DESIGN OF ROBUST H_{∞} TECHNIQUE USING LINEAR MATRIX INEQUALITIES FOR LOAD FREQUENCY CONTROL

A Dissertation submitted in fulfillment of the requirements for the Degree
of

MASTER OF ENGINEERING
in
Power Systems

Submitted by

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DECLARATION

I hereby certify that the work which is presented in dissertation entitled, "**Design of robust H_∞ technique using linear matrix inequalities for load frequency control** ", in partial fulfillment of the requirements for the award of the degree of **Master of Engineering in Power Systems,** submitted to Electrical & Instrumentation Engineering Department of Thapar Institute of Engineering & Technology (Deemed to be University) is as authentic record of my own work carried under the supervision of **Dr. Sanjay K. Jain**. It refers others researcher's work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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NOMENCLATURE

Δf_1& Δf_2 : Frequency Deviations in Areas 1&2

$\Delta P_{tie_{12}}$: Tie Line Power Deviation in Two Areas Systems

R_1 & R_2 : Regulations of Governors in Areas 1, 2

K_I : Integral Controller Gain in Thermal Areas

u_1 &u_2 : Control Inputs in Areas 1& 2

ΔP_{g1}& ΔP_{g2} : Deviations in Governor Power Outputs in Thermal Areas 1 & 2

ΔP_{t1} & ΔP_{t2} : Deviations in Turbine Power Outputs in Thermal Areas 1 & 2

ΔP_{d1} & ΔP_{d2} : Load Disturbances in Areas 1& 2

K_{P1} & K_{P2} : Power System Constants in Areas 1&2

T_{P1} & T_{P2} : Power System Time Constants in Areas 1& 2

B_1 & B_2 : Tie Line Frequency Bias in Areas 1&2

T_0 : Synchronizing Coefficient for Tie Line for Two Area Systems

T_{12} : Synchronizing Coefficients for Tie Lines between Pair of Areas For the Two Area System

T_{g1} & T_{g2} : Governor Time Constants for Thermal Areas 1 & 2

T_{t1} & T_{t2} : Turbine Time Constants for Thermal Areas 1 & 2

a_{12} : Ratio of Rated Powers of a Pair of Areas in the Two Area System

ACE_1 & ACE_2 : Area Control Error (ACE) for Area 1 & 2

ΔP_{c1} & ΔP_{c2} Governor Load Set-Point of Area 1 & 2

ABSTRACT

In an interconnected power system, variation in frequency and tie line power exchange occurs subjected to changes in the load demand taking place in different areas. The primary control through local governors, although adjust the governor outputs in order to compensate the changes occurring in the load demand and tie line power exchange, the primary controls are not able to provide a full compensation for the load power changes. Therefore, a supplementary control is necessary for the power system to keep the system frequency at inconsequential values. The additional control mechanism must act to bring back the system frequency to it nominal value by adjusting the speed reference set-point. In this work, the method for robust decentralised control is proposed for load frequency control (LFC). For this, initially a plant transfer model is developed for a two area interconnected system with non-reheat thermal units. For this system, H_∞ control design based on linear matrix inequalities (LMI) technique is presented to achieve robustness against uncertainties. The H_∞ technique achieve the tuning of the parameters of the proportional-integral (PI) controller under LMI constraints. The robust performance of the proposed technique is tested on an interconnected two-area power system with non-reheat thermal turbine units for different load disturbances in the form of step perturbations. The system is implemented under MATLAB/SIMULINK environment. The simulation results for the developed controller are compared with two area interconnected system with non- reheat thermal units having conventional PID controller as the control mechanism. The results obtained demonstrate that the dynamic response obtained on introduction of robust control in the interconnected system is far more satisfactory than from the conventional control method used.

CHAPTER 1

INTRODUCTION

This chapter gives an introduction to the concept of Load frequency control (LFC). An insight to the LFC literature in regard to the past achievements is given and the main objectives of the dissertation work are penned down.

1.1 CONTROL STRATEGY IN A POWER SYSTEM.

The concept of control in a power system is to ensure that the power is generated and distributed and delivered in a reliable and economical manner whilst ensuring that the system frequency, voltage and tie-line power exchange in an interconnected system remain at their scheduled values and the deviations if occur should be under permissible limits. Power system has a pecking order type structure. The power system control structure is composed a number of loops which as designated for controlling different system parameters. These control loops are of lower level and higher level type. The lower level control loops are a part of smaller systems which are less complex in nature and size and their time constants are small. A generator is a fitting example of such kind of a system. On the contrary, an automatic voltage regulator (AVR) is ideal example of a higher order system and has a high value of time constant and therefore, its response for voltage regulation of generator terminals lies within a second or even less. In comparison , a secondary voltage source (SVC) being a small control system takes around tens of seconds or minutes for determining the reference values of devices controlling the voltage. It can be fairly concluded, that both the control loops are decoupled in nature.

Load frequency control (LFC) problem is also an example of a control loop and it controls the real power exchange and frequency. AVR on the other hand controls reactive power and magnitude of voltage. The dynamics of LFC control remain unaffected as the time constant of the excitation system is very small compared to that of the prime mover and its transient response is fast decaying. As e result in event of coupling between the two loops is treated to be negligible. This is also the case for a number of control loops generally.

It has therefore been safely concluded that various de-coupled control loops can operate in a power system under different scales of time for performing the functions of voltage control, tie-line power exchange control, protection, turbine control and frequency control as well.

A major advantage resulting from this decoupled scenario is that even though overall control system continues to become more and more complex, for most of the cases, we can study individually study several different control loops.

Fig 1.1 shows the present different time scales in which the developed controllers in power system operate.

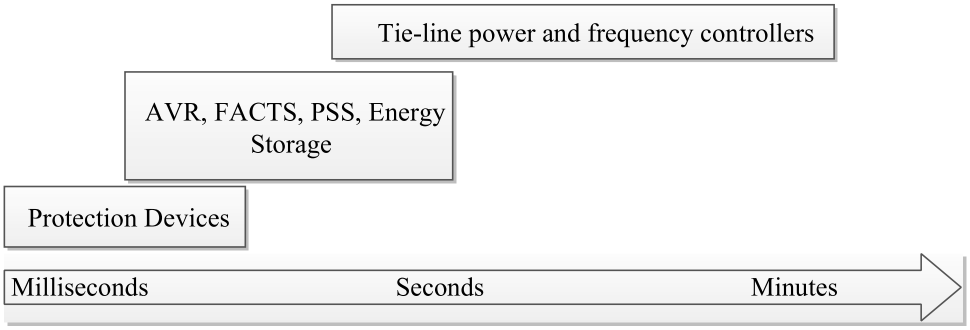

Fig 1.1. Time scale of operation of present day power system controllers.

It can be clearly seen the fastest response is that of the protection devices which is fitting as they need to protect other important devices in the system quickly. In the next level, response time is aimed and mainly related to power system stabilizers (PSS), energy storages, reactive power controllers and flexible AC transmission systems. The response time of the frequency and tie-line exchange power controllers is the highest.

1.2 LOAD FREQUENCY CONTROL (LFC) PROBLEM

In a power system, LFC is basically a supplementary control action and is aimed completely to maintain the system frequency deviation and tie-line power exchange within the permissible limits i.e. close to their scheduled nominal values in an even of occurrence of load disturbances which are frequently in an interconnected power system.

The concept of LFC has become immensely problem with the ever changing power system. The level of complexity of system designing and controlling has increased manifolds as the electric power system is becoming deregulated resulting in interconnection of different areas.

Fig 1.2 depicts one the most commonly studied and classical LFC structure for a control area.

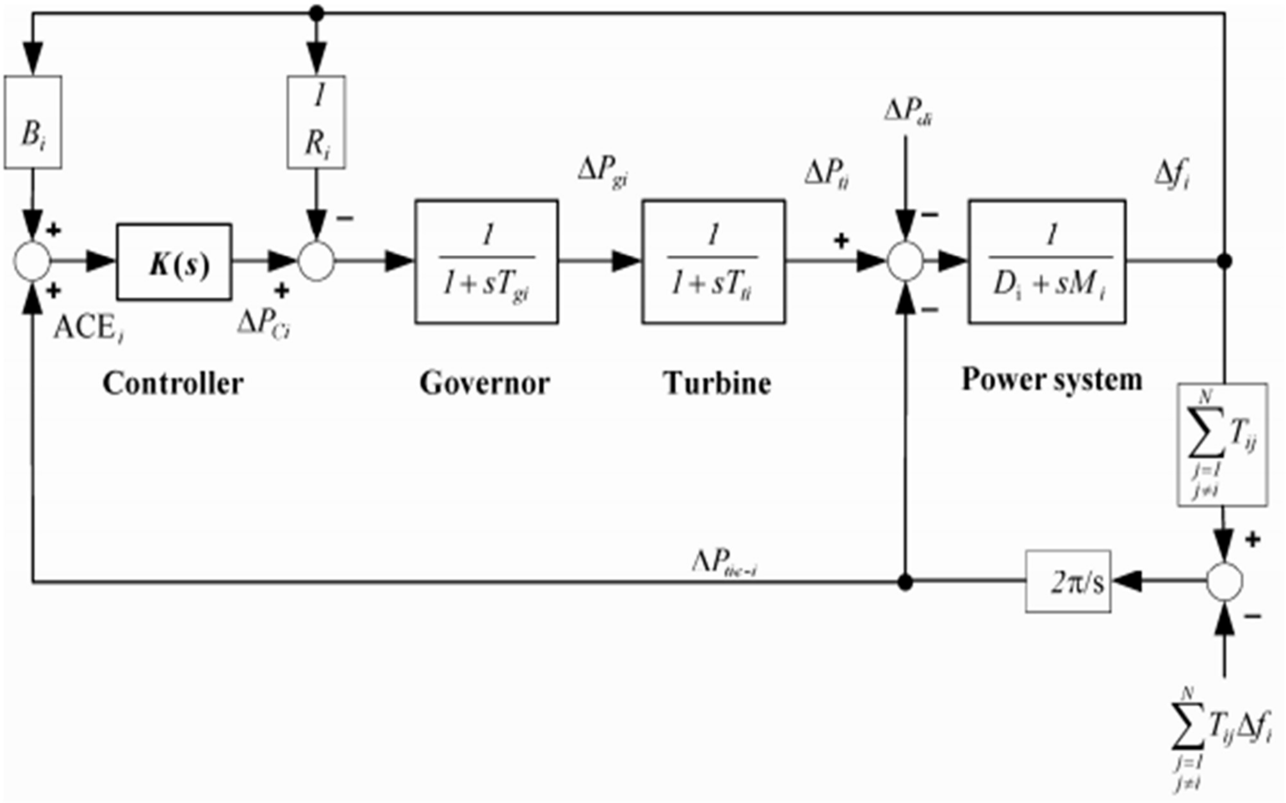

Fig 1.2. Control area set with LFC

Fig 1.2 depicts one the most commonly studied, classical LFC structure for a control area. The system parameters are given below:

Δf : Frequency deviation,

ΔP_{ci} : Governor load set point,

ΔP_{ti} : Turbine power,

ΔP_{gi} : Governor valve position,

ΔP_{tie_i}: Net tie-line power flow,

M_i : Equivalent inertia constant,

ΔP_{di} : Local load disturbance,

D_i Equivalent damping coefficient,

T_{ij}: Tie-line synchronizing coefficient between area i & j,

T_{ti} : Turbine time constant,

R_i: Drooping characteristic,

B_i : Frequency bias,

ACE_i : Area control error (ACE).

The classical LFC model as shown in Fig. 1.2 is composed of three first order transfer functions which are fairly easy to solve for modeling of the generator, turbine and power system. The two input signals are load demand deviation or change and tie-line power exchange scheduled between the interconnected areas. Each individual control area is responsible for monitoring its own net tie-line power exchange and system frequency from the area control center. The input to the controller (K(s)) is given in the form of Area Control Error (ACE). ACE is a linear combination of the deviation in tie-line power exchange and product of bias factor and deviation in the frequency. The resulting control action from the controller used in the system is applied to the turbine-governor unit.

The operational objectives of the LFC are essentially to maintain the system frequency near its nominal value and to ensure that the net tie-line exchange of powers it brought back to the scheduled values whenever system is subjected to some form of power demand disturbance

The LFC mechanism is discussed deeply in [1] [2] [3] . The most common structure of conventional LFC controller used is of Integral (I) type as suggested in texts. However, as the power system complexity increases and it turns into a multi-areas system, tie-lines and even high voltage transmission (HVDC) line come into play. The amount and tendency by which frequency variation occurs in a control area is indicative of how the tie-line power exchange intends to vary in the interconnected power area [4].

Therefore, whenever a power demand fluctuation occurs within a control area, or mismatch in tie-line power exchange occurs, a transient change occurs in the area frequency. Here, the modeled feedback mechanism starts acting and a control signal is generated which is supplied to the turbine-governor which then tracks this load fluctuation and mismatch of power exchange. The response of the controller takes a few seconds to tens of seconds depending entirely on constraints in the power system area and the type of the generating unit.

Response of the generating units to the control signal is the basic criteria on which both the performance and design of the LFC structure depends. These control structure are a necessity as they maintain a certain level of control rate and reserved range between the system parameter variations can be controlled easily.

This dissertation work proposes a control strategy which is flexible and sets a desirable level for the performance specifications demanded in the practical power system which is placed under numerous constraints. Ever since the power system modeling using state- variable approach was developed, the structure described in Fig 1.2 has been extensively used as a basis for LFC designing. However, now the ever expanding deregulated power system industry with new constraints been included requires a newer insight into the LFC scheme to improve their efficiency in accordance to the new environment.

1.3 LFC LITERATURE SURVEY:

The aspect of developing a controller for the problem of load frequency control of an interconnected power system is considered to be an optimization problem. The major challenge of this optimization problem is to meet with design objectives which sometimes come out to be conflicting in nature. The evolving of power system control scheme is attributed to continuous efforts involved towards designing a controller which would provide satisfactory dynamic response to the load disturbances which occur in a practical power system design. The challenge is ensure that in an event of load demand fluctuation, the frequency deviation and tie line power exchange comes back to their scheduled values. Also, once the controller is designed it should not require parameter changes for different scenarios of load demand changes. It should be able to adapt itself for any possible combination of disturbances that might occur in the power system and stay dynamically stable. The work done towards achieving these objectives is humongous and a brief outlook of the same is given below.

One of the major publications in space of LFC was that of 'Fosher and Elgard'[1]. They gave a state variable mathematical model of an interconnected system and this has ever since acted as a base around which various modern robust control design methods have been designed. References [5][6][7][8][9][10][11][12] show a number of controller designs taking inspiration from state variable model and being able to successfully implement them for ensuring system dynamic stability and optimal control. All these methodologies were aimed towards applying the concept of a state-feedback linear controller for LFC. Some of the known techniques and self-tuning algorithms used for optimization were used for optimizing the LFC objective of a constructed cost function.

A number of researchers also used variable or state-space structure of the power system plant to develop a controller structure [13][14][15]. Some of the authors reportedly worked on frequency regulator which was essentially discrete in nature[16][17]. One of the main aims behind developing so many control techniques is to ensure that system response to various load disturbances is robust. Several researches have been dedicated to this cause since the past three decades [18][19][20][21][22][23][24][25][26][27]. The most common and foremost objective of all these works is dynamic stability and a robust system performance against any kind of possible disturbance that might come up in an interconnected power system. Techniques such as H_∞ [22][18][26], H_2 [28], Ricatti equation approach[25], Lypanov theory of stability[27] , Q parameterization [29], Kharitnov's theorem [30], Structured singular value theory called μ theory[18], Linear Matrix Inequatilities (LMI) [19][20], Genetic algorithm –LMI[22] and the technique of pole placement [31] have been extensively applied for fulfillment of robust control objective.

Most recent control strategy is based on the concept of intelligent control. Authors have come up with a vast option of intelligent control techniques which can be effectively applied for deign of power system controller [32][33][34][35]. Artificial neural network (ANN) was one of the earliest intelligent control technique introduced in the light of LFC[32]. Further advancement was using fuzzy logic for LFC. Fuzzy logic found mainly found usage for scheduling load frequency control parameters based on PI design [36]. Later, genetic algorithm also joined the party of control methods for LFC [37]. New and evolving intelligent algorithms are being applied for designing of LFC [38][39][40].

Some of the research works in the field of LFC have also been able to carve a niche for special alternative techniques, not conventionally used for LFC [41]. These alternatives include using Capacitive energy [42][43], Battery energy storage[44][45] , Photovoltaic power generation [46], solid state phase shifter [47].

As the concept of LFC evolves further, a number of constraints which practically exist in a power system are being employed to increase the practical implementation of the controllers being designed. Modeling of the power plants and increased standards of performance with new model identification schemes have also been put forth by researchers [28]. All these research works have been done for power systems which work under a vertically integrated system.
The above mentioned works have been done for the power systems under vertically integrated association. These utilities work as a part of the LFC framework using classical tuning methodologies which are very simple in nature to operate and handle.

Presently, modern day power system is not integrated but is deregulated in nature. It has separate areas interconnected together. Each area has several power plants and therefore, a deregulated power system has separate generating units and the distribution and transmission are also operated separate to other areas. In such an environment generation companies may not necessarily become a part of the LFC structure. As the independent power producer (IPP) comes into picture, it poses to be a major problem technically for the electric power market.

Therefore the implementation of control methods in the deregulated environment where LFC participation is not sown by every electric utility is not as easy and straight forward when compared to a the vertically integrated utility. Because of this model dynamics of the plant gets modified leading to urgency of a novel design of control which entertains these changes being brought to the LFC problem.

A number of practically possible scenarios for deregulated environment have been developed in view of solving the problem of LFC in terms of plant model development, control structure development and describing the structure [48]. In an electric industry which is restructured, supplementary services are being provided under several schemes and under various organizations. The basis for differentiating between the kinds of control structure that needs to be implemented in an area is dependent on the type of authority controlling generation, structure and freedom of power flow between different areas in market and the organization taking responsibility of ensuing system stability under LFC scheme [49][50].

Under deregulated power structure, several control and modeling strategies have been successfully tested for under well-established classical LFC schemes [51][52]. References[53] [54] propose neural network based controllers for interconnected two generation companies and the control schemes are quite flexible.

The effects of rising deregulated power industry on various technically important and challenging scenarios on LFC have been enlisted and discussed in [55][56][57]

1.4 OBJECTIVES OF THE PRESENT DISSERTATION

The electric power system is essentially changing its face from an integrated form to a deregulated one. Because of this in many countries the mechanism of working of the electric utilities is changing in wake of companies selling power at competitive low rates and aiming to achieve the goal of better efficiency. The power structure has outgrown itself and has become extremely complex making the operation of such a humongous system a mammoth's task in comparison to the earlier less complicated integrated power system environment.

Market power exercise is known to affect the dynamics of market operation. Additionally, a number of generator units operating in distribution areas and the emerging new independent electric utility companies will be hugely impacting the operation and control of the power system. Owing to these increasing challenges, need of a novel system model and better control strategy has come up as a major concern and need of the hour to ensure robust system response and efficiency.

