EFFECT OF COMMUNICATION NETWORK INFRASTRUCTURE ON LOAD FREQUENCY CONTROL

By

SUDIPTO BHOWMIK

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The members of the Committee appointed to examine the thesis of SUDIPTO BHOWMIK find it satisfactory and recommend that it be accepted.

Chair

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Abstract

by Sudipto Bhowmik M.S.
Washington State University
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Chair:. Kevin Tomsovic

Deregulation in the power sector has raised several new issues. Of particular interest to the studies here are those relating to communication infrastructure. Traditional methods for providing communications and control need to be reviewed. One such service is load frequency control, which now needs to incorporate bilateral contracts between generation companies and loads. For frequency control to be effective, a secure, reliable and open communication network needs to be implemented.

As of now, few load frequency simulation models include the effects due to the communication channel. The effects of communication were not a major concern in the vertical utility structure as utilities were cohesive in their actions and the control locations was relatively fixed and known. Thus, signal decimation was achieved using dedicated links. However with deregulation in the power generation sector, a necessity for enhanced communication infrastructure to support increasingly varied services and dynamic generation-load geographical structure, is inevitable. A new distributed and duplex communication system based on datagram packet switching using common off the shelf (COTS) hardware seems to offer the most features and support for most of the services envisaged. This gives rise to a need to define the parameters and variability introduced with this new communication topology.

In this thesis, communication models, based on the requirement and structure of the load frequency control, are proposed based on modern queuing theory. These models help approximately define bounds for delay times in the network layer. The approximations are adequate for including the effects of network behavior in a robust load frequency control model. Simulations of constant delays and random delays are performed on different configurations of generators involved in pure load frequency control as well as different bilateral participations. The effects of these and their consequences are tabulated. Simulations integrating the AGC model with a data network simulator were performed and the effects of various network parameters on the automatic generator control are subsequently investigated. Results indicate the possibility of failures arising from communication system problems and suggest the importance of precise communication models. In addition to these modeling issues, data and information security design issues pertinent to the load frequency control signals are presented.

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DEDICATION

This thesis is dedicated to my mother and father who gave me an abundance of emotional and mental support. I would also like to include Siraj mama without whom this whole chapter of my life would be missing.

Lord be my guiding light ……………………..

Pranaam, Devi Saraswati

Chapter 1

Introduction

1.1 Deregulation

In the last few years, a thrust to make the power industry competitive in order to decrease prices for the customers, and encourage better quality of service, has been made in the United States. Several countries, including Great Britain, Australia, Netherlands, and Norway, have already undergone such a transition. Most have focused on the deregulation of the generation and distribution sector. Currently, efforts to deregulate the transmission sector are underway. The responsibility of overseeing the security, reliability and fair practice now lies in the hands of respective non profit neutral organizations, namely the Security Coordinators (SC) or Interconnected Service Operators (ISO) depending on the type of market formed at each geographical locations in the US [1,9]. Due to this deregulation process, a free market is now available in many areas and has given rise to additional services, beyond energy, often referred to as ancillary services. These services act to maintain the conditions necessary for reliable operation of the power system.

One such issue related to these services is that concerning communication between different entities. The commonality amongst the diverse market structure is the need for a more distributed, robust and open communication network to support the deregulation process. The need for communication is especially pertinent to the ISO as all activities within its jurisdiction are its responsibility, and keeping track of all activity can only be achieved with a vast amount of data. In the traditional vertical utility structure, communication between various utilities was achieved using dedicated channels. This was sufficient given the restricted number of utilities and the centralized ownership. Here, we concentrate on the new communication requirements for load frequency control or automatic generation control, that is, the tracking of small load fluctuations and maintaining system frequency. The importance of such a communication system is also underlined in the recent NERC's Policy 1 and 7 [1-3]. One of NERC's requirements is real-time voice and data communication that every supplier has to maintain with the operating authority at the center.

