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Stability Analysis and Delay-dependent robust load frequency control for time delay Power systems

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Abstract: Traditionally, frequency regulation in power system is achieved by balancing generation and demand through load following, i.e., spinning reserve and non-spinning reserves. In such cases, energy storage and responsive loads show great promise for balancing generation and demand. This paper investigates delay-dependent stability of load frequency control (LFC) emphasizing on multi-area and deregulated environment. Based on lyapnov theory and the linear matrix inequality technique, a new stability criterion is proposed to improve calculation accuracy and to reduce computation time, which makes it be suitable for handling with multi-area LFC schemes. The interaction of delay margins between delay margins and control gains are investigated in details. Case studies are carried out based on two-area traditional, two-area and three-area deregulated LFC schemes, all equipped with PID-type controllers, respectively. The main objective of this paper is to proposing an improved stability criterion with higher accuracy and less computation time to determine delay margins of multi-area LFC schemes and to reveal the interaction effects between different areas. The presented principles and controls have been verified by MATLAB simulation techniques.

Index terms: Delay margin, deregulated environment, feedback signals, Communication network, LFC, Propagation delay, Multi area.

I. INTRODUCTION

Frequency control is traditionally provided through automatic generation control (AGC). Through dedicated communication channels, the AGC signals are sent are the responsibility of the large utilities. In the case of failure of channel, backup was provided by voice communication through telephone lines. To guarantee fault tolerance in case of link failures, the new infrastructure need to have redundant links. It is an important factor to a distributed infrastructure for migrating because it inherently offers redundancy.

Traditionally, analysis of communication network parameters such as delays using queuing theory are performed. These models are largely based on exponential arrival rate to quantify the waiting time in queues as it allows several simplifications. Recently, the possibility of allowing a bilateral market for the provision of frequency control and load following services has arisen provided there exists an appropriate communication channel [3].

A certain number of generating units receive a signal input for operation of the load frequency control in the form of data packets, as to increase or decrease power output.

II. NETWORK DELAY MODELS FOR LFC

For the analyzation of network delays, models like queuing theory are introduced now which focus maximum in the network layer on packet delays. The packet delays are the sum of delays consisting of processing delay, queuing delay, transmission delay and propagation delay [6]. The retransmission effects are neglected since they are rare for maximum links.

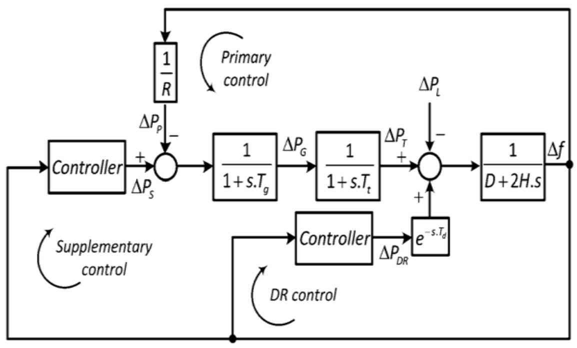

Fig1 : Dynamic model of one-area LFC scheme

The focus of this paper is mostly on two scenarios, namely a dedicated start topology for the traditional AGC model and a distributed model based on a dedicated network configuration. The latter also applies to the non dedicated distributed structure. The increase of the scale and load ability of power system, inter-area low frequency oscillations become a serious problem and often suffer from poor system damping. Traditionally, the damping of low frequency oscillations is provided by installing a power system stabilizer (PSS) which uses local measurements such a rotor speed or active power as feedback signals.

Recently, the delay margin of the power system considering time delays has been investigated by using direct methods , such as the tracing critical eigenvalue and cluster treatment of characteristic roots. These direct methods can indicate the accurate delay margin by calculating eigenvalues of the whole system. The full-

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order system model is required in this case, which significantly increases the design complexity. Moreover, these two direct methods can only deal with constant time delays.

