Load Frequency Control of an Interconnected Power System Using H α Loop-Shaped Controller with Communication Delays

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Abstract

In an Interconnected power system, as a power demand varies randomly, both area frequency and tie-line power interchange also vary. Load frequency control (LFC) is of importance in electric power system operation to damp frequency and voltage oscillations originated from load variations or sudden changes in load demands. The objectives of load frequency control (LFC) is to minimize the transient deviations in these variables (area frequency and tie-line power interchange) and to ensure their steady state errors to be zeros. It is considered to the problem of power system load frequency control design incorporating the effect of using open communication network instead of a dedicated one for the area control error signals. A delay-dependent two-term Hα loop-shaped controller design has been proposed using linear matrix inequalities. The control error signal in LFC is called Area Control Error (ACE) which is a linear combination of net tie-line power error and frequency error. Comparison of effectiveness of the delay-dependent two-term H∞ loop-shaped controller design of the proposed two-term controller with that of existing one-term and two-term controller designs establishes the superiority as well as applicability of the present design for the LFC problem. The controller is constructed for a two area power system and the dynamic model of the power system and the controller design based on the model are elaborated in the thesis. Simulation results and frequency-domain analysis proved that Hα loop-shaped controller is attractive to the LFC problem in its stability and robustness.

Keywords: Load frequency control (LFC), Time-delay system, H α loop controller, Two-term controller Delay-independent, Linear matrix inequality (LMI).

1 Introduction

Load frequency control (LFC) is of importance in electric power system operation to damp frequency and also voltage oscillations originated from load variations or sudden changes in load demands. In a deregulated environment load-frequency control (LFC) is very important in order to supply reliable electric power with good quality and to provide better conditions for the electricity trading. The main goal of LFC is to maintain zero steady state errors for frequency deviation and good tracking load demands in a multi-area power system, it is treated as an ancillary service essential for maintaining the electrical system reliability at an adequate level. LFC is one of the important power system control problems in deregulated power systems, which there have been considerable control strategies based on robust and optimal approaches. In an interconnected power system that consists of several control areas, as the system varies, the tie-line power will change and the frequency deviations will occur. The load–frequency control is a part of the automatic generation control (AGC) system. The objective of LFC is to damp the transient deviations in area frequency and tie-line power interchange. This signal is used to regulate the generator output power based on network load demand. Different types of controllers have been proposed in literature for the load frequency control. To maintain the balances of both the active and reactive powers without control. As a result of the imbalance, the frequency and voltage levels will be varying with the change of the loads. Thus a control system is essential to cancel the effects of the random load changes and to keep the frequency and voltage at the standard values. The foremost task of LFC is to keep the frequency constant against the randomly varying active power loads, which are also referred to as unknown external disturbance. Another task of the LFC is to regulate the tie-line power exchange error. A typical large-scale power system is composed of several areas of generating units. In order to enhance the fault tolerance of the entire power system, these generating units are connected via tie-lines. The usage of tie-line power imports a new error into the control problem, i.e., tie-line power exchange error. When a sudden active power load change occurs to an area, the area will obtain energy via tie-lines from other areas. But eventually, the area that is subject to the load change should balance it without external support. Otherwise there would be economic conflicts between the areas. Hence each area requires a separate load frequency controller to regulate the tie-line power exchange error so that all the areas in an interconnected power system can set their set points differently. Another problem is that the interconnection of the power systems results in huge increases in both the order of the system and the number of the tuning controller parameters. As a result, when modeling such complex high-order power systems, the model and parameter approximations cannot be avoided. Therefore, the requirement of the LFC is to be robust against the uncertainties of the system model and the variations of system parameters in reality. The LFC has two major assignments, which are to maintain the standard value of frequency and to keep the tie-line power exchange under schedule in the presences of any load changes. In addition, the LFC has to be robust against unknown external disturbances and system model and parameter uncertainties. The high-order interconnected power system could also increase the complexity of the controller design of the LFC..

2 H α Controller

The modern approach to characterizing closed-loop performance objectives is to measure the size of certain closed-loop transfer function matrices using various matrix norms. Matrix norms provide a measure of how large output signals can get for certain classes of input signals. Optimizing these types of performance objectives over the set of stabilizing controllers is the main thrust of recent optimal control theory, such as L_1, H_2, H_α, and optimal control. The Hα norm of a system is the peak value for the magnitude of the transfer function over the whole frequency range. Given a state space form of a generalized plant P(s) (as shown in Fig.

$$P(s) = \begin{bmatrix} A & B1 & B2 \\ C1 & D11 & D12 \\ C2 & D21 & D22 \end{bmatrix}$$

stabilizing feed back control law

$$u2(s) = F(s)\, y2(s)$$

Which maintains system response and error signals within prespecified tolerances despite the effects of uncertainty on the system