In the regulated scenario, responsibility of automatic generation control lay with the respective utilities. As a backup mechanism, voice channels (phone lines) were used between utilities to relation information about any contingencies. Thus, issues relating to the effect of communication network were not given much importance as it was relatively simple to control the generators due to the inherent vertical characteristic and with the relatively fixed customer locations. Furthermore, the use of dedicated lines to and from generators also ensured that signal dissemination was robust. However with the possibility of varied players entering the generation market to service loads, geographically distant, in a bilateral contract, makes the monitoring and control difficult using the existing radial dedicated structure. The possibility of optionally changing generation companies, by the customers, leads to a dynamic situation, which can only be effectively supported by a distributed communication approach. Additionally competition in load following or frequency control markets begets the need for a well-developed communication system with the possibility to monitor customer loads and offer enhanced services. For load frequency control, the supplier must be able to respond to the instructions from the authority, and the authority must be able to monitor the performance of the supplier. For bilateral contracts, the supplier must in addition, be able to monitor the load variation at the customer's end and suitably change generation to match the load.

Several proposals have been made regarding this, such as building on the existing communication system, offering services via the Internet or investing in a whole new infrastructure that primarily caters to the power system. Common to these approaches will be a sharing of communication resources and an opening of the existing closed and centralized links to create a more distributed and open infrastructure. A widely distributed and interconnected communication system carries inevitable signal delay and other data problems. With these networks being shared by other entities apart from the power sector, it introduces additional reliability risks for this critical infrastructure. These concerns have been voiced by government officials as well as the Department of Energy [5].

1.2 Background

1.2.1 Load frequency control

For satisfactory operation of the power system, the frequency of a system, which is dependent on active power balance, should remain nearly constant at all times. Due to the large number of generators, primary speed control function using governors is now mandatory for all generating units. Secondary control function is provided to primarily maintain uniform frequency, divide load between generators and to control tie-line interchange schedules. Most modern control centers are equipped with on-line computers performing all signal processing through supervisory control and data acquisition (SCADA) systems.

For the purposes here, we are interested in only small changes in power demand, which is mainly reflected by changes in system frequency. Due to the small deviations, the system model can be obtained by linearizing the detailed non-linear equations that describe the system. Additionally, due to the concentration on slow dynamics of the system, most models of generator, turbine, governor and load can be simplified to include only the low frequency terms. The modelling of the system can be further simplified by concentrating only on the collective performance of all generators in the system. Thus, intermachine oscillations and transmission system performance are not considered. All generators are in turn tacitly assumed to respond coherently and this is represented by a lumped equivalent inertia constant (Meq in Fig 1.1) and the same applies to the damping characteristic of the Load (D). A block diagram representing a load frequency control scheme for a two control area system is shown in Fig 1.1.