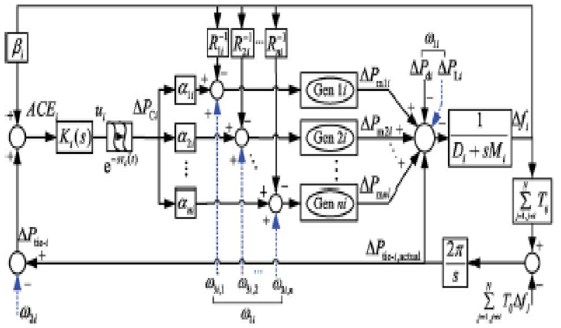

Fig.2. LFC structure of I control area

A. Deregulated Multi-Area LFC Scheme

For multi-area LFC in deregulated environment, as shown in fig. 2 including the dotted line connection , in which each Genco can contract with various Discos in or out of the area this Genco belonging to. Those bilateral contracts are usually visualized by an augmented generation participation matrix (AGPM). For a large-scale power system with areas and Discos and Gencos in each area, the AGPM is given by

= AGPM =

.where

$$AGPM_{ij} = \begin{bmatrix} gpf_{si+1,z\,j+1} & \cdots & gpf_{si+1,zj+m} \\ \vdots & \ddots & \vdots \\ gpf_{si+n,zj+1} & \cdots & gpf_{si+n.zj+m} \end{bmatrix}$$

A PI controller, which is the load frequency controllers used currently in industry, is included in the model.

$$\begin{cases} \dot{\bar{x}}(t) = \bar{A}x(t) + Bu(t) + \bar{F}\Delta P_d \\ \bar{y}(t) = \bar{C}x(t) \end{cases} \quad (2)$$

Where

(t) = T

(t) = ACE ,

$$= \begin{bmatrix} -\frac{D}{M} & \frac{1}{M} & 0 \\ 0 & -\frac{1}{Tch} & \frac{1}{Tch} \\ -\frac{1}{RTg} & 0 & -\frac{1}{Tg} \end{bmatrix}$$

= T

On the other hand, the practical LFC controllers are operated in discrete mode as the ACE signals of the LFC scheme are usually updated in a period from 2 s-4 s [7]. It is found that the optimal integral controller gains designed in the continuous mode can't be applied in discrete mode directly, while the simulation studies revealed that a relatively large sampling period in or around 20s can still result in satisfactory results for some special cases. In fact, a continuous controller with an input delay can be used to model such sample-based controller, in which the input delay is bounded by the sampling period. Based on this understanding, the delay margin can be used as the UBSP to guide the choice of the sampling period of an LFC controller.

$$\omega_{1i} = \Delta P_{Li} + \Delta P_{di} = \sum_{j=1}^{m} \Delta P_{Lj\text{-}i} + \sum_{j=1}^{m} \Delta P_{ULj\text{-}i} \quad (3)$$

$$\omega_{2i} = \sum_{k=1,k\neq i}^{N} \Delta P_{tie,ik,sch} \quad (4)$$

$$\Delta P_{tie,ik,sch} = \sum_{j=1}^{n}\sum_{t=1}^{m} gpfs_i + jiz_k + t\Delta P_{Lt\text{-}k}$$

$$-\sum_{j=1}^{n}\sum_{t=1}^{m} gpfs_k + jiz_i + t\Delta P_{Lt\text{-}k} \quad (5)$$

$$\omega_{3i} = [\omega_{3i,1}, .., \omega_{3i,k}, ..., \omega_{3i,n}] \quad (6)$$

$$\omega_{3i,k} = \sum_{j=1}^{N}\sum_{t=1}^{m} gpfs_i + kiz_j + \Delta P_{Lt\text{-}j} \quad (7)$$

$$\Delta P_{m,k\text{-}i} = \omega_{3i,k} + \alpha_{ki} \sum_{j=1}^{m} \Delta P_{ULj\text{-}I} \quad (8)$$

where ΔP_{Li} and ΔP_{di} are the total contracted and un-contracted demands in area i, respectively; $_{Lj\text{-}i}$ and $\Delta P_{ULj\text{-}i}$ the contracted and un-contracted demands of the *j*th Disco in area i, respectively ; $\Delta P_{tie,ik,sch}$ the scheduled power tie line power flow between areas I and k