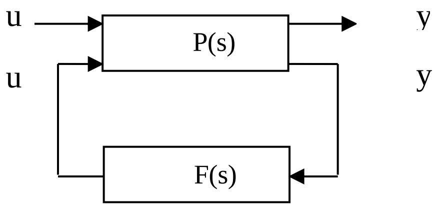

Fig.1. Generalized block diagram of H∞

u_1(s) would contain disturbances, y_1(s) would contain the performance variables one wishes to keep small in the presence of the disturbances contained in u_1(s) that would tend to drive y_1(s) away from zero. On other words one want to minimize the effect of u_1(s) (disturbance) on y_1(s). Hence, the disturbance rejection performance would depend on the "size" (infinity norm) of the closed loop transfer function from u_1(s) to y_1(s), which one shall denote as Ty1u1 $_{\alpha}$. H_∞ (i.e. "H-infinity") methods are used in control theory to synthesize controllers achieving robust performance or stabilization. The problem formulation is important, since any synthesized controller will be "optimal" in the formulated sense. H_∞ techniques have the advantage over classical control techniques in that they are readily applicable to problems involving multivariable systems with cross-coupling between channels. The term H_∞ comes from the name of the mathematical space over which the optimization takes place: H_∞ is the space of matrix-valued functions H_∞ techniques can be used to minimize the closed loop impact of a perturbation: depending on the problem formulation, the impact will either be measured in terms of stabilization or performance. It allows the control designer to apply classical loop-shaping concepts to the multivariable frequency response to get good robust performance, and then optimizes the response near the system bandwidth to achieve good robust stabilization. One great advantage with this technique is that it allows the designer to tackle the most general form of control architecture wherein explicit accounting of uncertainties, disturbances, actuator/sensor noises, actuator constraints, and performance measures can be accomplished. H-Infinity control method had a significant impact in the development of control systems; nowadays the technique has become fully grown and it is applied on industrial problems. In the control theory in order to achieve robust performance or stabilization, the H-Infinity control method is used. The control designer expresses the control problem as a mathematical optimization problem finding the controller solution. These techniques have the advantage over classical control techniques in which the techniques are readily applicable to problems involving multivariable systems with cross-coupling between channels. H-Infinity design provides more straightforward design equations than optimal control, which requires solving three coupled equations. H-infinity control theory deals with the minimization of the H-infinity-norm of the transfer matrix from an exogenous disturbance to a pertinent controlled output of a given plant. Most of the works on LFC have not considered the problems associated with the communication network and are valid under the traditional dedicated communication links. In view of the structure of existing power system model used for LFC, the area control error (ACE) acts as a control input to regulate the frequency deviation automatically. In general, the ACE signals are sought through high speed communication channel and may involve negligible communication delay. In the need for open communication network has been highlighted, which may cause a significant amount of communication delay present in the ACE signal. In the LFC design considering communication delay in the ACE signal, and subsequently a memory less state feedback control law (u(t) = Kx(t)) for such system is considered. The method assumes that load frequency control is performed by an ISO based on parameters defined by the participating generating units. The participating units comprise utility generators and independent power producers. The utilities define the units, which will be under load frequency control, while the independent power producers may or may not participate in the load frequency control. LFC in a interconnected power system has four principal objectives or preventive operating states: Matching total system generation to total system load, Regulating system electrical frequency error to zero, Distributing system generation amongst control areas so that net area tie flows match net area tie flow schedules, Distributing area generation amongst area generation sources so that area operating costs are minimized, subject to appropriate security and environmental constraints.

3 Design of H α Loop Shaping Controller

The design of load frequency controller in a deregulated environment should be such as to accommodate different kinds of transactions possible. Thus practically, we can see that a conventional controller may not be able to handle the risks associated with the large volume of transactions taking place. This is because a fixed controller design is done based on the plant model corresponding to a particular load-demand combination. Hence we see the necessity of a robust controller which would take care of the uncertainties in the plant model considering the nature of bilateral transactions. Objectives of robust controller synthesis include ensuring the stability of systems in the face of uncertainties in the system referred to as robust stability. In the control design for uncertain systems, it is necessary to know the level of performance once stability is ensured. This is called as robust performance. The term 'loop-shaping' refers to adjustment of frequency response of whole system within certain bounds so as to ensure sufficient robust performance and robust stability.

