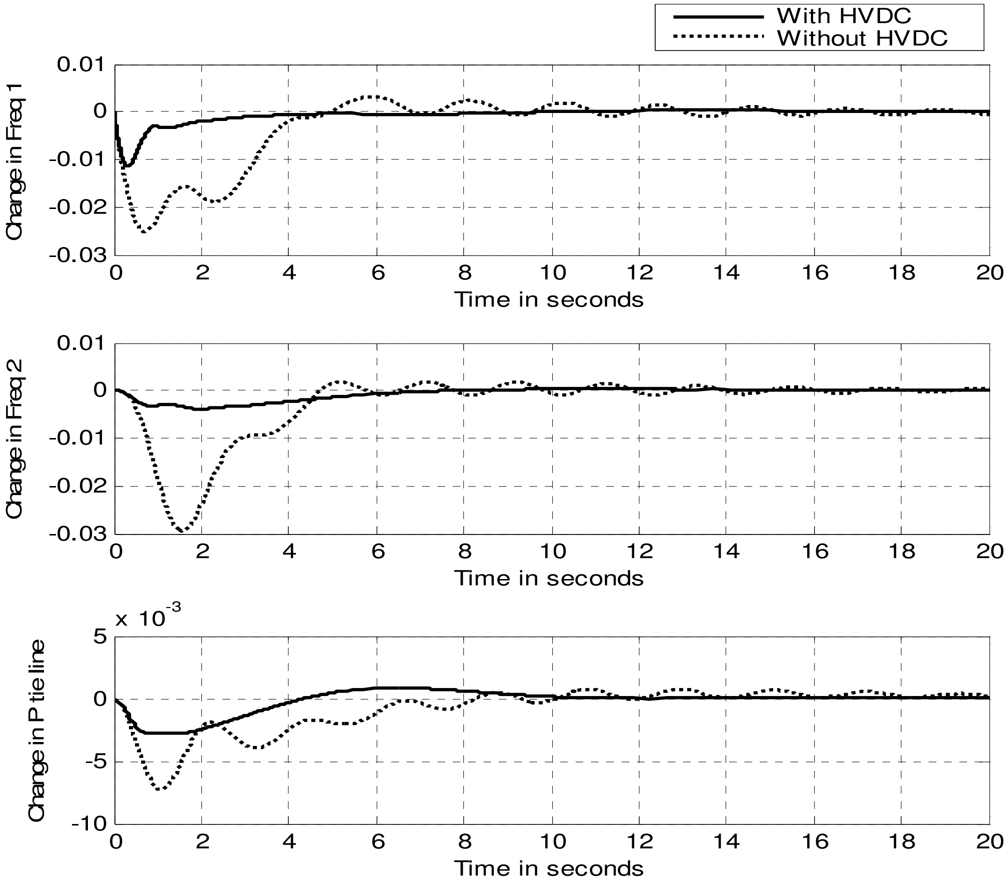

Figure 5.20: Responses with AC/DC link when area 1 is subjected to load change of 1%.

Settling time and peakovershoot for the above study are found to be -0.0115 Hz and 4.33 seconds respectively and frequency deviation in area 1 is less oscillatory. These observations are better when compared with the results of [119].