The state space model for area I can be obtained as

$$\begin{cases} \dot{x}_i(t) = A_i x_i(t) + \sum_{j=1,j\neq i}^{N} A_{ij} x_j(t) + B_i u_i(t-\tau_i) + F_i \omega_i \\ y_i(t) = C_i x_i(t) + D_i \omega_i \end{cases} \quad (9)$$

where

$$x_i^T = [\Delta f_i, \Delta P_{tie\text{-}i}, \Delta P_{mli}, \Delta P_{mni}, \Delta P_{gli}, \Delta P_{gni}]$$

$$y_i = ACE_i, \ \omega_i^T = [\omega_{1i}, \omega_{2i}, \omega_{3i}] \quad (10)$$

and Δf_i , $\Delta P_{tie\text{-}i}$, ΔP_{mki} ,ΔP_{gki} are the frequency deviation, power exchange in tie-line , generator mechanical output, and valve position, respectively ; M_i , D_i , T_{gki} , R_{ki} the moment of inertia of generator , generator unit damping coefficient , time constant of the governor, turbine time constant , and speed drop respectively ; β_i the frequency bias factor; α_{ki} the ramp rate factor; and ACE_i the ACE.

For area I, using ACE_i as corresponding control input , a PID controller is designed as follows :

$$u_i(t) = [-Kp_i ACE_i - K_{Ii} \int ACE_i \, dt - K_{Di} ACE_i] \quad (11)$$

where K_{Pi}, K_{Ii} , and $K_{D,i}$ are proportional, integral, and differential gains, respectively, define $K_i = [K_{Pi} K_{Ii} K_{Di}]$

B. Traditional Multi – Area LFC Scheme

Traditional model of LFC system can be obtained by excluding the dotted line connection of Fig . 2, as shown in the following :

$$(t) = Ax(t) + \sum_{i=1}^{n} A_{di}x(\mathrm{t}-\mathrm{d_i(t)}) + F\Delta P_d$$
$$(t) = Ax(\mathrm{t}) + A_d x(\mathrm{t}-\mathrm{d_i(t)}) + F\Delta P_d \qquad (12)$$

For a multi-area LFC scheme, the net tie-line power exchange between each control area satisfies the following equation

$$\sum_{i=1}^{n} \Delta P_{tiei} = 0 \qquad (13)$$

III. DELAY-DEPENDENT STABILITY ANALYSIS METHOD

The delay–dependent criterion for linear systems with time varying delay proposed is used to determine the delay margin of power system with an LFC scheme embedded. The study stability of system with time delay has been investigated extensively at the control society.

A. Improved Stability Criterion

Theorem I : Consider the following time delay system :
For given scalar T_i0 satisfying $0 = T_0\ T_1\ T_2 T_i$, the system is asymptotically stable if there exist matrices P 0 , Q_i 0 , and R_i 0 . $i = 1,2,\ldots\ldots,l$ such that $\Xi = \Phi + \sum_{i=0}^{l-1} \Phi_i$ 0

(14)

Proof : Construct a Lyapunov functional as

$$V(\mathrm{t}) = x^{\mathrm{T}}(\mathrm{t})Px(\mathrm{t}) + \sum_{i=0}^{i-1}\left(\int_{t-\tau_{i+1}}^{t-\tau_i} x^{\mathrm{T}}(s)Q_{i+1}x(s)\,\mathrm{d}s + (\tau_{i+1}-\tau_i) \times \int_{-\tau_{i+1}}^{-\tau_i}\int_{t+\theta}^{t} \dot{x}^{\mathrm{T}}(s)R_{i+1}\dot{x}(s)\,\mathrm{d}s\,\mathrm{d}\theta\right) \qquad (15)$$

Where P_i , Q_i , and R_i are positive define symmetric matrices. Which means $V(t) \geq 0$. It follows from Jensen inequality that

$$(\tau_{i+1}-\tau_i)\int_{t-\tau_{i+1}}^{t-\tau_i} \dot{x}^{\mathrm{T}}(s)R_{i+1}\dot{x}(s)\,\mathrm{d}s \geq \varepsilon^{\mathrm{T}}(t)R_{i+1}\varepsilon^{\mathrm{T}} \qquad (16)$$