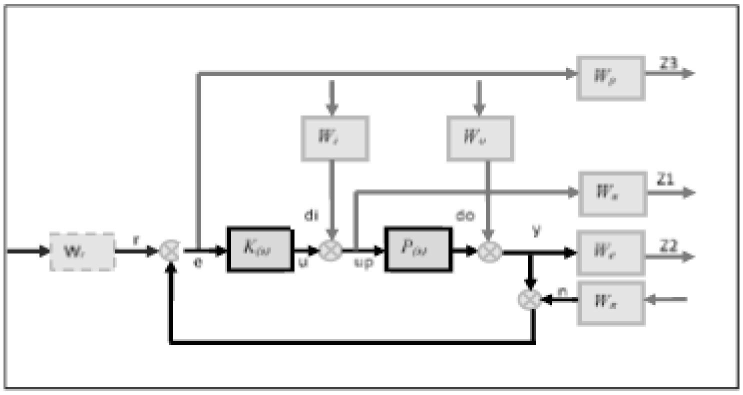

Fig.2. General Flow of Conventional H∞ Controller Design

The loop-shape is selected based on the following criterions,

1. For stability robustness, the target loop-shape should have low gain at high frequencies.

2. For performance, the desired loop-shape should have high loop-gain at low frequencies to ensure good control accuracy and disturbance attenuation.

3. Desired loop-gain should have its 0 dB crossover frequency, ω_c, between the above two frequency ranges and below ω_c, it should roll-off with a negative slope between -20 dB/decade and -40 dB/decade which helps to keep phase lag to less than -180º inside control loop bandwidth($0<\omega<\omega_c$).

4. The 0 dB crossover frequency should be more than the magnitude of any right half plane poles of the plant and less than the magnitude of any right half plane zeroes of the plant.

The loop-shaping design procedure is listed below:

1. Choose a desired loop-shape whose transfer function is given by G_d whose performance bound and robustness bound are as in fig. 3.

2. Conversion of G*d* to the form in which the singular values of the nominal plant are shaped to give the desired open-loop shape. The shaped plant can be expressed as $G_d = W_2 G W_1$, where W_1 is a pre-compensator and W_2 is a post-compensator. Here W_1 could be assumed unity for simplification.

$$\left\| \begin{bmatrix} I \\ K_\infty \end{bmatrix} (I + G_d K_\infty)^{-1} \tilde{M}_S^{-1} \right\|_\infty \leq \epsilon^{-1} \triangleq \gamma$$

3. The final feedback controller is constructed by combining H∞ controller K∞ with the shaping functions W_1 and W_2 such that $K = W_1 W_2$. The value of γ indicates that the achieved loop shape differs from the specified loop shape by only a limited amount. It can be shown that there will be a minimum deterioration in the desired loop-shape at frequencies of high or low loop-gain.

4 LFC Model Design with Loop Shaped H α Controller

The conventional controllers are no more capable of satisfying the control requirements. It is hence that robust controllers are suggested for load frequency control which can handle the uncertainties that are rampant in the system. H infinity control technique has the advantage over the classical control techniques which can be applicable to problems involving multivariate systems with cross-coupling between channels and simultaneously optimizing robust performance and robust stabilization is difficult. One method that comes close to achieving this is H loop shaping, which gives the control multivariable frequency response to get good robust performance in optimization and response near the system bandwidth to achieve good robust stabilization. H infinity controller based on loop-shaping has deals with interconnected two-area non-reheat thermal power system. The objectives of H-infinity controller synthesis include ensuring the stability of systems in the face of uncertainties in the system referred to as robust stability. In the control design for uncertain systems, it is necessary to know the level of performance once stability is ensured. The term ‘loop-shaping’ refers to adjustment of frequency response of whole system within certain bounds so as to ensure sufficient robust performance and robust stability. This method does not require an iterative procedure for robust stability margin and thus improves the computational efficiency. n this paper, a robust H_∞ loop-shaping controller is used as load frequency controller for a two-area deregulated power system with non-reheat thermal power plants. Load frequency control forms an essential component of Automatic Generation Control, which helps to maintain the power system frequency constant while maintaining the tie-line power flow with neighbouring areas at scheduled values for an interconnected power system.

The different types of possible LFC structures under regulated and deregulated power markets are

(i) free LFC-it does not support deregulation of power market and here LFC commands are sent out traditionally through point to point communication

(ii) charged LFC and bilateral LFC-it supports deregulated power market scenario and requires open communication network for passing the LFC command and various other ancillary services.

H α loop controller have much lower overshoot, rise time and settling time than the conventional integral controller. It may be noted that the power market scenario in most of the countries is “free LFC” type, but gradually across the globe the power generations are getting less importance which ultimately means an end to existing “free LFC” structure. The time delays in a LFC problem are invariably considered on the communication channels between the control centre and operating stations, notably on the measured frequency and measured tie-line power flow and have impacts on the performance of LFC and even cause system instability. In general, the ACE signals are sought through high speed communication channel and may involve negligible communication delay. LFC design using H∞ control may be classified based on the state feedback controllers into two types,

[1] One-term controller (no delayed state) and

[2] Two-term controller (control law is generated using both delayed and present state information).