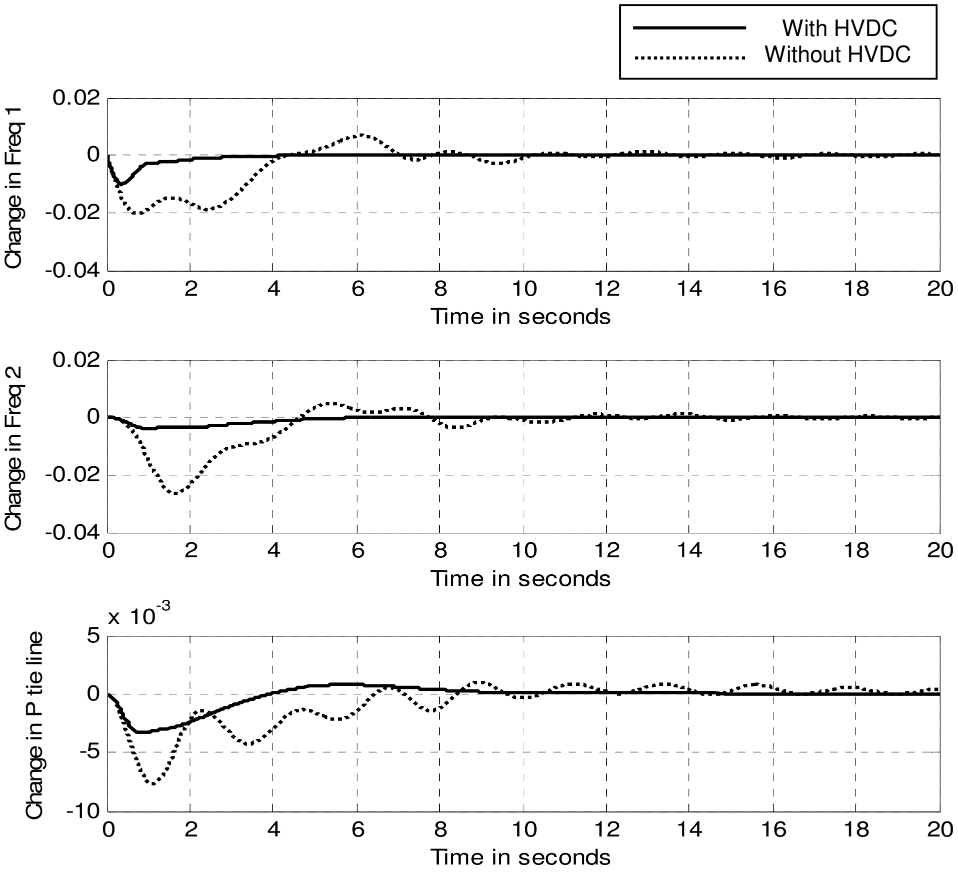

Figure 5.21: Responses with AC/DC link at +30 % of nominal values of parameters when area 1 is subjected to load change of 1%

Table 5.3: Comparative statement of dynamic parameters of system with reheat turbine with and without HVDC link

Value of Parameters	With HVDC Link		Without HVDC Link	
	Settling Time (s)	Peakovershoot (Hz)	Settling Time (s)	Peakovershoot (Hz)
Nominal	4.33	-0.0115	18.15	-0.025
+30 % of Nominal	3.266	-0.0100	18.6	-0.020
-30 % of Nominal	10.97	-0.0137	14.3	-0.0328