Where $\varepsilon(t) = x(t - \tau_i) - x(t - \tau_{i+1})$, then calculating the derivative of (15) and applying (14) and (16) yield $(t) \leq \xi(t)\,\Xi\,\xi^{\mathrm{T}}(t) \leq 0$ with $\xi(t) = [x(t-\tau_0), x(t-\tau_1),, x(t-\tau_l)]$. Therefore, the system is stable if $P > 0$, $Q_i \geq 0$ and $R_i \geq 0$

Theorem 1 reduces conservativeness by taking into account relationship between different delays during the construction of Lyapunov functional. The total number of decision variables for the criteria used in [9] and in this paper is respectively is given as

$$Num_{[9]} = \frac{l^4 + 4l^3 + 6l^2 + 7l + 4}{4}\mathrm{n}^2 + \frac{l^2 + 5l + 4}{4}\mathrm{n} \qquad (17)$$

$$Num_{[this\ paper]} = \frac{2l+1}{2}\mathrm{n}^2 + \frac{2l+1}{2}\mathrm{n} \qquad (18)$$

B. Summary of Analysis of steps

Detailed implementation of the method proposed is summarized as the following steps:
Step 1) Obtaining linear model of the LFC scheme excluding the controller, All types of turbines, such as reheat turbine, non-reheat turbine and hydro turbine , can be modeled.
Step2) Calculate the state–space model of the closed-loop LFC equipped with a PID controller.
Step 3) The trajectory of delay margins of two-area LFC scheme can be described by a set of polar coordinate points.
Step 4) Determining the delay margin. Based on the model obtained in step 2, the stability of system for a given time delay is determined by using *feasp* solver described in previous section and binary search algorithm.
Step 5) Verify the accuracy of the calculated value via simulation method based on the detailed model of the LFC scheme considering the physical constraint.

IV. CASE STUDIES

Case studies are carried out based on one-area and multi-area(two-area and three-area) LFC scheme, respectively. Simulation studies are used to investigate how the control performance of LFC scheme is effected by the time delay, and verify the effectiveness and accuracy of the stability criterion used.

A. Delay Margin Calculation

1)Traditional Two-area LFC: The delay margins of two-area Load Frequency Control installed with the I-controller (K_I ϵ{0.10,0.20,0.40}), PI-controller [K_P ϵ 0.20, K_I = 0.20, K_D ϵ {0.10,0.20,0.50}] are calculated. The stability region is compared with the simulated results obtained in [9].

2) Deregulated Two-Area LFC : The delay margins of a two-area Load Frequency Control installed with the I-controller (K_I ϵ {0.10,0.20,0.40}), a PI-controller (K_P ϵ {0.050,0.10,0.20}, K_I= 0.20), or PID-controller (K_P = 0.051, K_I = 0.21, K_D ϵ {0.020,0.040,0.050}) are calculated. The stability region is compared with the one obtained by the method used in [9].

3) *Deregulated Three-Area LFC :* The delay margins of a three-area Load Frequency Control equipped with I-controller [K_1 = 0.050], PI-controller (K_P = 0.20,K_I = 0.050),or PID-controller (K_P = 0.20, K_I = 0.050, K_D = 0.10) are calculated.

4) *Observations:* Only Theorem 1 provides necessary conditions, here exists conservativeness of delay margin estimated.

- The obtained results in the proposed method shows that the dynamic coupling between different areas effect the delay margins for both traditional and deregulated LFC schemes. Most of the control gains except for the

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deregulated LFC with $K_P = K_1 = 0.201$, $K_D = 0.01$ or ($K_P = 0.0501$, $K_I = 0.20$, $K_D \in \{0.0402, 0.0501\}$), incease in the time delay of one area , increases firstly then decreases in the delay margin of the other area, for example, the delay margin of area 2 is 13.71 s when t=0s and it increases to 14.52 s when t=10s. It shows that the delay in one area may increase the delay margin of the other area.