[3] The power system model under consideration takes in to account of time-delays in the ACE signals as state delays.

[4] The power system time-delay model is discussed in presents of different state feedback stabilizing criterion for H∞ loop shaped controller design using LK functional approach in an LMI framework.

Area Control Error: The goals of LFC are not only to cancel frequency error in each area, but also to drive the tie-line power exchange according to schedule. Since the tie-line power error is the integral of the frequency difference between each pair of areas, if we control frequency error back to zero, any steady state errors in the frequency of the system would result in tie-line power errors.

Area control error (ACE) is defined as

$$\mathbf{ACEi} = \sum_{j-1,..n, j\neq i}^{n} \mathbf{\Delta Ptie\ ij} + \mathbf{Bi\Delta fi}$$

$$B_i = D_i + \frac{1}{R_i}.$$

where *Bi* is the frequency response characteristic for area *i*

This ACE signal is used as the plant output of each power generating area. Driving ACEs in all areas to zeros will result in zeros for all frequency and tie-line power errors in the system.

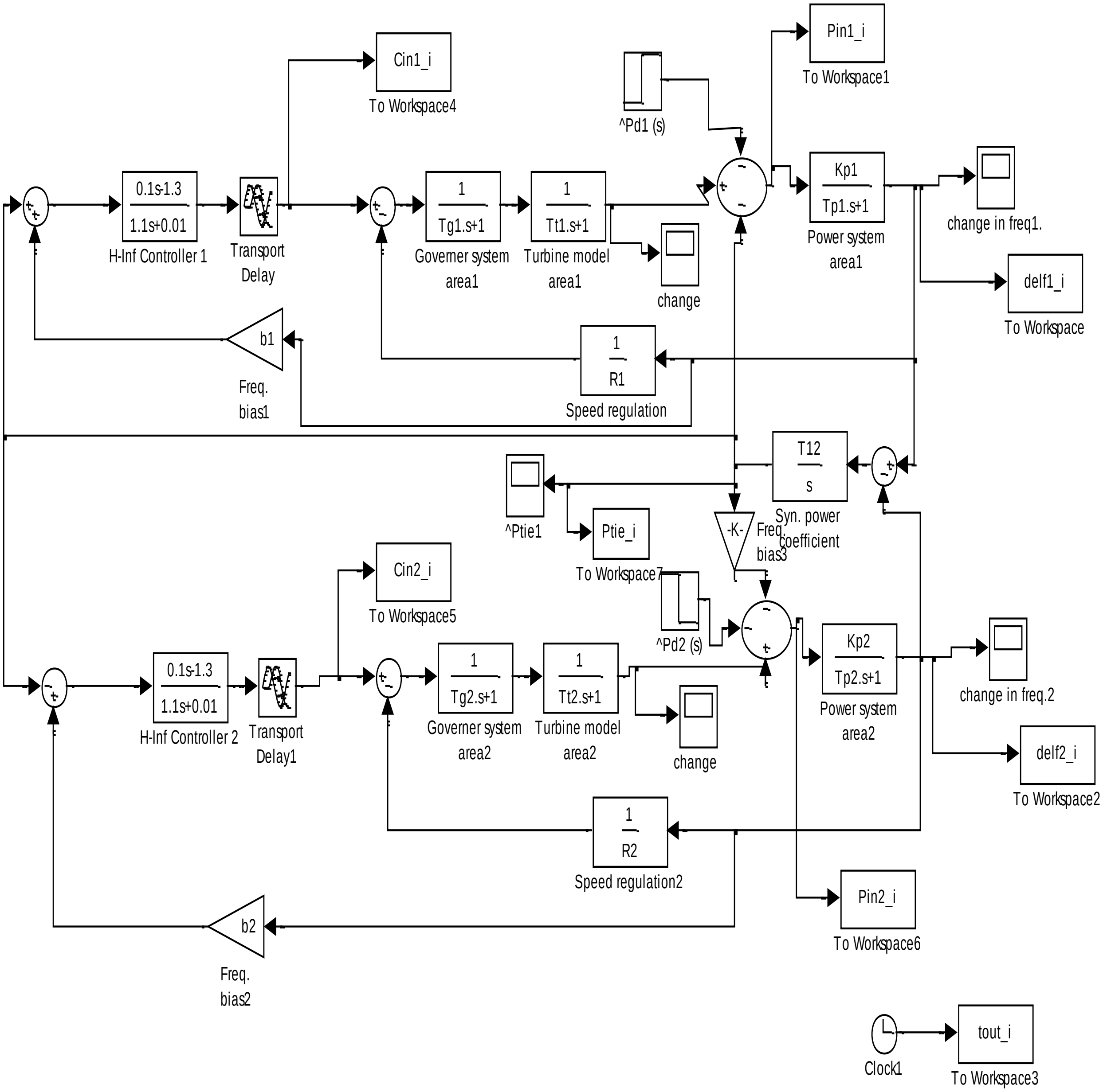

Fig.3. Simulink diagram for LFC of Two-Area Interconnected system with H infinity loop shaped controller

5 Simulation Results

I.