In light of the challenged mentioned above, this dissertation work is dedicated to proposing a LFC methodology for an interconnected thermal power system using the well established base of state variable approach and applying a robust control technique to the same in order to design a control structure.

The designed controller is indented to comply with the following requirements:

- Robustness: It should be highly robust in nature in terms of system stability and performance for all the possible sets of perturbations that can occur in the system. To ensure this, a robust H_∞ technique based on linear matrix Inequalities (LMI) is developed.
- Decentralized property: As the practical power system is decentralized in nature and has numerous advantages, the controller design should also be decentralized in nature which is a much easier approach towards control design compared to design of a centralized controller In addition, the possibility of sequential decentralized LFC design is to be studied.
- Simplicity of the structure: In order to make the design of the controller practically viable and easy to be operate, it is of utmost importance that a either a lower order or a Proportional- Integral (PI) type controller is synthesized.
- Formulation of constraints and uncertainties: In an operational power system, system parameters are highly affected by various uncertainties present such as governor dead band as well as constraints such as generation rate constraint. Any kind of load flow control synthesis needs to be flexible enough to incorporate done these factors.
- To cover the main LFC objectives: LFC is mainly aimed and defined for maintain the system frequency at its nominal value and keeping the tie-line power exchange at it scheduled value. Another important aspect is to approach the synthesis of LFC as a multi-objective problem.

Above mentioned specifications emphasize the importance of physical understanding of a power system so that a diligent approach can be devised for controller design.

CHAPTER 2

MODELLING OF POWER SYSTEM FOR LFC

2.1 INTRODUCTION

The first step towards designing a robust controller is modeling of the system. For the research presented in this dissertation, a two area interconnected power system with non-reheat thermal units is considered and its structure is shown in Fig 2.1.

The structure used here is the fundamental control proposal for an interconnected power system. This chapter deals with modeling of the selected power system using state-space approach. This model is then modified in Chapter-3 for implying and designing the optimal robust controller and to study the overall system stability.

2.2 MODEL OF A TWO-AREA INTERCONNECTED POWER SYSTEM WITH NON-REHEAT THERMAL UNITS

Fig 2.1 depicts the model of two-area interconnected power system with non reheat thermal units. The control mechanism provided is of Integral (I) type.

The components of the power system are numbered from 1 to 7 and all the state-space equations are derived using them.

The system is provided with two control inputs namely, u_1 and u_2. The two thermal power areas are connected through a tie-line (block 7) which has its own dynamics.

The control is essentially made of three main blocks shown in Fig 2.1. These blocks are:

- Governor block
- Turbine block
- Power system

Each of these blocks is provided with an integral control block bringing up the total count to nine blocks.

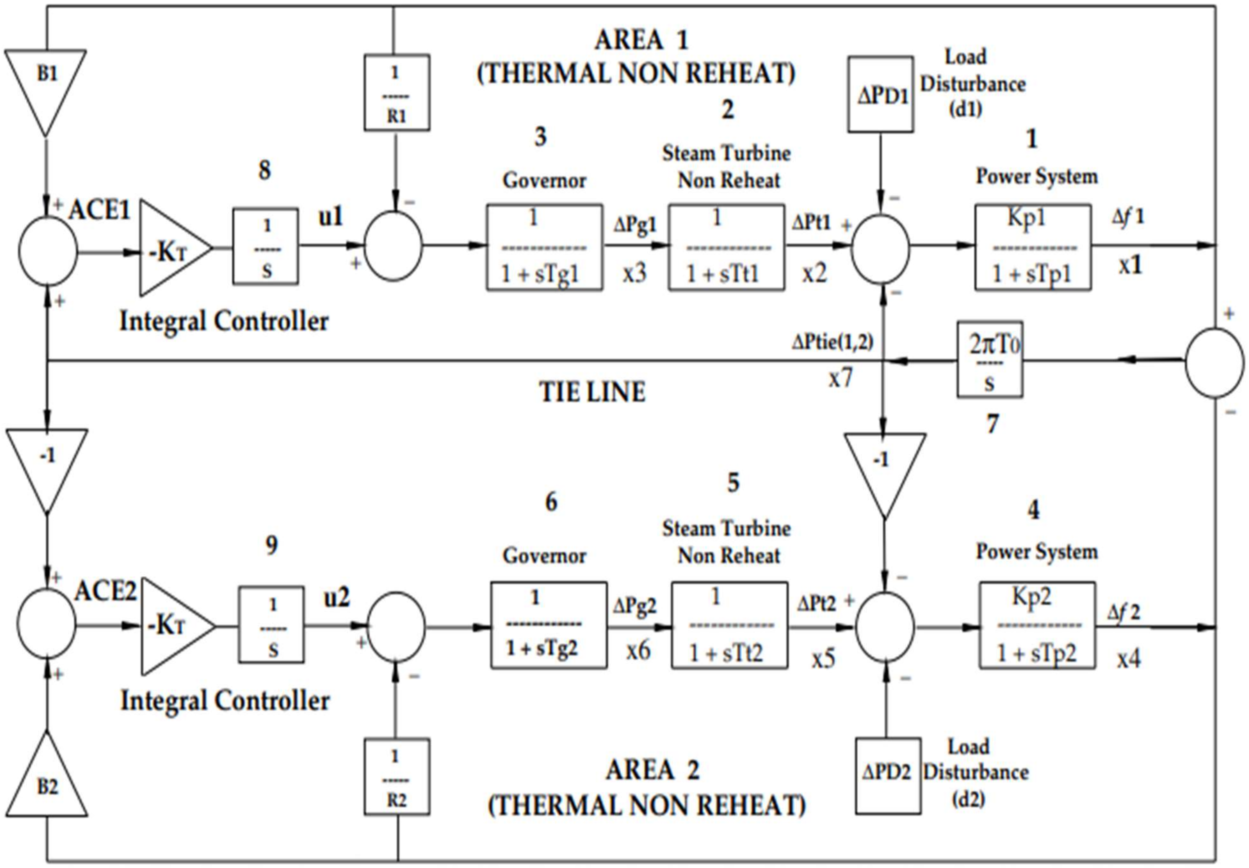

Fig 2.1 Two-Area interconnected power system with non thermal-reheat units.

The total number of state-space equations for the system shown above is nine.

The two input equations are:

- Area 1 (block 8)

$$\dot{u} = -K_i(ACE_1) = -K_i(B_1)x_1 + x_7 \tag{2.1}$$

- Area 2 (block 9)

$$u^{\cdot} = -\ K_i(ACE_2) = -K_i(B_2)x_4 - x_7 \tag{2.2}$$

Where, K_i: Integral gain for both the areas

ACE_1 : Area Control Errors of Area 1

ACE_2 : Area Control Error of Area 2

2.3 STATE SPACE REPRESENTATION OF THE TWO AREA INTERCONNECTED POWER SYSTEM WITH NON- REHEAT THERMAL UNITS

The state space modeling of the system shown in Fig 2.1 is depicted in Fig 2.2

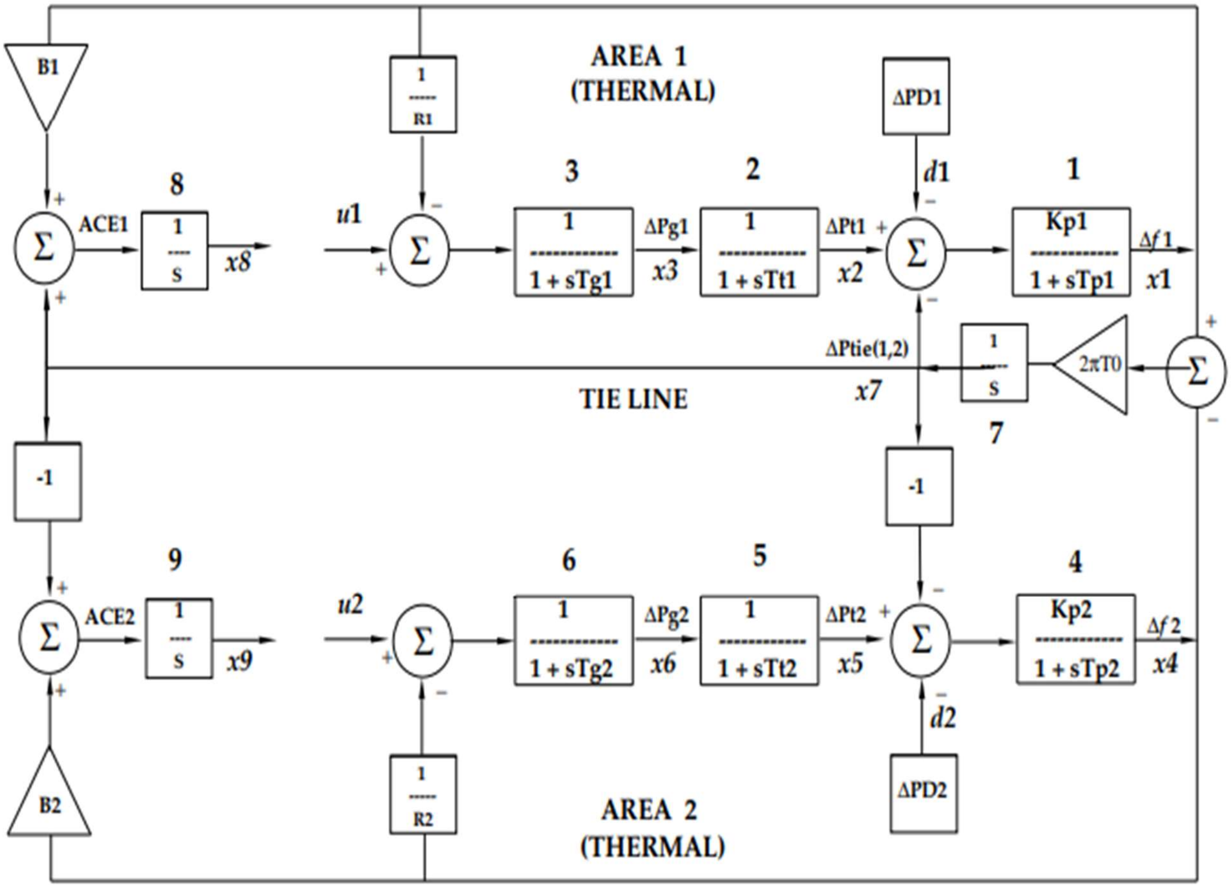

Fig. 2.2: State space model of two area interconnected power system with non-reheat thermal units

For the system shown in Fig 2.2, there are a total of nine state space equations.