5) Simulation Verification: Simulation studies are carried to verify the accuracy in calculation in the method proposed. The results of the two-area deregulated LFC system designed with a PI controller ($K_P = 0.0512$, $K_I = 0.2001$) and the angle $\theta = 45$. The GRC is assumed to be ±0.1 pu/min, and the updated period of Area Controlled Error signals is 2.12s [7]. Total Discos contract with the available gencos as the following matrix

$$AGPM = \begin{bmatrix} 0.5 & 0.25 & 0 & 0.3 \\ 0.2 & 0.25 & 0 & 0 \\ 0 & 0.25 & 1 & 0.7 \\ 0.3 & 0.25 & 0 & 0 \end{bmatrix} \qquad (19)$$

Assume that a step load of 0.1 pu is demanded by each Disco in the areas, and Disco 1 in area 1 and Disco 2 in area 2 all demand 0.08 pu as large un-contracted loads, i.e..,$\Delta P_{Lj\text{-}i} = 0.10$ pu, $\Delta P_{ULi\text{-}I} = 0.080$ pu, $i = 1, 2$; $j = 1, 2$; performance test on the closed-loop LFC scheme by the increase in the delay time from 0 in steps until the system become unstable. The responses of area 1 for different delays are shown in Fig. 3.1. The results show that the magnitude of two delays margins, , is within the range [10 s,12 s]. The result obtained is9.73 s by the method used in [9] and is 10.57 s by the proposed method, which slows a better accuracy.

Considering the two-area deregulated LFC system designed with a PI controller as example, the area 1 responses for both cases (Case I: $\tau_1 = 10.701$s and $\tau_2 = 0$s and Case II: $\tau_1 = 10.70$s and $\tau_2 = 3.502$s) are showed in Fig.3.2. From the fig, the system is unstable for case I since the $\tau_1 = 10.701$s is larger than its delay margin 9.89s. while, for Case II, the system becomes stable because the delay of area 2 the delay margin of area1 increases, increasing from 0 to 3.502s.

B. Comparison of calculation time

The subsection discusses the improvement in calculation of speed. The avg time of calculation spend by the method proposed for the traditional two-area LFC designed with different controllers is found to be about 10.02s, and the average time of calculation spend by the method used in [9] is found about 2500s. The time required of the method proposed is about only 0.4% of the one of the published method. The proposed method has greatly reduced the time spent on the delay margin calculation, which makes it be more suitable to deal with the multi-area LFC schemes.
The responses of the following three cases are shown in Fig.3.3.

- *Case I:* normal condition without fault.
- *Case II:* Fault occurs at 16sec and cleared at 30sec, the UBFC was set to 14sec depends on delay margin calculated. From 16sec to 30sec, Area Controlled Error signal does not update and remain constant by zero-order holder, and control signal is calculated.
- *Case III* : Fault occurs at 16sec and cleared at 30sec, the UBFC was set to be 6sec based on operations. The controller terminates at 22sec and starts at 30sec at the time of fault cleared.