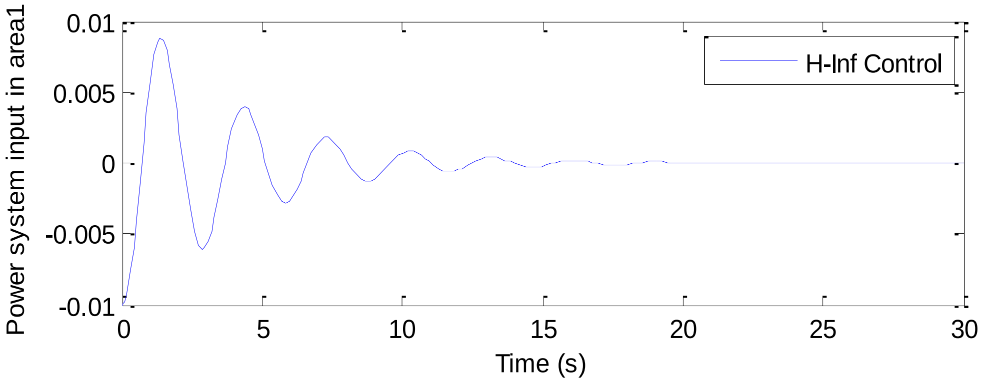

Fig.4. Power in Area-1

Figure.4 shows the characteristics between power versus time in Area-1 for unit step disturbance (frequency disturbance of area-1 is -0.01)

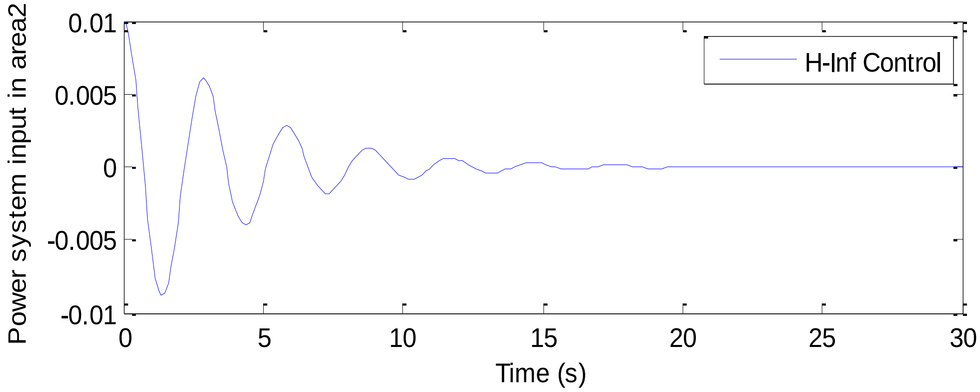

Fig.5. Power in Area-2

Figure.5 gives the characteristics between power versus time Area-2 for unit step disturbance (frequency disturbance of area-1 is -0.01 and area-2 is 0.01)