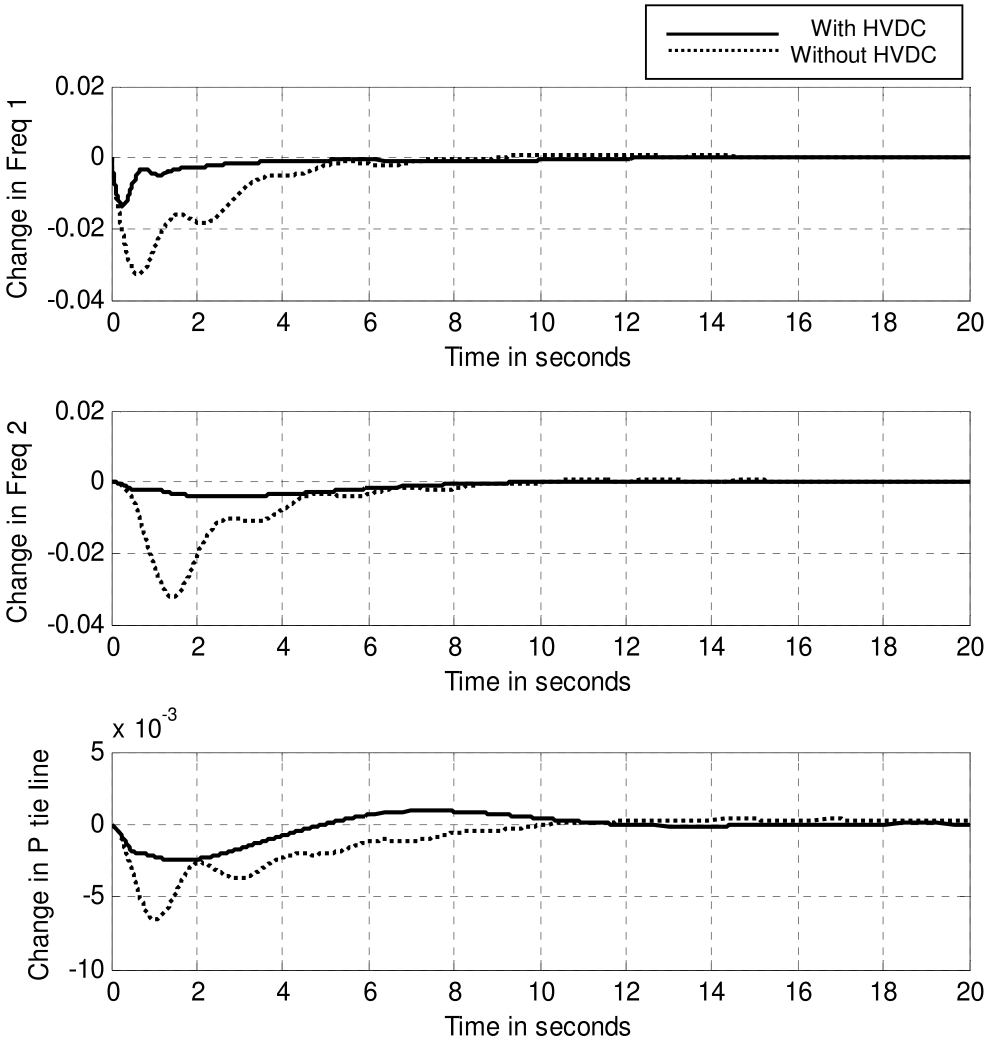

Figure 5.22: Responses with AC/DC link at -30 % of nominal values of parameters when area 1 is subjected to load change of 1%

5.4.2 Two area system with one reheat turbine and one hydro turbine

In another case study with HVDC link, one area is with reheat turbine and another is with hydro turbine, area 1 is experiencing 1 % step load change and variations are noted in three important parameters i.e. change in frequency of area 1, area 2 and power in tie- line. These results when compared with [119] are found to be improved in terms of settling time and peak peakovershoot. Figure 5.23 is presented the responses of the system.

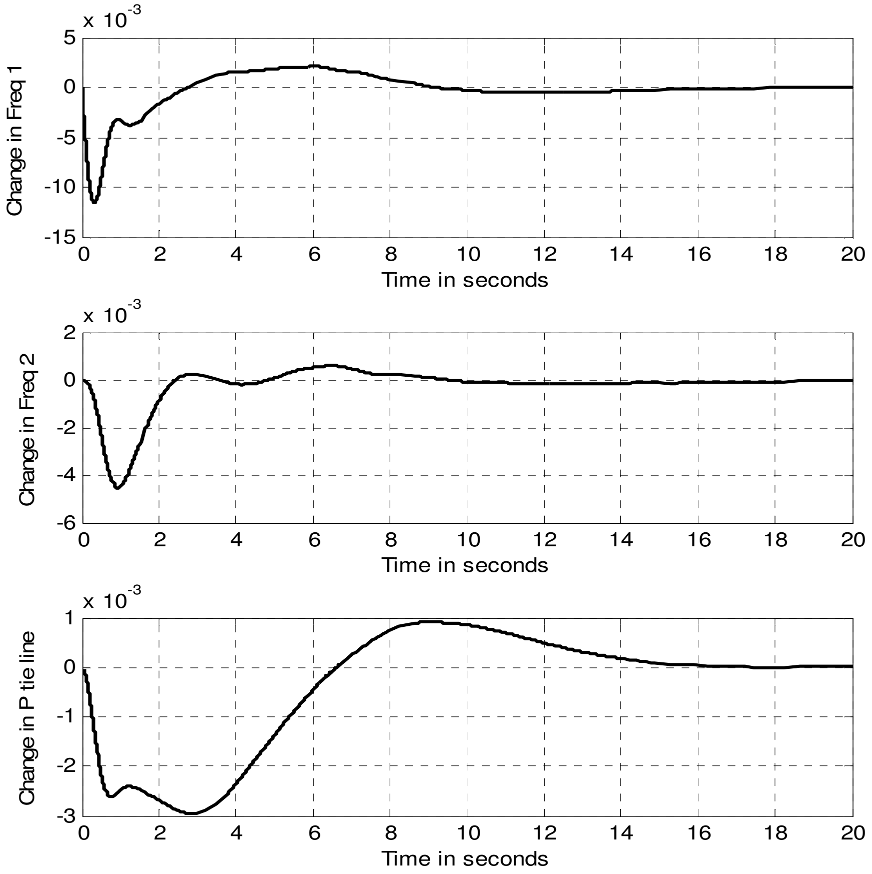

Figure 5.23: Responses with AC/ DC link upon load change in area 1

5.5 Summary

Two area interconnected systems with various options and with different control strategies are comprehensively studied and results are compared with work of other researches. All the cases are studied for the disturbance in area 1 with 1% change in load. LQR technique used for load frequency control is first discussed and later fuzzy based integral control strategy is implemented on various cases of two area system. Responses obtained are shown. In third part of chapter, DC link is connected in parallel to AC link to improve the system response. Fuzzy based integral control technique is used for this as well and responses noted are better as compared with other researchers.