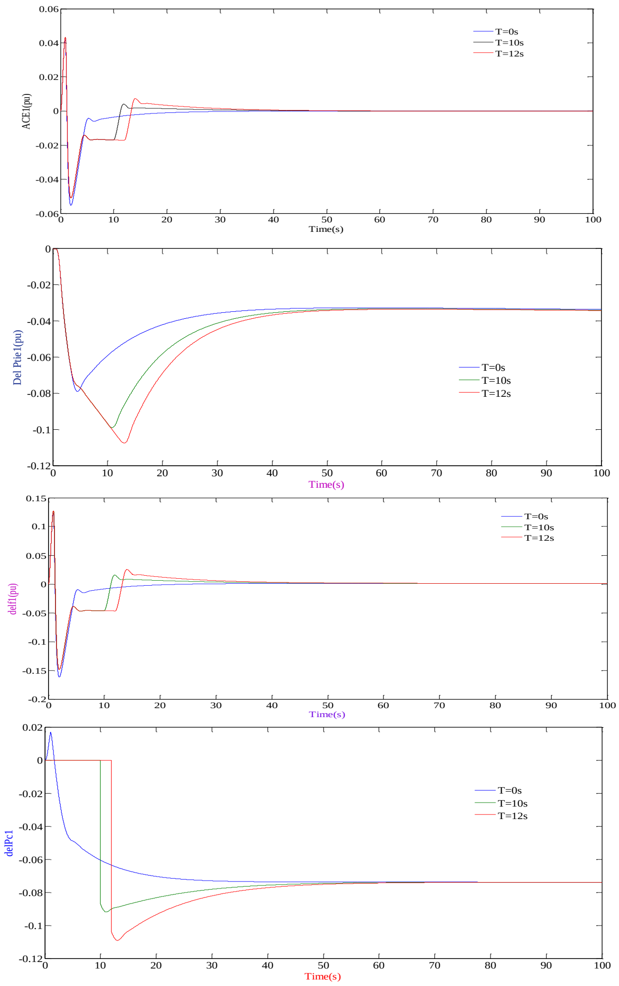
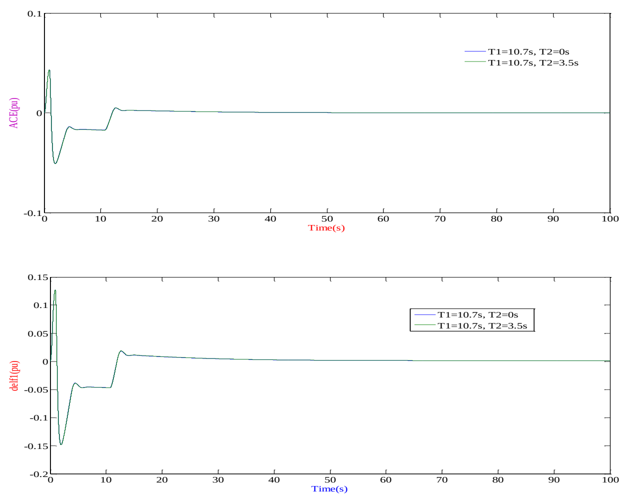


Fig 3.1:Area 1 responses for the PI-based deregulated LFC scheme with different delays



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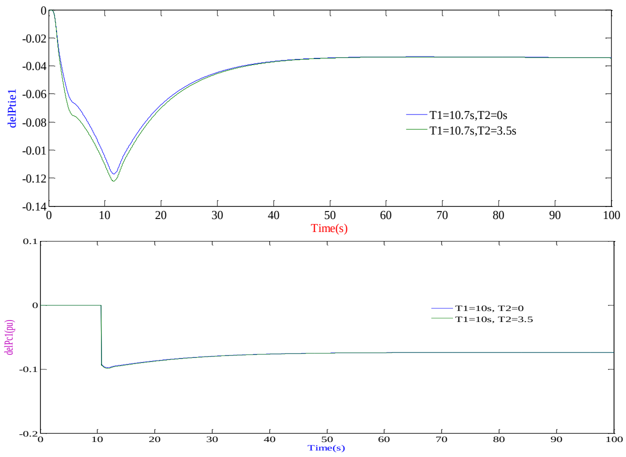


Fig 3.2: Area1 responses for the PI-based deregulated LFC scheme with different delays