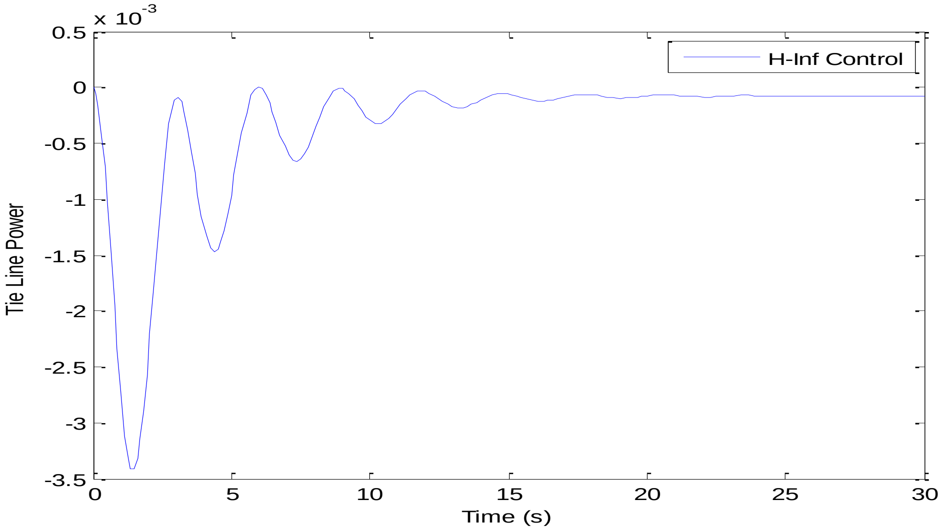

Fig.6. Tie Line Power of the two area power system

Figure.6 shows the tie line power deviation of the two area power system versus time which gives the variation of small amount of tie line power and its scheduling time of 20 to 25 sec.

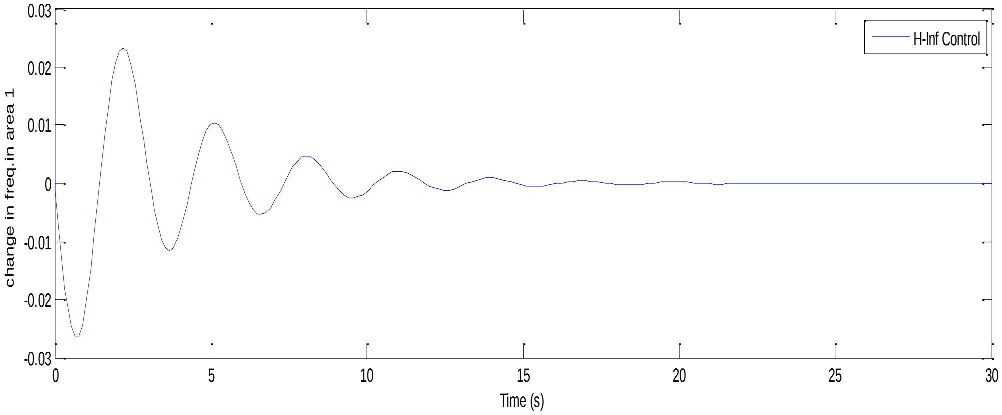

Fig.7. Frequency deviations in Area-1

Figure.7 gives the frequency deviations in the system with proposed controller for random step load disturbance of area-1 (disturbance of area-1 is -0.01)

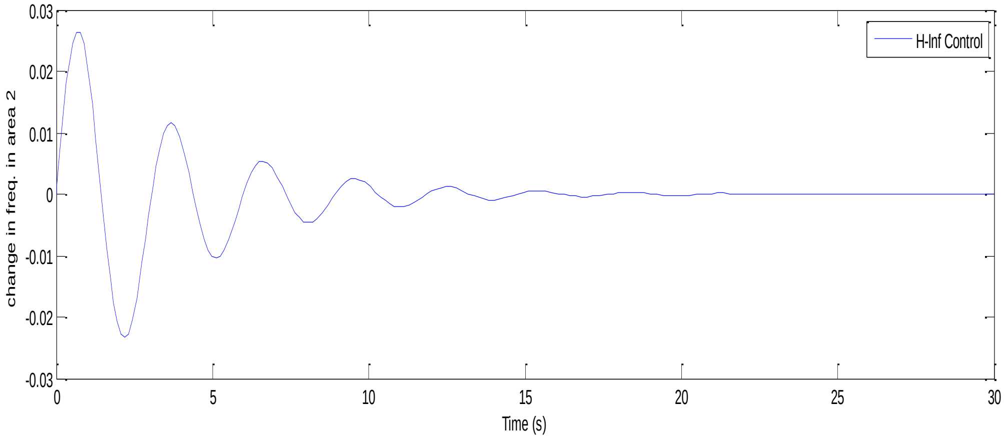

Fig. 8. Frequency Deviations in Area-2

Figure.8 gives the frequency deviations in the system with proposed controller for random step load disturbance of area 2 (disturbance of area-2 is 0.01)