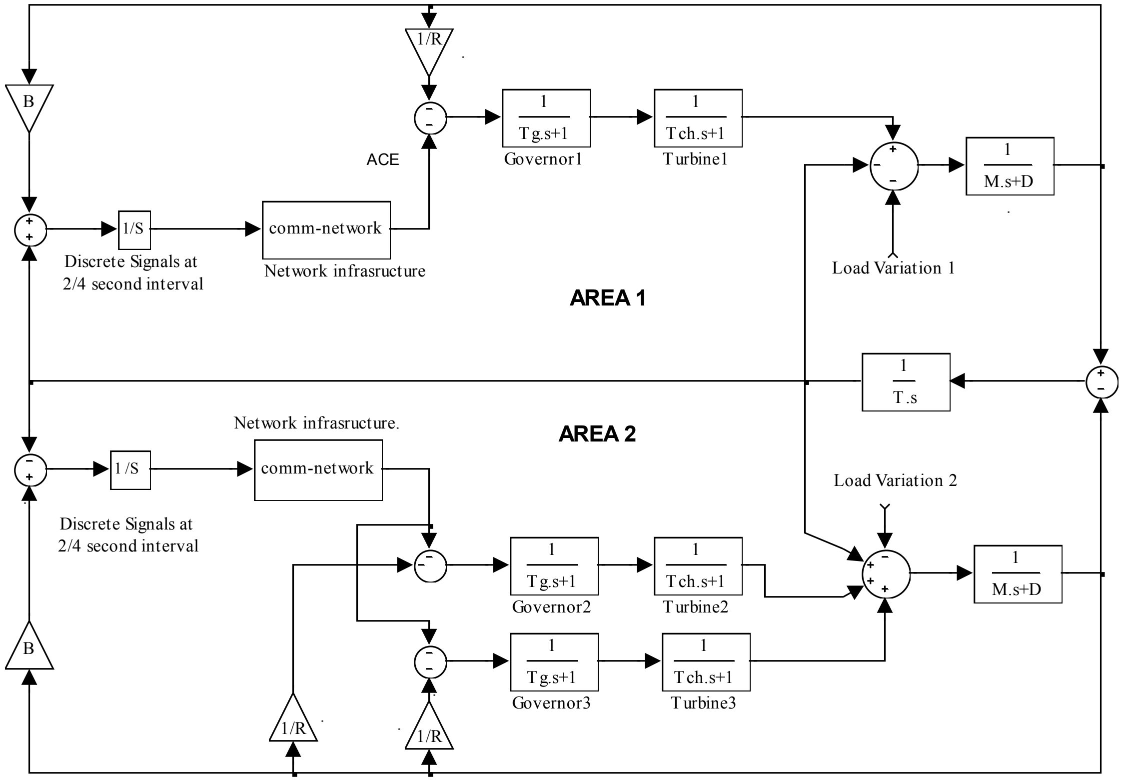

Fig 1.1 Block diagram of two area system with supplementary control

The equations for Area 1 can be summarized as follows:

$$\Delta\dot{P}_m(1,i) = \frac{-\Delta P_m(1,i) + \Delta P_v(1,i)}{T_{ch}(1,i)} \tag{1-1}$$

which is the equation for the mechanical output of the generator. Where:

ΔP_m is the deviation in the mechanical output for a generator

ΔP_v is the deviation in the output of the turbine

T_{ch} is the charging constant of the turbine

$$\Delta\dot{P}_v(1,i) = -\frac{\Delta P_v(1,i)}{T_G(1,i)} - \frac{\Delta\omega_1}{R_1\, T_G(1,i)} + \frac{K(1,i)\, X_1}{T_G(1,i)} \qquad (1\text{-}2)$$

Shows the output of the Governor. Where

$\Delta\omega_1$ is the deviation in frequency

K is the participation factor of the generator

X is the ACE signal

T_G is the governor constant

R is the regulation factor for the generator

$$\Delta\dot{\omega}_1 = \frac{-D_{eq1}\,\Delta\omega_1 + \sum_{i}^{n} \Delta P_m(1,i) - \Delta P_{12} - \Delta P_{L1}}{M_{eq1}} \qquad (1\text{-}3)$$

Which is the equation for the frequency deviation.Where

ΔP_{12} is the deviation is the deviation in the inter tie power

ΔP_{L1} is the deviation in the load in the respective area

M_{eq1} is the lumped equivalent inertia constant of all generators in the area

D_{eq1} is the equivalent damping factor of the load

$$\Delta\dot{P}_{12} = T_1(\Delta\Delta_1 - \Delta\omega_2) \tag{1-4}$$

Which is the equation for the inter-tie powerWhere:

T is the tie line stiffness constant

$$\dot{X}_1 = -B_1\Delta\omega_1 - \Delta P_{12} - \Delta P_{21} \tag{1-5}$$

Which is the equation for the automatic control error (ACE) signal.Where:

B_1 is the frequency bias factor

Recently, the possibility of realizing a bilateral market for the provision of these services has arisen. In this case, a customer is allowed to enter into bilateral contracts directly with a supplier or customer provided there exists a communication channel connecting them [2]. This is shown to be possible with an additional feedback from the customer [6]. In both situations, a certain number of generating units receive an input, in the form of packet of data (for a packet switched network), from either the center responsible for the AGC or from the customer for the bilateral market. This is achieved through one or more communication channels, in order to adjust real power output accordingly. The signals are sent out usually every 4 seconds to the respective generator units. Guidelines on the correct operation and monitoring the effectiveness of the load frequency control are fixed by NERC [3]. An update of the customer load requirement every 4 seconds for the bilateral contract is understood to be adequate for response to load variation. A model including a bilateral contract is shown below, Fig 1.2, for one control area.

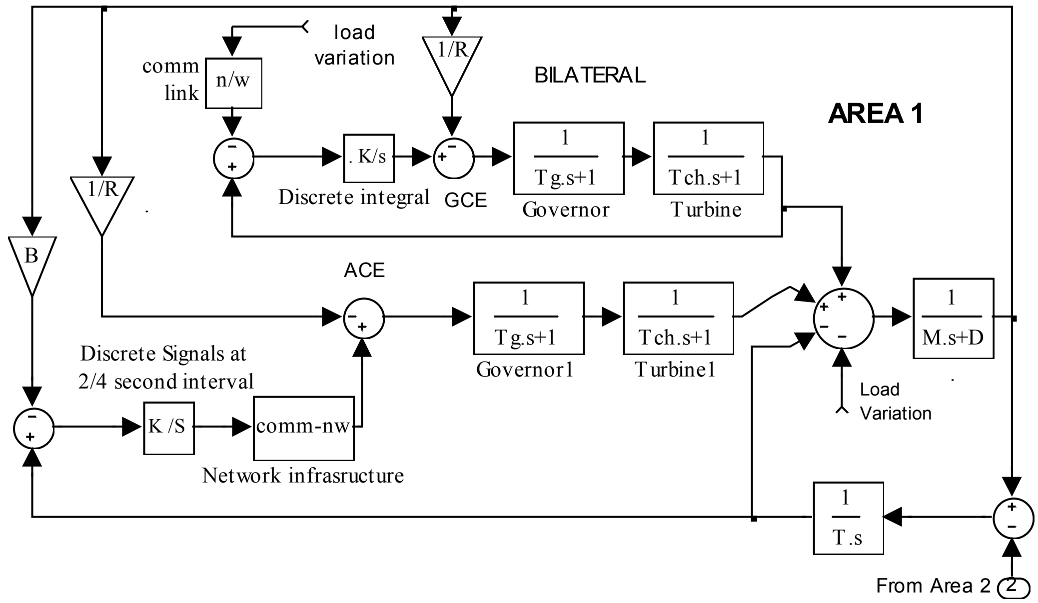

Fig 1.2 Model of secondary control including bilateral contract

1.2.2 Communication network

Communication networks for the power industry have matured over the years to reflect newer and better technology. However, most of the technology relies on dedicated links and use of propriety communication protocols for data transfer. In addition, the physical substrate usually uses a wide variety of hardware, such as RF links, power line carrier, phone lines, and so on [7,8]. This leads to several incompatibilities amongst competing products. Of late, efforts to standardize on these communication protocols and data format are underway. However, due to the critical nature of the power industry, a simple migration to existing standards does not seem to be a prudent choice. Extensive research, to characterize the suitability of these standards, or to customize it to the particular use for the power system is being actively pursued by research organizations such as EPRI and PSERC [9]. For most purposes, it should be possible to achieve this using existing technology with minor modifications. Investments in using fast link backbone (specifically optic links which support bandwidths upto terabytes per second) are being carried out by several companies. Still, this migration to a distributed network structure requires research to understand the suitability of existing software and power system programs.