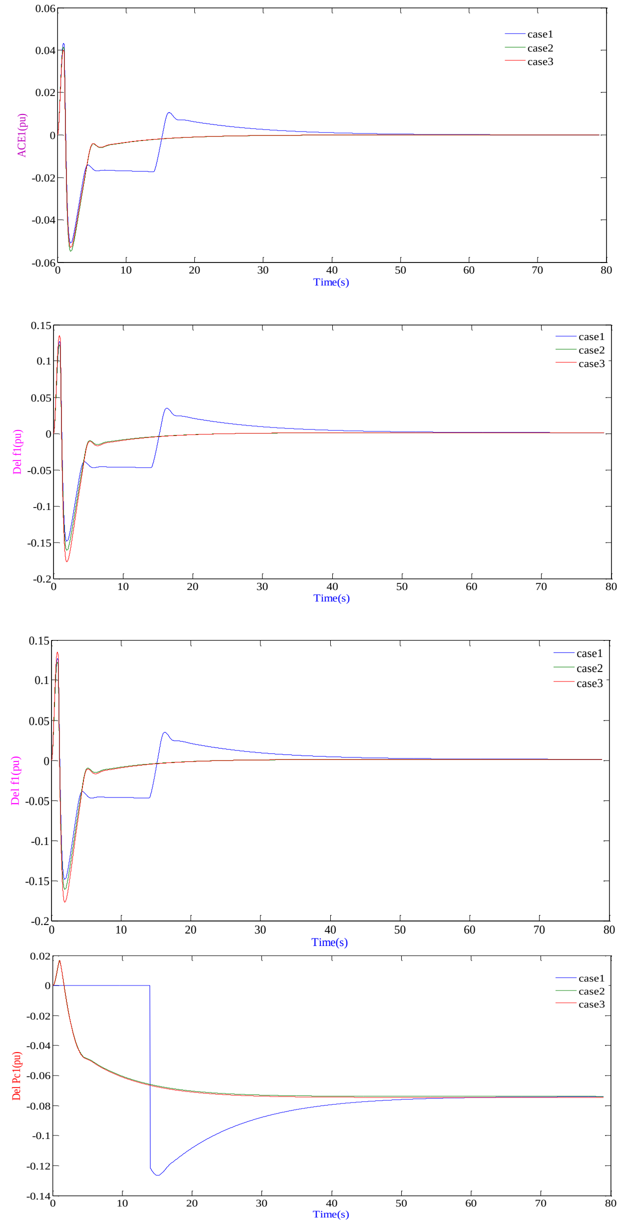


Fig.3.3: Area1 responses for the I-based deregulated LFC scheme with different fault cases

The results show that the performance of Case II is better than that of Case III (*ACE* and Δf) or is similar to that of Case III(ΔP_{tie}).

Thus, a larger UBFC can be set to improve the performance of the LFC under a communication channel fault.

Moreover, for Case II, the controller does not need to be stopped and restarted since the ACE renews before the fault duration reaching the preset UBFC of 14 s.

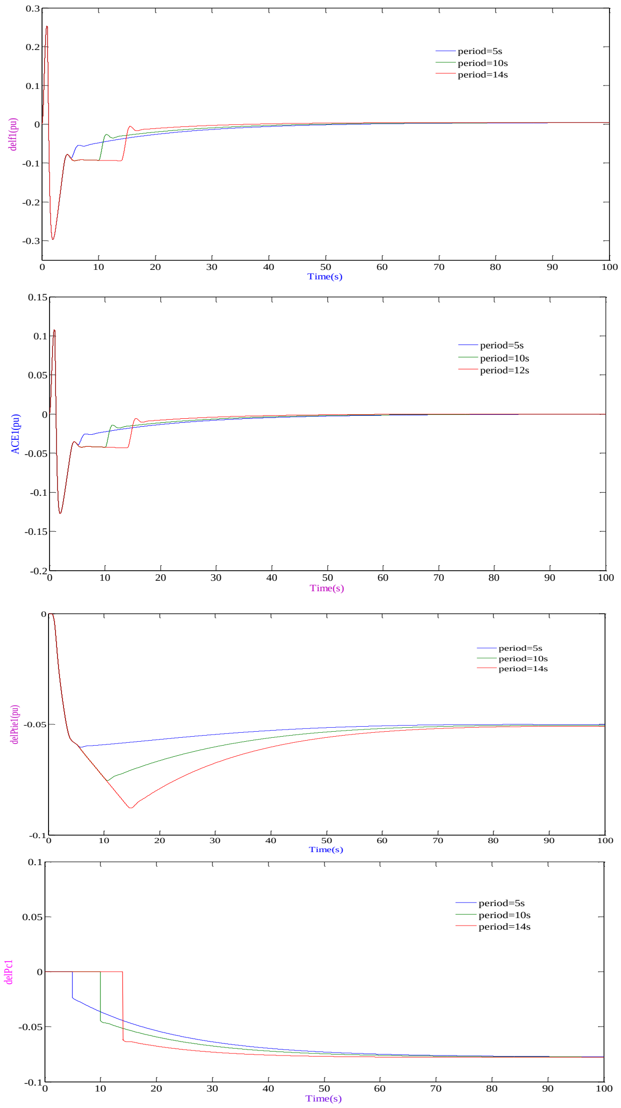
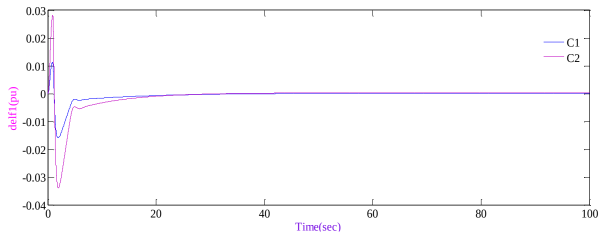