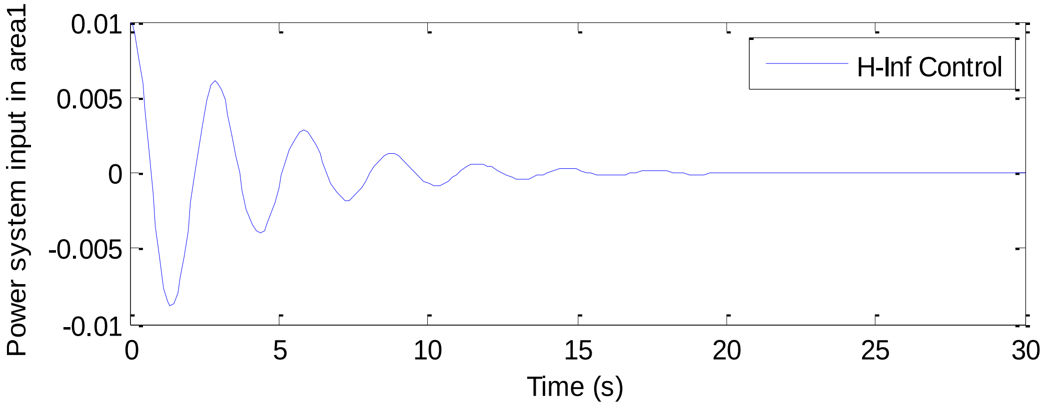

Fig.9. Power in Area-1

Figure.9 gives the control input power to the system in Area-1 for unit step disturbance (frequency disturbance of area-1 is 0.01)

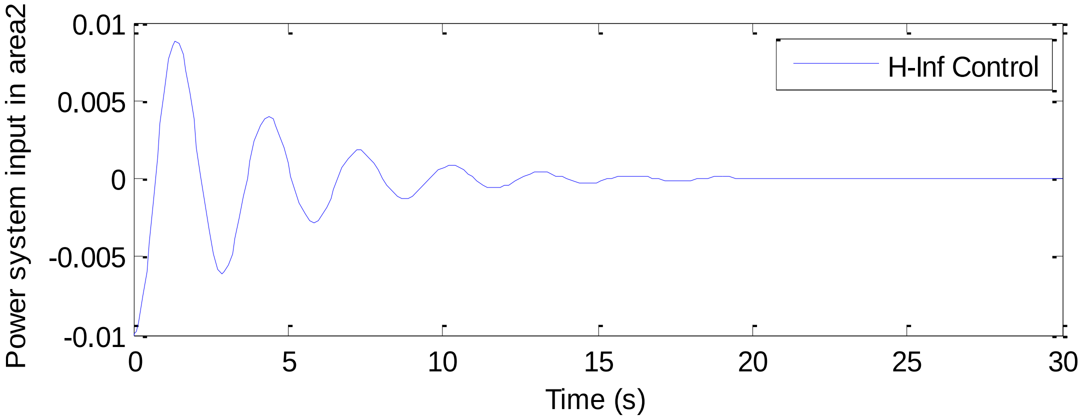

Fig.10. Power in Area-2

Figure. 10 shows the control input to the system in Area-2 for unit step disturbance (frequency disturbance of and area-2 is -0.01)

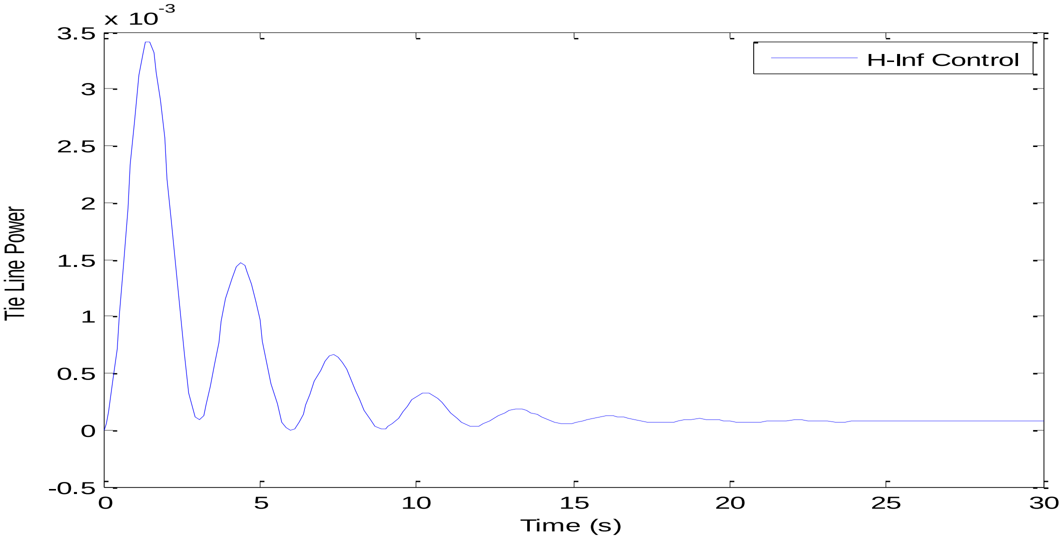

Fig.11. Tie Line Power of the two area power system

Figure.11 shows the tie line power deviation of the two area power system versus time which gives the variation of small amount of tie line power and its scheduling time of 20 to 25 sec.