The popular internet infrastructure uses packet switching for most purposes, as this seems to be the most optimised solution for the bursty characteristics of the data being sent. For real time data requirements, bulk data (in addition to traditional bursty data) for the power sector has led to looking at other technologies such as virtual circuit switching, or bandwidth reservation. For load frequency control, the use of a user datagram protocol (UDP) for signal dissemination should be sufficient. Additional signals for bookkeeping and monitoring of generator/link status can also be done using UDP heartbeat messages sent at a faster rate than the signal data. The internet is modeled around a 7 layer protocol mode, which encompasses most communication issues, and thus, can easily assimilate the power system communication needs. UDP promises a simple and effective delivery guarantee. There are possibilities of packets being lost or extensively delayed along the way due to link/node/router failures, error introduction, and heavy congestion; however, with broad distribution the likelihood of these failures decreases. Further with the possibility of using acknowledgement for each message received, certain guarantees on delivery of the messages may be made. Parameters such as delay latency, throughput, message receiving guarantees are typically the ones required for load frequency control.

1.3 Previous Research

Extensive research to define the models for a load frequency model have been undertaken. Most of these focused on the vertical utility structures [7,10-25]. Thus, assumptions of a good communication system were valid for that structure and work related to the effects of communication system problems on load frequency control was never pursued. With the on set of the deregulated system, communication system issues have become important. Contemporary research in communication systems as applied to the power sector is still focuses primarily on application on the distribution side including those related to substation automation [25-30]. Most of this research are concept type efforts proposing various methods to make the communication infrastructure as economic as possible. Admittedly, analysis of communication systems suitable to meet all demands is non-trivial due to its dependence on a large number of intangible and interrelated factors, such as security policy. Clear definitions for assessing suitability of a communication networks, are yet to be set, as the power sector is still undecided as to the additional modifications to existing procedures and power analysis mechanisms under the open market. Migrations to the internet for load frequency control is already underway in some systems. Still, these implementation are essentially identical to the old system with the mere addition of using the internet as the communication media. This additionally opens up security threats [31-38].

1.4 Contribution of thesis

This thesis contributes to understanding of the communication system networks for power systems in the following ways:

- Concrete adequate requirements for LFC communication are proposed.
- Both the network characteristics and that of the load frequency model are integrated in order to obtain various characteristics and parameter effects. Specifically, parameters such as high load, congestion, lossy links, failure of links and inherent hard limits on processing buffer sides at each intermediate nodes are simulated using ns (network simulator) [39] and the corresponding effects on the load frequency are investigated.
- Communication models based on queuing theory are proposed [40-53].
- Propose additional concerns, constraints and control mechanism to be implemented
- Enumerate security concerns in an open market and shared communication media for LFC.

Chapter 2

Simple Communication Models

2.1 Background

One of the most important performance measures of a data network is the average delay required to deliver a packet from origin to destination. Furthermore, delay considerations strongly influence the choice and performance of network algorithms, such as routing and flow control. For these reasons, it is important to understand the nature and mechanism of delay and the manner in which it depends on the characteristics of the network. Queueing theory is the primary methodological framework for analyzing network delay. It often requires simplifying assumptions since more realistic assumptions make meaningful analysis extremely difficult. Nevertheless, these models do provide a basis for adequate delay approximations as well as qualitative results. The focus here is on packet delay within the network layer. This delay is the sum of delays on each subnet link.

The delays consist of four components [40]:

- Processing delay: the delay between the time the packet is correctly received at the head node of the link and the time the packet is assigned to an outgoing link queue for transmission, with an addition of delays introduced at DLC and physical layers.
- Queuing delay: the delay between the time the packet is assigned to a queue for transmission and the time it starts being transmitted. During this time, the packet waits while other packets in the transmission queues are transmitted.
- Transmission delay: the delay between the times that the first and last bits of the packet are transmitted.
- Propagation delay: the delay between the time the last bit is transmitted at the head of the link and the time the last bit is received at the tail node. This is proportional to the physical distance between transmitter and receiver.