The state space variables are given as:

$$x_1 = \Delta f_1$$

$$x_2 = \Delta P_{t1}$$

$$x_3 = \Delta P_{g1}$$

$$x_4 = \Delta f_2$$

$$x_5 = \Delta P_{t2}$$

$$x_6 = \Delta P_{g2}$$

$$x_7 = \Delta P_{tie(1,2)}$$

$$x_8 = \int ACE_1 \, dt$$

$$x_9 = \int ACE_2 \, dt \tag{2.3}$$

The control input variables are given as:

$$u_1 \ and \ u_2 \tag{2.4}$$

The disturbance input variables are given as:

$$d_1 = \Delta P_{d1}$$

$$d_2 = \Delta P_{d2} \tag{2.5}$$

From Fig 2.2, the transfer function blocks numbered 1-9 are used for writing the state space equations. The corresponding equations for each block are:

- Block no.1:

$$\dot{x}_1 = -\frac{1}{T_{p1}}x_1 + \frac{K_{p1}}{T_{p1}}x_2 - \frac{K_{p1}}{T_{p1}}x_7 - \frac{K_{p1}}{T_{p1}}d_1 \tag{2.6}$$

- Block no. 2:

$$\dot{x}_2 = -\frac{1}{T_{t1}}x_2 + \frac{1}{T_{t1}}x_3 \tag{2.7}$$

- Block no. 3:

$$\dot{x}_3 = -\frac{1}{R_1 T_{g1}}x_1 - \frac{1}{T_{g1}}x_3 + \frac{1}{T_{g1}}u_1 \tag{2.8}$$

- Block no. 4:

$$\dot{x}_4 = -\frac{1}{T_{p1}}x_4 + \frac{K_{p1}}{T_{p2}}x_5 + \frac{K_{p2}}{T_{p2}}x_7 - \frac{K_{p2}}{T_{p2}}d_2 \tag{2.9}$$

- Block no.5:

$$.\dot{x}_5 = -\frac{1}{T_{t2}}x_5 + \frac{1}{T_{t2}}x_6 \tag{2.10}$$

- Block no. 6:

$$\dot{x}_6 = -\frac{1}{R_2 T_{g2}} x_4 - \frac{1}{T_{g2}} x_6 + \frac{1}{T_{g2}} u_2 \tag{2.11}$$

- Block no. 7:

$$\dot{x}_7 = 2\pi T^0 x_1 - 2\pi T^0 x_4 \tag{2.12}$$

- Block no. 8:

$$\dot{x}_8 = B_1 x_1 + x_7 \tag{2.13}$$

- Block no. 9:

$$\dot{x}_9 = B_2 x_4 - x_7 \tag{2.14}$$

Mathematical solution of the state space equations can be found much easily by transforming them into a vector state space matrix described as:

$$\dot{x} = Ax + Bu + Fd \tag{2.15}$$

Where,

- A is the state matrix of dimension 9×9 .
- B and F are the control and disturbance matrices respectively of order 9×2
- 'x' is the 9×1 State Vector,
- 'u' is the 2×1 Control Vector
- 'd' is the 2×1 Disturbance Vector. The vectors 'x', 'u', 'd' can be written as

$$x = [x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5 \quad x_6 \quad x_7 \quad x_8 \quad x_9]^T$$

$$u = [u_1 \quad u_2]^T$$

$$d = [d_1 \quad d_2]^T \tag{2.16}$$

Where, $x_1 \ldots\ldots x_9$, represent the nine states.

- The state matrix A (9×9) is

$$A = \begin{bmatrix} -1/T_{p1} & K_{p1}/T_{p1} & 0 & 0 & 0 & 0 & -K_{p1}/T_{p1} & 0 & 0 \\ 0 & -1/T_{t1} & 1/T_{t1} & 0 & 0 & 0 & 0 & 0 & 0 \\ -1/R_1T_{g1} & 0 & -1/T_{g1} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1/T_{p2} & K_{p2}/T_{p2} & 0 & K_{p2}/T_{p2} & 0 & 0 \\ 0 & 0 & 0 & 0 & -1/T_{t2} & 1/T_{t2} & 0 & 0 & 0 \\ 0 & 0 & 0 & -1/R_2T_{g2} & 0 & -1/T_{g2} & 0 & 0 & 0 \\ 2\pi T^0 & 0 & 0 & -2\pi T^0 & 0 & 0 & 0 & 0 & 0 \\ B_1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & B_2 & 0 & 0 & -1 & 0 & 0 \end{bmatrix} \tag{2.17}$$

The control matrix B (9×2) is:

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1/T_{g1} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1/T_{g2} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{2.18}$$

The disturbance matrix F (9×2) is:

$$F = \begin{bmatrix} -K_{p1}/T_{p1} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -K_{p2}/T_{p2} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{2.19}$$

CHAPTER 3

LMI BASED H_∞ ROBUST DECENTRALIZED LFC DESIGN

3.1 INTRODUCTION

A number of design methodologies in order to improve the robustness and performance of LFC such as parameter variations, modeling uncertainties, nonlinearity, Generator Rate Constraints (GRC), effects of deregulation and load characteristics have to be been taken into account while designing LFC. For the purpose of solving these design issues, robust control technique is applied to the LFC problem.

The classical PI controllers are preferred in industry due to the satisfactory result across a wide range of working conditions and processes. These controllers are usually tuned online based on trial-and-error approach. Because of this experimental tuning methodology, they are not able to give a satisfactory dynamic performance in case a huge power system with a number of interconnected areas undergoing various loads changes and various operating conditions. A number of optimization techniques have been projected which simulate the entire power system and not just the control area being studied. The main limitation of these proposals is the assumption that all the subsystems in the system under study are taken to be identical [2][3]. The failure of these proposals therefore led to the introduction of a decentralized LFC[58][59][60][61][62].

A robust LFC controller based on H_∞ theory is presented in this section. The structure of the controller is a taken as proportional-integral (PI) type as it is poses to be practically ideal of industrial applications. H_∞ technique under linear matrix inequalities (LMI) constraints obtains gain constant values for this controller so that it exhibits robust characteristics whenever changes occur in the system because of change in tie line power exchange. This is achieved when the dynamic model of each area is modified according to the H_∞ based LMI technique [22][63][64].

3.2 H∞ TECHNIQUE BASED CONTROLLER DESIGN USING AN LMI ALGORITHM

An overview of H∞ control based on LMI approach is presented here. Amongst all the feedback controllers, H∞ controller is the most robust. The H∞ norm of a stable linear time-invariant system is given by the largest input/output RMS gain of its transfer function G(s) [65].

Fig.3.1. Closed-loop system via H∞ control

Consider a linear fractional transformation model of the system as shown in Fig 3.1 where, w is disturbance input vector, z the controlled output, y the regulated output vector and u the control input, and the state matrices $P(s)$ and $K(s)$ are the transfer matrices of the plant and the controller respectively[65].The plant elements are assumed to be rational, real and proper transfer functions. The relation of the input and output vectors to the plant transfer matrix P is:

$$\begin{bmatrix} Z\,(s) \\ Y(s) \end{bmatrix} = \begin{bmatrix} P_{11}(s) & P_{12}(s) \\ P_{21}(s) & P_{22}(s) \end{bmatrix} \begin{bmatrix} W(s) \\ U(s) \end{bmatrix} \tag{3.1}$$

For disturbance (w) to the controlled output (q), the closed loop transfer function is:

$$T.F(P,K) = P_{11} + P_{12}K(I - P_{22})^{-1}P_{21} \tag{3.2}$$

The closed-loop H∞ control technique using parameter γ is used to design a controller K(s) such that:

- Internal stability of the control loop is guaranteed,

- The H norm of $\mathcal{F}\ (P, K)$ i.e. the maximum gain from w to z is strictly less than γ, i.e. $||T_{zw}(s)||_\infty < \gamma$.

γ is the performance parameter which is returned as a non-negative scalar is the basic testimony as to whether a robust controller capable of showing a satisfactory dynamic response can be designed for the given system or not. Higher the value of γ, better is the disturbance attenuation capability of the deigned controller. Once the optimal performance index was obtained, LMI control toolbox was used for automatically designing the PI structured robust controller using H∞ technique.