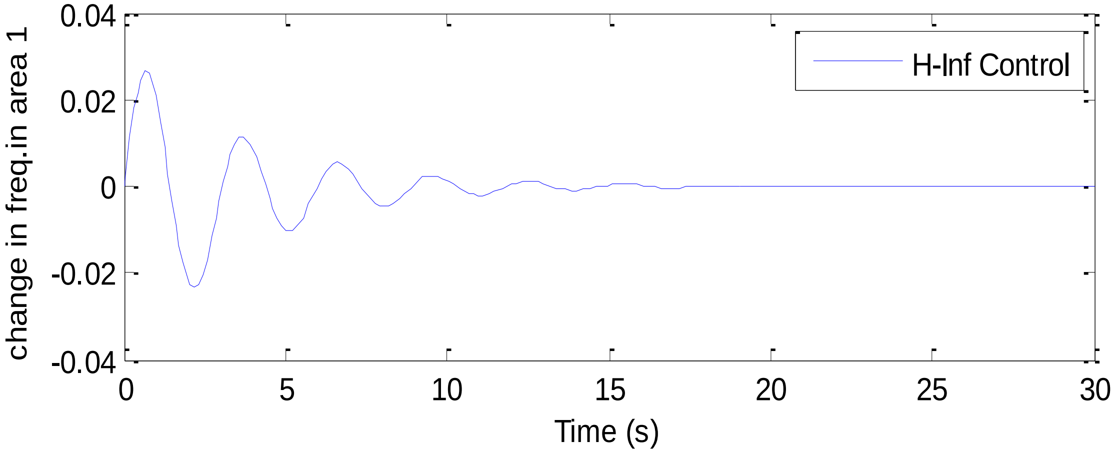

Fig.12. Frequency deviations in the system with controller for random step load disturbance in area-1

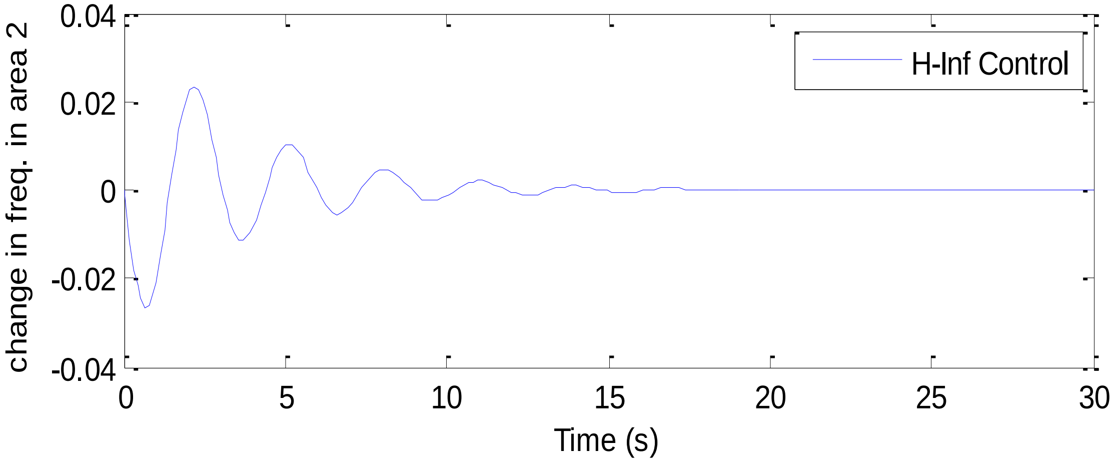

Fig.13. Frequency deviations in the system with controller for random step load disturbance in area-2

Abbreviations:

DPvi	governor valve position
DPmi	mechanical power output of the alternator
Dfi	frequency deviations
DEi	ACE signals
DP12	tie-line power flow from area 1 to area 2
Bi	Proportional gains of local PI controllers
Ki	Integral gains of local PI controllers
Tpi	Power system time constants
Di	Generator damping coefficients

Tgi	Governor time constants
Tchi	Turbine time constants
Ri	Speed droops
Ti	Stiffness coefficients
DPdi	load disturbances
Mi	Moment of inertia of the generators

6 Conclusions

The problem of designing delay-dependent two-term H∞ loop-shaped controller for stabilizing and load disturbance rejection for a two-area power system LFC model with multiple state delays has been dealt in this paper. An LMI based stability criterion has been derived based on Lyapunov–Krasovskii approach including the delay dependent functional terms in it. It has been shown that existing delay-independent design approach of two term controller actually leads to one-term controller. Performance and applicability of the proposed delay-dependent two-term controller is superior one and provides better damping characteristics compared to the existing one-term design of, whereas it is shown that delay-independent two-term controller strategy discussed in fails to provide solution for the present LFC model with communication delays.

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