Other basic concepts such as Little's theorem are elucidated in the Appendix. A general introduction to queuing models can be found in [45]. Simplified models are suggested since to a large extent these can cover the basic behavior of the communication network, as it will apply to load frequency control. The models used are largely based on an exponential arrival rate as it allows several simplifications in quantifying the waiting time in queues. Still, contemporary researches on data of the internet suggest a more statistically similar distribution for the arrival process of the internet traffic [47-50]. Empirical research has been performed to quantify the traffic and to model the delays based on these premises [48], however for a dedicated network the assumption that the arrival process follows a Poisson distribution is adequate. We propose queuing models based on the network that may be included in the load following system and which are also based on constant packet length unlike that usually performed for exponentially distributed packet length. Other scenarios considered include queue server failures and recovery and servers under a denial of service attack. Of late, greater emphasis has been applied in order to ensure that the communication system remains robust in the face of malicious attacks. Of course, physical security will always remain the weakest point for large scale damage, but it is important to see the effects of software related malicious attacks.

Extensive work has been done in the telephony sector and on the existing internet in order to characterize and model the behavior of the data network [40,46]. These need to be referenced and customized to suit the structure of the power industry. Of late, certain types of internet traffic arrival (such as telnet connection requests) have been shown to be similarly independent unlike the traditional modeling using a Poisson distribution arrival [40]. On the other hand machine induced or user typed data does still loosely follow the Poisson distribution, which lends some rather useful properties for efficient calculations. Here, bounding of the delays are needed as these can be utilized by a higher layer abstraction for configuration and to pinpoint potential vulnerability points for network congestion. Further, they offer good insight for basing further analysis that quantifies requisite parameters for higher layer services. Simulations of the load following model and that of the network model can effectively be disjoint as the sending of the signal is deterministic. Based on these models, appropriate higher level protocols can be determined and tuned for best performance to meet the high reliability requirements under the scalability and the heterogeneous mix of the load following entities.

2.2 Delay Network Models for Load Frequency

To begin, the effects of retransmission are neglected since they are rare for most links. In addition, the models give a good approximation due to the load frequency communication using UDP for sending signals. UDP does not require a two way connection setup before transmitting but sends data in the form of datagrams thus avoiding the need to model acknowledgement packets, and retrqansmission. The focus here is mostly on two scenarios, namely a dedicated star topology for the traditional AGC model and a distributed model based on a dedicated network configuration, which also applies to the non dedicated distributed structure.

2.2.1 Star Topology

The traditional AGC model consists of dedicated links emanating from the control center which processes the signal and sends them to the respective generators. The signal packets are all of the same length and are sent out every 4 seconds. This conforms to a D/G/1 model, with the arrival packet distribution deterministic and the service times some general distribution due to variety at the outgoing links. Note, further simplification to a D/D/1 model can be assumed if the outgoing links are all assumed the same, in which case the result is a trivial form of the G/G/1 model. Queueing theory models are all founded on three main entities,

i) The arrival process denoted by the first alphabet, which in this case refers to a general arrival distribution;
ii) The service process denoted by the second alphabet,
iii) The number of servers or queues denoted by the last number

Assume one, that the interarrival times at the queue are independent of each other and that the service times are independent identically distributed (i.i.d), meaning that they are independent of interarrival times and each packet service is mutually independent of each other; and two, that all parameters (such as waiting time, number of packets in the system, etc.) reach a steady state value. These assumptions should hold as the signals sent to each generators are independent, and the outgoing links are independent of the neighboring channels. Note that in the case when the arriving signal packets are indeed dependent of each other (in case of concurrent signals being sent to the same site but differing generators), modeling can be done using either batch arrival models [46] or ON-OFF [44] processes. This is beyond the scope of this thesis.