The minimal realization under H∞ norm for the plant $P(s)$ is:

$$P(s) = \begin{bmatrix} D_{11} & D_{12} \\ D_{21} & D_{22} \end{bmatrix} + \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} [sI - A]^{-1} (B_1\, B_2) \tag{3.3}$$

The corresponding state-space equations are:

$$\dot{x} = Ax + B_1 w + B_2 u$$
$$z = C_z x + D_{z1} w + D_{z2} u$$
$$y = C_y x + D_{y1} w + D_{y2} u \tag{3.4}$$

Lemma 3.1: The assumptions applied to the plant parameters are that matrices A, B_2, C_y are stabilizable and detectable while $D_{y2} = 0$. For existence of the matrix K in an H∞ controller existence of a symmetric matrix X is necessary such that:

$$\begin{bmatrix} A_f^T X + X A_f & X B_f & C_f^T \\ B_f^T X & -\gamma I & D_f^T \\ C_f & D_f & -\gamma I \end{bmatrix} < 0 \tag{3.5}$$

$$X > 0 \tag{3.6}$$

The rational controller $K(s)$ is given by:

$$K(s) = D_k + C_k (sI - A_K)^{-1} B_k \tag{3.7}$$

State space model of controller is

$$\dot{\varsigma} = A_k\varsigma + B_k y$$

$$u = C_k\varsigma + D_k y \tag{3.8}$$

A realization of closed loop transfer function from w to z is obtained as

$$T.F(G,K)(s) = D_f + C_f(sI - A_f)^{-1}B_f \tag{3.9}$$

And the corresponding state space model is

$$\dot{x_f} = A_f x_f + B_f w$$

$$z = C_f x_f + D_f w \tag{3.10}$$

Where,

$$x_f = \begin{bmatrix} x \\ \varsigma \end{bmatrix}, \quad A_f = \begin{bmatrix} A + B_2C_kC_y & B_2C_k \\ B_kC_y & A_k \end{bmatrix}$$

$$B_f = \begin{bmatrix} B_1 + B_2C_kD_{y1} \\ B_kD_{y1} \end{bmatrix}$$

$$C_f = [C_z + D_{z2}D_kC_y \quad D_{z2}C_k]$$

$$D_f = D_{z1} + D_{z2}D_kD_{y1} \tag{3.11}$$

3.3 DYNAMIC MODEL OF INTERCONNECTED POWER SYSTEM FOR DESIGNING H∞ TECHNIQUE BASED ROBUST CONTROLLER.

Power system is composed of a numerous subsystem of interconnected generating units forming various sets of control areas. The dynamic model of a control area i comprising of n units of generation is shown in Fig 3.3. Coherency is assumed among the units of each area. For the power system shown in Fig 3.3, we can present the H∞ design using equation (3.4) as:

$$\dot{x}_i = A_i x_i + B_{iu}u_i + B_{iw}w_i$$

$$y_i = C_i x_i$$

$$z_i = C_{iz}x_i + D_{iz}u_i \tag{3.12}$$

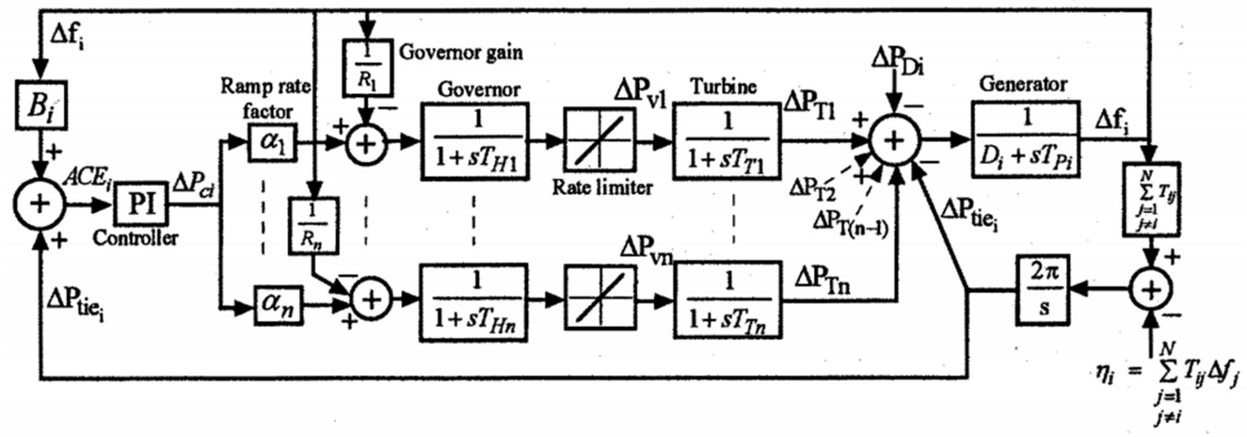

Fig 3.2 Dynamic model of interconnected power system for designing H∞ technique based robust controller.

Or

$$z_i = \left[\beta_{1i}\Delta f_i \quad \beta_{2i}\int ACE_i \quad \beta_{3i}\Delta P_{Ci}\right]^T$$

$$w_i = [\eta_i \quad \Delta P_{Di}]^T \tag{3.13}$$

Where

$$x_i^T = [x_{ia}^T \quad x_{i1}^T \quad x_{i2}^T \quad \dots \quad x_{in}^T]$$

$$u_i = \Delta P_{Ci}$$

$$y_i^T = \left[ACE_i \quad \int ACE_i\right]$$

$$\eta_i = \sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij}\,\Delta f_j \tag{3.14}$$

$$x_{ia}^T = \left[\Delta f_i \quad \Delta P_{tie_i} \quad \int ACE_i\right]$$
$$x_{i1}^T = [\Delta P_{T1} \quad \Delta P_{V1}]$$
$$x_{in}^T = [\Delta P_{Tn} \quad \Delta P_{Vn}] \tag{3.15}$$

$$A_i = \begin{bmatrix} AREA_i & MP_i \\ DROOP_i & TG_i \end{bmatrix} \tag{3.16}$$

$$C_i = [C_i^* \quad 0]$$

$$B_{iu} = \begin{bmatrix} 0 \\ B_{iu}^{*} \end{bmatrix}$$

$$B_{iw} = \begin{bmatrix} B_{iw}^{*} \\ 0 \end{bmatrix}$$

$$C_{i\infty} = \begin{bmatrix} C_{i\infty}^{*} & 0 \end{bmatrix} \tag{3.17}$$

$$AREA_i = \begin{bmatrix} -D/T_{pi} & -1/T_{pi} & 0 \\ 2\pi \sum_{\substack{j=1 \\ j\neq i}}^{N} T_{ij} & 0 & 0 \\ B_i & 1 & 0 \end{bmatrix} \tag{3.18}$$

$$C_i^{*} = \begin{bmatrix} B_i & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3.19}$$

$$MP_i = \left[\begin{pmatrix} 1/T_{P_i} & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \cdots\cdots \begin{pmatrix} 1/T_{P_i} & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \right] \tag{3.20}$$

$$TG_i = \begin{bmatrix} \begin{pmatrix} -1/T_{T1} & -1/T_{T1} \\ 0 & -1/T_{H1} \end{pmatrix} & & 0 \\ & \ddots & \\ 0 & & \begin{pmatrix} -1/T_{T1} & 1/T_{T1} \\ 0 & -1/T_{H1} \end{pmatrix} \end{bmatrix} \tag{3.21}$$

$$DROOP_i = \begin{bmatrix} \begin{pmatrix} 0 & 0 & 0 \\ -1/R_1T_{H1} & 0 & 0 \end{pmatrix} \\ \vdots \\ \begin{pmatrix} 0 & 0 & 0 \\ -1/R_1T_{H1} & 0 & 0 \end{pmatrix} \end{bmatrix} \tag{3.22}$$

$$B_{iu}^{*} = \begin{bmatrix} \alpha \begin{pmatrix} 0 \\ T_{H_n} \end{pmatrix} \\ \vdots \\ \alpha \begin{pmatrix} 0 \\ T_{H_n} \end{pmatrix} \end{bmatrix} \tag{3.23}$$

$$B_{iw}^{*} = \begin{bmatrix} 0 & -1/T_{P_i} \\ -2\pi & 0 \\ 0 & 0 \end{bmatrix} \tag{3.24}$$

$$C_{iz}^{*} = \begin{bmatrix} \beta_{1i} & 0 & 0 \\ 0 & 0 & \beta_{2i} \\ 0 & 0 & 0 \end{bmatrix} \tag{3.25}$$

$$D_{iz} = \begin{bmatrix} 0 \\ 0 \\ \beta_{3i} \end{bmatrix} \tag{3.36}$$

Where,

P_T: Turbine power

P_C: Governor load set-point

f : Area frequency

η : Area interface

D : Area load governing characteristic

Δ: Deviation from nominal values

T_{ij}: Tie-line synchronizing coefficient between area i and j

T_T: Turbine time constant

R : Droop characteristic

α : Ramp rate factor

P_V: Governor valve

P_D: Power demand

P_{tie}: Net tie-line flow

T_P : Area aggregate inertia

T_H : Governor time constant

B : Frequency bias

N : Number of control areas

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

In this work, first modeling of a two area interconnected power system is done using the state space analysis. Next, H_∞ technique under linear matrix inequalities (LMI) constraints is applied to each area to design the robust controller desired. The structure of the controller designed is of Proportional-Integral (PI) type. The system proposed is checked for its robust performance under different cases of load disturbances introduced. The results of the H_∞ deigned controller are compared with conventional PID controller for load frequency control in both the areas.

4.2 RESULTS FOR H_∞ CONTROLLED TWO AREA INTERCONNECTED POWER SYSTEM

The system under study is shown in figure 2.1 is a two-area interconnected power system with non-reheat thermal turbine units and their parameters are tabulated in table 4.1. A robust H_∞ technique based decentralized load frequency controller (PI type) designed in accordance with algorithm given in section 3 is implemented on each area. For both the areas, there robust performance obtained is compared with conventional industrial PI controller for different scenarios (table 4.2) of load disturbances. In each of the scenarios, an increment in load demand of each area is applied in the form of a step increase.

The weighting coefficients in equation are taken to be 0.5,1 and 500 respectively such that the control exertion for limiting overshoot and governor-load set-point reversals are reduced.