*Fig.3.4:*Area1 responses for the I-based deregulated LFC scheme with different periods of ACE



(a) Without delay

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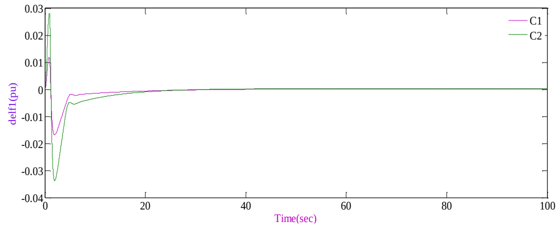
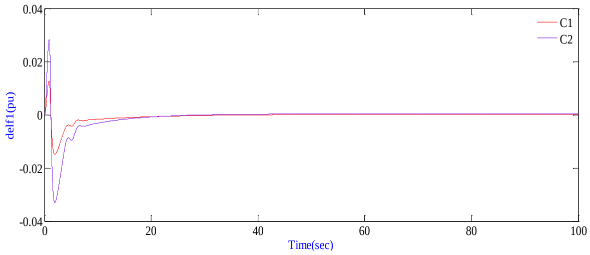


(b) $\tau = 0.5$s



(c) $\tau = 5$s

Fig.3.5: Frequency deviation responses of the system with respect to different time delays

1) Tuning of Controller: To tune controller delay margin is used as an additional performance index based on trade-off between delay margin and dynamic performance or combined with the other tuning method .An example is taken and discussed on one area load frequency control. The tuning of the PID controller are dependent on two parameters which are artificially selected i.e., λ and λ_d,

For $\lambda = 0.10$, $\lambda_d = 4.0$ and $\lambda = 0.20$, $\lambda_d = 4$, gains obtained using the method are

$$C1: [K_P, K_I, K_D] = [0.2019, 0.1362, 0.1615] \quad (20)$$
$$C2: [K_P, K_I, K_D] = [-0.1, 0.0668, 0.0531]. \quad (21)$$

The delay margins provided by C_1 and C_2 are calculated as 0.56 s and 7.94 s. The frequency response of the system undergoing a positive load disturbance of o.o1pu is shown in Fig. 3.5. When there is no delay, although C_1 provide a better transient response than C_2 , transient dynamic provided by C_2 is still acceptable; when a small delay (τ = 0.5 s) is applied, the performance under C_2 is better than C_1; when the delay increases to 5 s, larger than the delay margin provided by $C_{1.}$

TABLE I: Deregulated Two-Area LFC System

	GENCOs (*k-i: k* in area *i*)					Areas	
	1-1	2-1	1-2	2-2		1	2
T_t	0.31	0.28	0.29	0.30	M	0.1665	0.2080
T_g	0.05	0.07	0.05	0.06	D	0.0081	0.0083
R	2.38	2.46	2.48	2.69	B	0.4248	0.3962
A	0.5	0.5	0.5	0.5	T_{12}	0.2446	

V. CONCLUSION

The delay-dependent stability of the multi-area LFC scheme in deregulated environment has been analysed. The deregulated LFC scheme equipped with PID-type controllers has been modeled as a linear system with multiple delays, including the traditional LFC schemes as a special case. To deal with the increased problem dimension caused by multi-area LFC scheme and reveal the interactions between different control areas, an improved LMI-based delay–dependent stability criterion, which has less conservatism and fewer decision variables than the existing criterion, has been derived to calculate the delay margins.The proposed method will also validate through experimental studies. The practical implementation of the designed controller depends on the accuracy of local studies of each area. Those states can be obtained from the measurements of monitoring system or using the state estimation methods. Although the detailed methods of the state estimations are not focused in this thesis, the errors from the measurements and state estimations have been considered as a future work of this thesis in controller design to guarantee the robustness and effectiveness of the proposed controller.

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