The robust performance index of the H_∞ -LMI based controller for the two control areas is given in table 4.3. The performance index is a non-negative scalar γ and is an optimization parameter. This performance index is obtained using the Robust Control toolbox in MATLAB.
This parameter basically tests whether an effective robust controller can be designed for the given area placed under LMI constraints or not. Higher the value of the performance index better is the disturbance attenuation capability of the controller.

Table 4.1 Generating unit parameters

MVA_{base} **(1000 MW)**	$\boldsymbol{Area\ 1}$	$\boldsymbol{Area\ 2}$
Rate (MW)	1000	800
D(pu/Hz)	0.0150	0.0140
T_P pu-sec	0.1667	0.1200
T_T (sec)	0.4	0.36
T_H (sec)	0.08	0.06
R (Hz/pu)	3.00	3.00
B (p/Hz)	0.3483	0.3473
α	0.4	0.4
Ramp Rate (MW/min)	8	8

Table 4.2 Different scenario's of load disturbances

Scenario No.	Percentage step load increment in area1 (ΔP_{D1})	Percentage step load increment in area 2 (ΔP_{D2})
1	5%	5%
2	3%	4%
3	10%	10%

Once the performance index verifies whether the system is viable for designing H_∞ technique based PI structured controller, the function "hinflimi" provided in the LMI control toolbox is used to directly solve the modeled H_∞ based system.

Table 4.3 Robust performance index for H_∞ design

$\boldsymbol{Control\ Design}$	γ_{area1}	γ_{area2}
$\boldsymbol{H_\infty}$	500.0091	500.3490

The response of the designed system undergoing test is given below in the form of simulation graphs obtained for different parameters against different cases of load disturbances.

Figure 4.1 and 4.2 show the deviation in frequency (Δf), area control error (ACE) and deviation in governor-load-set-point (ΔP_c) for scenario no.1 in area 1 and area 2 respectively. Figure 4.3 and 4.4 show the deviation in frequency (Δf), area control error (ACE) and deviation in governor-load-set-point (ΔP_c) for scenario no.2 in area 1 and area 2 respectively. Figure 4.4 and 4.5 show the deviation in frequency (Δf), area control error (ACE) and deviation in governor-load-set-point (ΔP_c) for scenario no.3 in area 1 and area 2 respectively.

The purpose of testing the system for three different scenarios is to check whether the proposed controller depicts robust characteristics against frequently occurring small as well as some rare large disturbances. The load demand increment is very rarely large as it may lead to penalization of the party responsible for such a huge mismatch between power demand and supply. The only purpose of introduction large disturbances is to check the system robustness under extreme conditions.

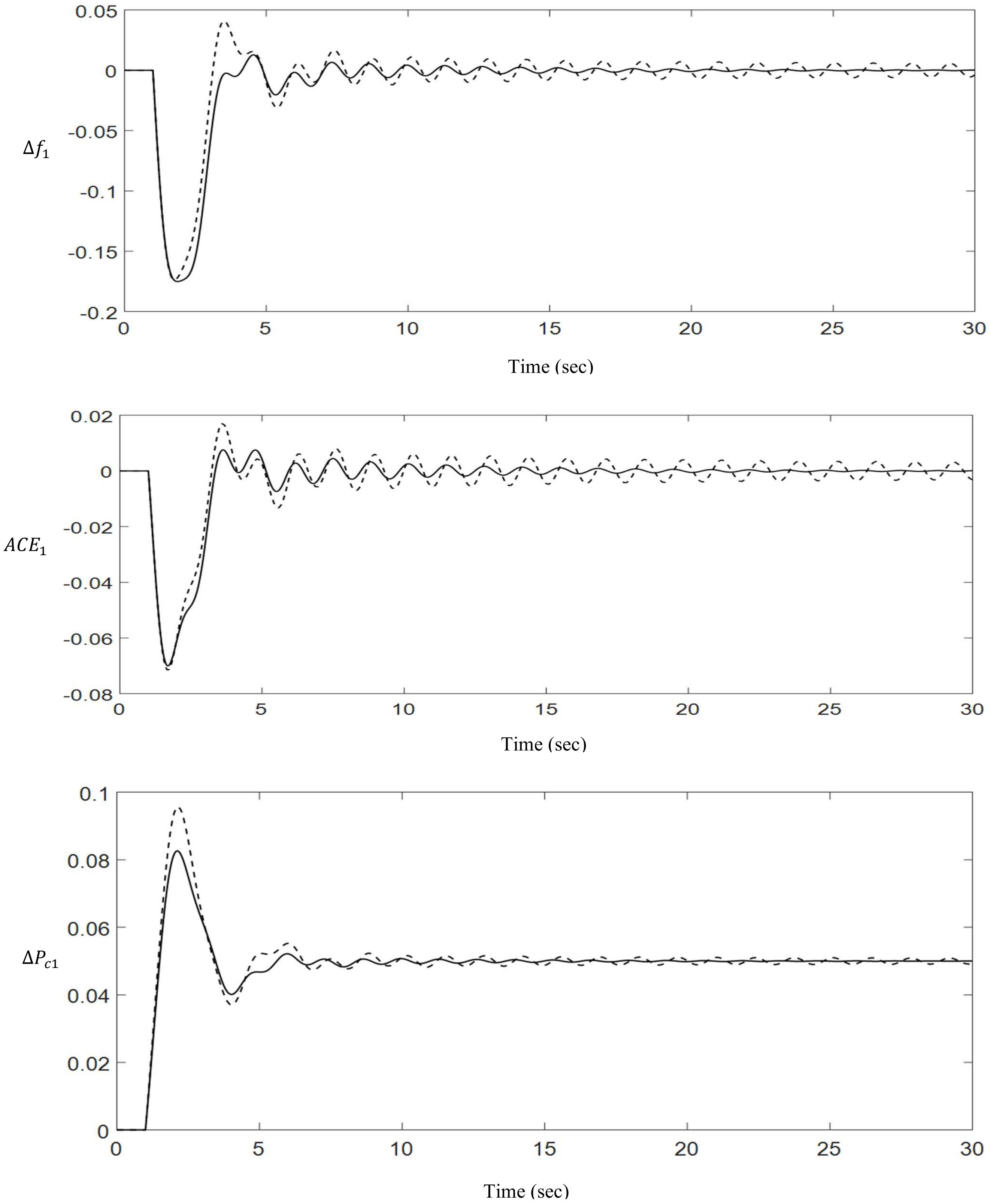

Fig 4.1 Response of Area 1 for scenario 1; Solid graph is for H_∞, dash-dotted is for PID

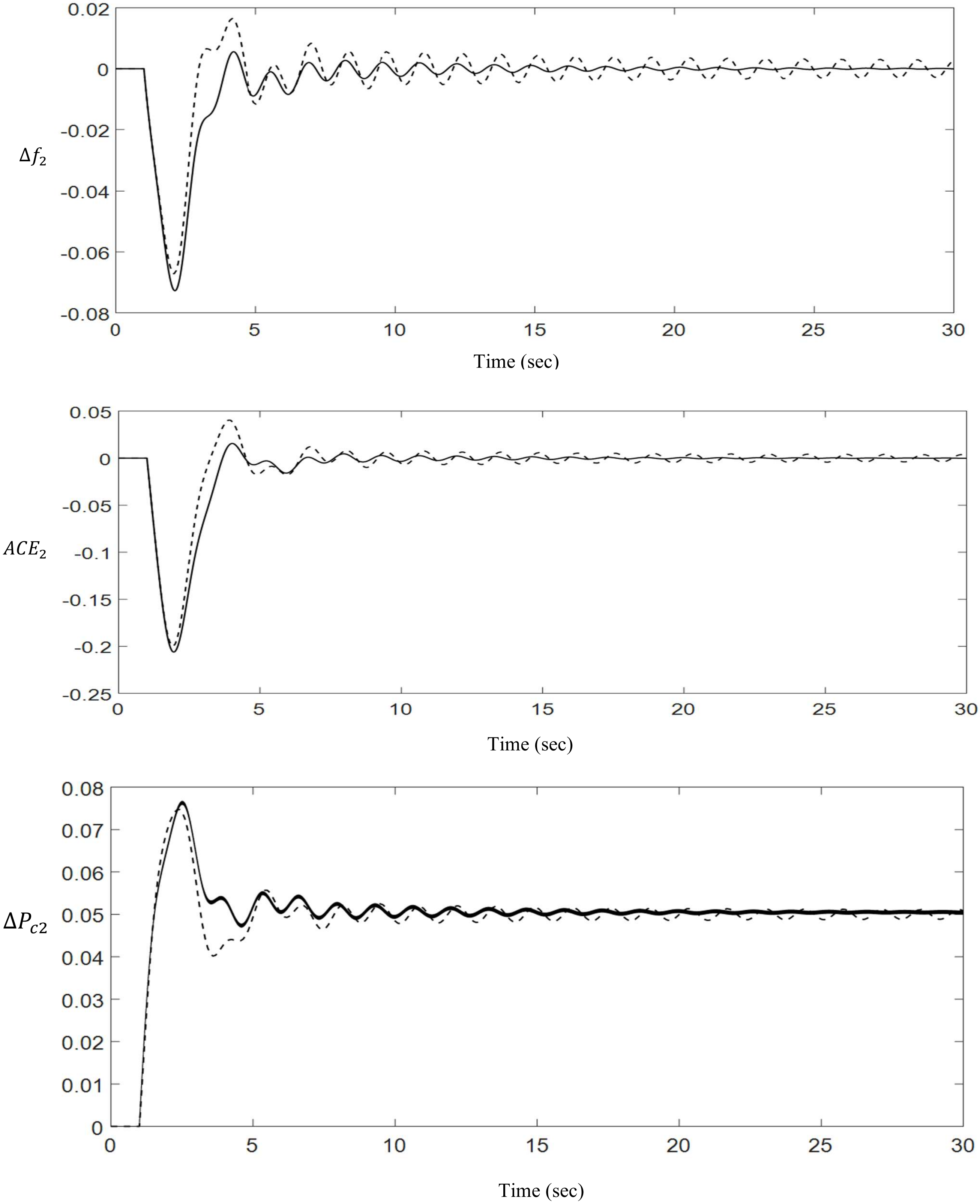

Fig 4.2 Response of Area 2 for scenario 1; Solid graph is for H∞, dash-dotted is for PID

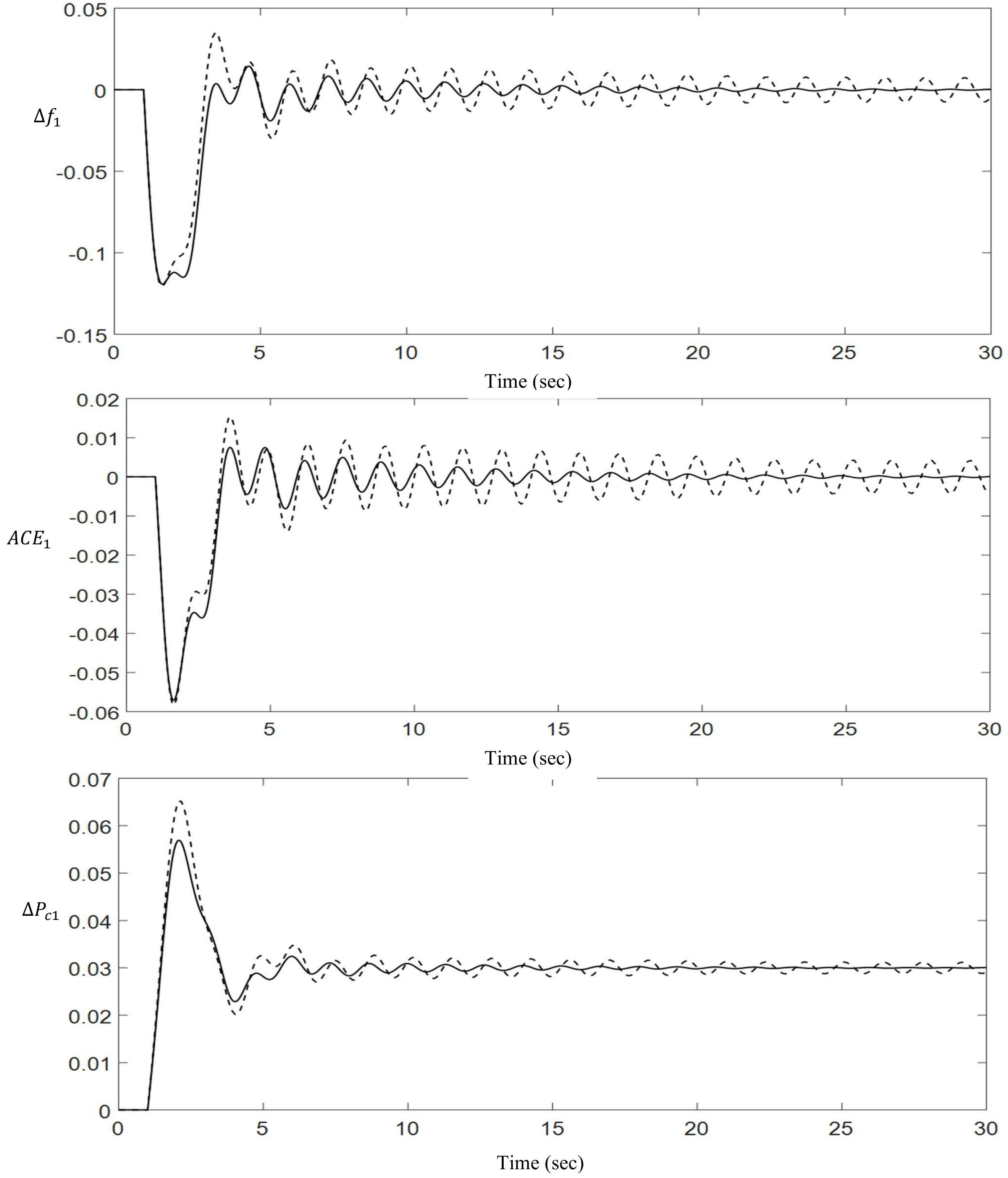

Fig 4.3 Response of Area 1 for scenario 2; Solid graph is for H_∞, dash-dotted is for PID

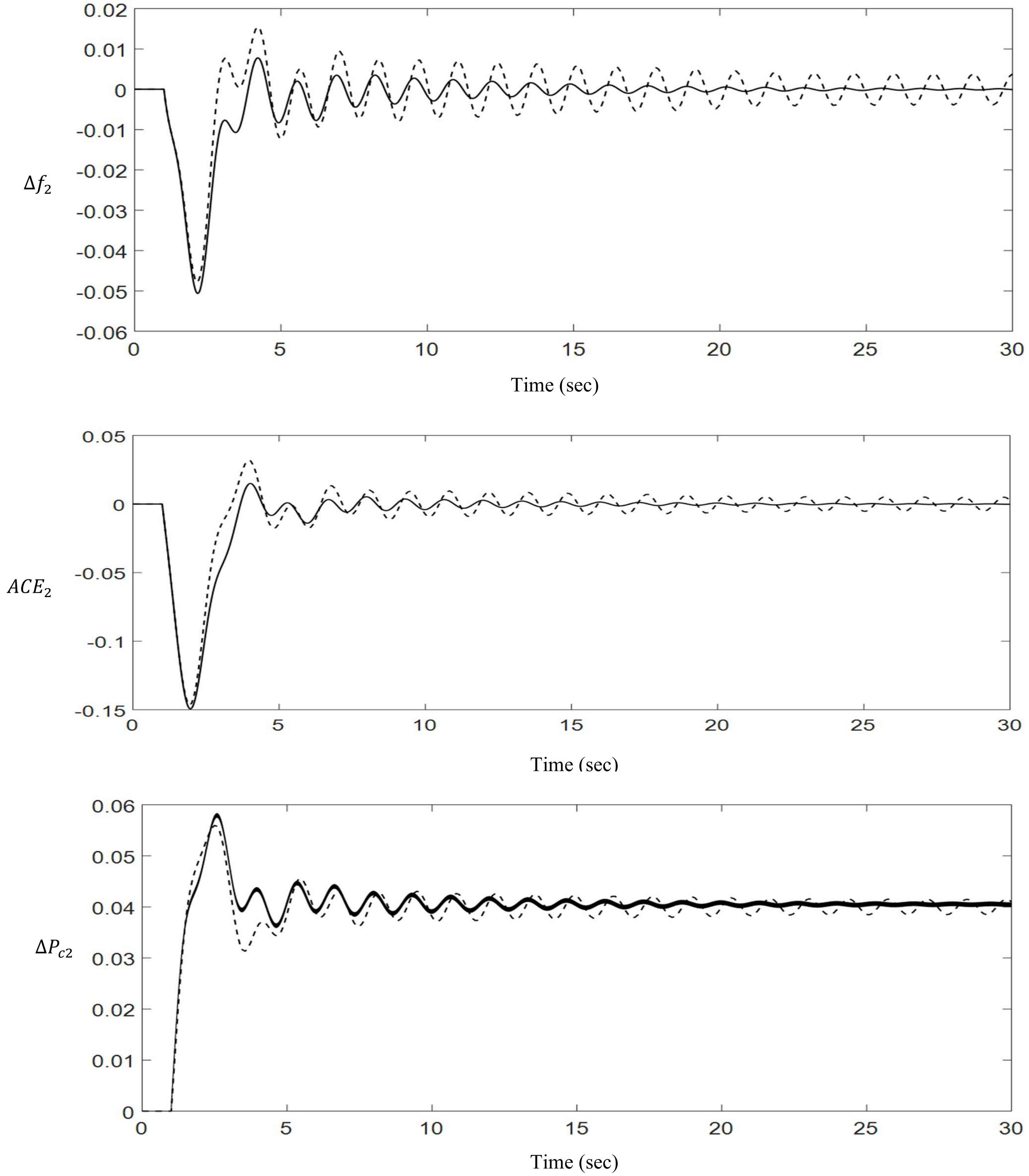

Fig 4.4 Response of Area 2 for scenario 2; Solid graph is for H_∞, dash-dotted is for PID

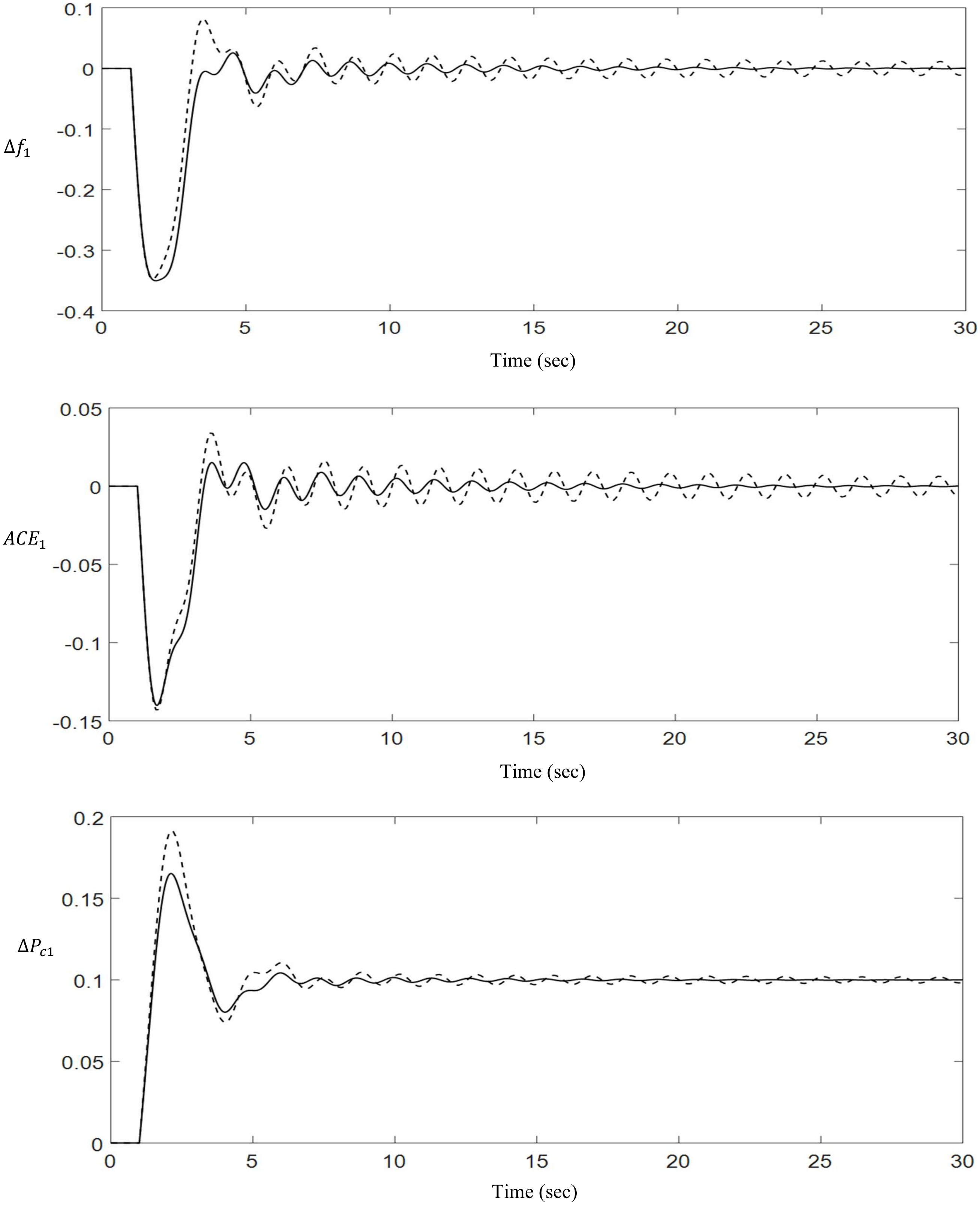

Fig 4.5 Response of Area 1 for scenario 3; Solid graph is for H_∞, dash-dotted is for PID

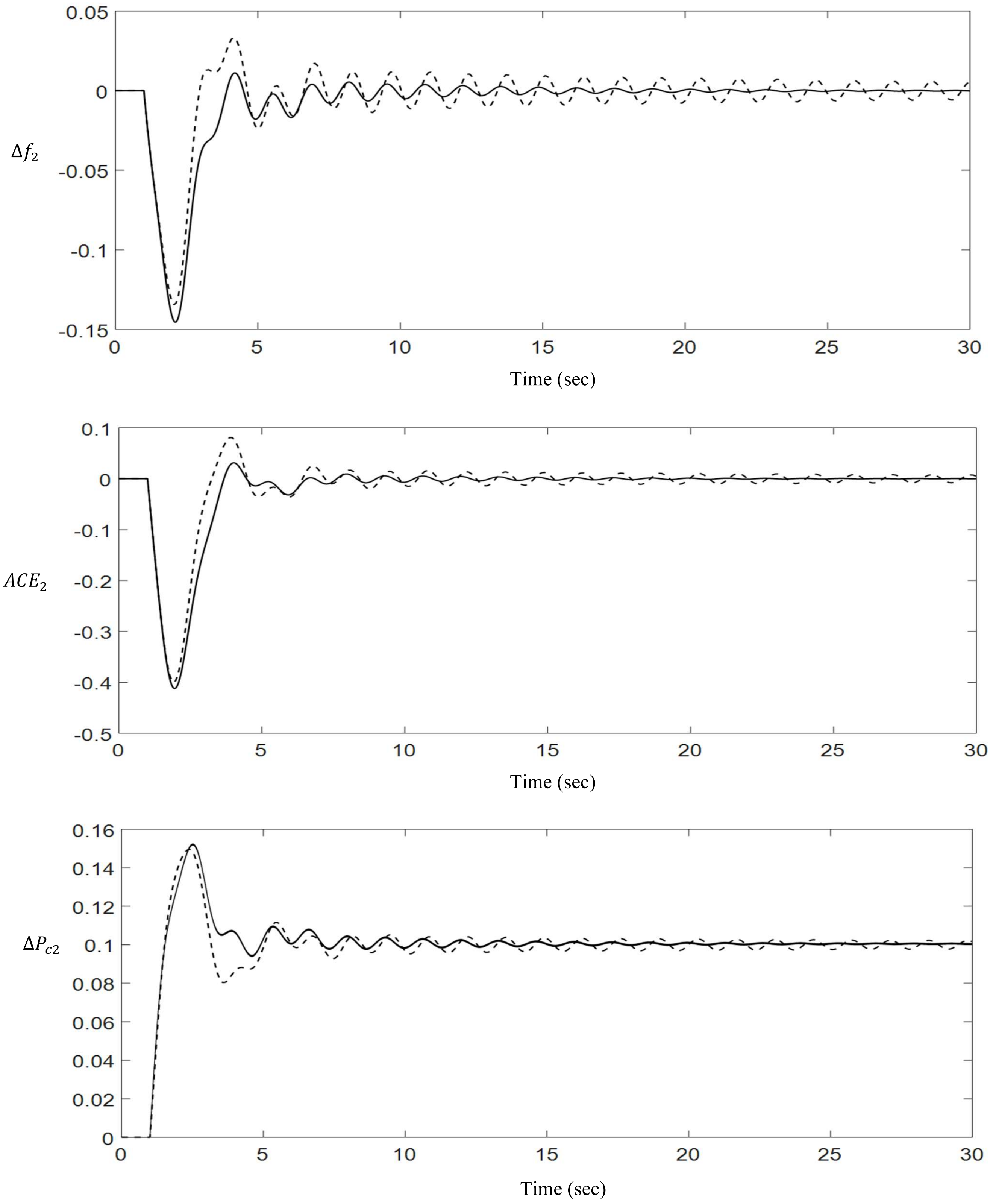

Fig 4.6 Response of Area 2 for scenario 3; Solid graph is for H∞, dash-dotted is for PID

From the simulation results shown above it can be seen that the proposed H_∞ controller performs better in terms of driving the frequency error and ACE to zero successfully in less time than PID controller.

It also successfully reduces undershoot and overshoot in the transient response of the system to the load disturbances introduced. Another major difference between the proposed controller and the conventional controller is the damping out the oscillations after the transient period for the case of system under load disturbance. It can be clearly seen that the designed controller very efficiently damps out the oscillations of the system response within few seconds while the conventional controller response exhibits oscillations for some time.

Also, the governor-load-set point response is better for the proposed controller for both the transient and steady state period as the oscillations successfully damp out within few seconds.

Scenario no. 3 i.e. when both the areas are under large load perturbation is major case of discussion. Large load fluctuations do not occur frequently but act as a testimony as to how stable is the system control. On carefully analyzing the deviation in frequency and ACE for both the areas, it can be concluded that the oscillations are damped out by H_∞ controller in almost same time as for frequently occurring load fluctuations. However, the conventional controller response is not satisfactory for this case as the oscillation do not damp out for a very long time making system unstable for case of system under large load fluctuation.

CHAPTER 5

CONCLUSION AND SCOPE OF WORK

5.1 CONCLUSION

Modeling of a two-area interconnected power system with non-reheat thermal turbine units is done using the state space analysis approach. System modeled is placed under Linear Matrix Inequalities (LMI) constraints and then controller is designed on the basis of H_∞ technique. The structure of the controller was taken to be of Proportional- Integral (PI) type as PI controllers are considered to be ideally suitable for industrial applications.

The control rule is based on the plant output of each area and the corresponding present system states. The optimal performance index of the proposed controller, γ which is the H_∞ norm of the closed loop system, was obtained using the robust control toolbox in MATLAB and was returned as a non-negative scalar. Once the optimal performance index was obtained, LMI control toolbox was used for automatically designing the PI structured robust controller using H_∞ technique.

The designed controller was tested for small and large cases of load disturbance in the system and a dynamically stable system was obtained. For comparison of the system response to load fluctuations, both the areas equipped are with conventional PID controller and studied. When placed under load fluctuations given in the form of step disturbance response of the PID controlled system was in particularly not satisfactory for the case of large disturbances.

The system stability for tie-line power deviation and area frequency deviation on occurrence of load disturbances proved the effectiveness of H_∞ technique using LMI based controller proposed in this work. Therefore, all the design and performance specifications desired from the proposed controller (mentioned in section 1.4) namely, robustness, decentralization and structure simplicity were successfully met and design objective was realized.

5.2 SCOPE OF WORK

The future scope in the area of robust controller synthesis based on H_∞ is vast and this technique can be exploited further efficiently and tested for its stable performance. A number of possible scenarios can be explored.

- One the major area of expansion of this technique is that it can be extending it multi-area power system. The probability of success of the case is very high as this controller can design is decentralized which is in accordance with the decentralized power system structure.
- Another possibility is collaborating intelligent control methods with this design. This scenario can result in design of a controller of a much lower order. A lower order controller is highly appreciated in power system control for easy implementation and ability to be extended to a large interconnected system.
- The need of the hour is to include more number of system uncertainties in the model and test the dynamic robustness of the controller against the same.

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