For a G/G/1 queue we show that the average waiting time in queue asymptotically approaches

$$W \leq \frac{\lambda(\sigma_a^2 + \sigma_s^2)}{2(1-\rho)} \tag{2.1}$$

Where

σ_a^2 is the variance of the interarrival time,

σ_s^2 is the variance of the service time,

λ is the average interarrival time,

$\frac{1}{\mu}$, is the average service time,

$\rho = \frac{\lambda}{\mu}$ is the utilization factor

If the k+1 packet arrives when the queue is empty then its waiting time is 0 else it is equal to the difference of the time taken to process the kth packet and the time for the k+1 packet to arrive. Thus,

$$W_{k+1} = \max\{0, W_k + X_k - \tau_k\} \tag{2.2}$$

Where

W_k is the waiting time of the kth customer,

X_k is the service time of the kth customer, and

τ_k is the interarrival time between packets k and k+1.

The idle time is 0 if the k+1 packet arrives during the processing of the kth packet else it is equal to the difference between its arrival and the processing time for the kth packet. Now let $V_k = X_k - \tau_k$ so that

$$I_k = (W_k + V_k)^- \tag{2.3}$$

I_k is referred to as the idle period length between the arrival of the k^{th} and k+1 packet. For simplicity, denote

$$Z^{+} = \max\{0, Z\},$$

$$Z^{-} = -\min\{0, Z\},$$

$$\overline{Z} = E\{Z\}, \text{ and.}$$

$$\sigma_z{}^2 = E\{Z^2 - \overline{Z}^2\}.$$

It can be seen that $\overline{Z} = \overline{Z}^{+} - \overline{Z}^{-}$ and $\sigma_z{}^2 = \sigma_{z^+}{}^2 + \sigma_{z^-}{}^2 + 2\overline{Y}^{+}\overline{Y}^{-}$. Thus,

$$\sigma^2{}_{(W_k+V_k)} = \sigma^2{}_{\overline{W}_{k+1}} + \sigma^2{}_{\overline{I_k}} + 2\overline{W}_{k+1}\overline{I_k} \tag{2.4}$$

Now W_k and V_k are independent, additionally arrival time and service time are independent. Thus,

$$\sigma^2{}_{(W_k+V_k)} = \sigma^2{}_{W_k} + \sigma^2{}_a + \sigma^2{}_s \tag{2.5}$$

Taking the limit as $k \to \infty$, and assuming that steady state values exist (from assumption two), $\overline{W}_k \to W$, $\overline{I_k} \to I$.

The average idle time between two successive arrivals is equal to the fraction of the time the system is idle, multiplied by the average interarrival time. That is. $I = \frac{(1-\rho)}{\lambda}$. Replacing this in (2.4) and combining with (2.5),

$$W = \frac{\lambda(\sigma^2{}_a + \sigma^2{}_s)}{2(1-\rho)} - \frac{\lambda\sigma^2{}_I}{2(1-\rho)} \tag{2.6}$$

Note as the system gets heavily loaded $\sigma^2{}_I \to 0$ or

$$W \le \frac{\lambda(\sigma^2{}_a + \sigma^2{}_s)}{2(1-\rho)} \tag{2.7}$$

For any packet, the delay is the summation of the average waiting time and the average service time. Thus,

$$T \le \frac{\lambda(\sigma^2{}_a + \sigma^2{}_s)}{2(1-\rho)} + \frac{1}{\mu} \tag{2.8}$$

Where T is the steady state delay. For arrival distribution being deterministic $\sigma^2{}_a = \frac{1}{\lambda^2}$. Thus,

$$T \le \frac{1/\lambda + \lambda\sigma^2{}_s}{2(1-\rho)} + \frac{1}{\mu} \tag{2.9}$$

Note by Kingman's heavy traffic approximation, under heavy traffic the steady state waiting time distribution can be approximated by an exponential distribution with mean $\frac{\lambda(\sigma_a^2 + \sigma_s^2)}{2(1-\rho)}$.

2.2.2 Star topology- server outages or denial of service

This case is akin to the modeling of a server with non exhaustive preemptive resume vacations and FIFO service, which means that the vacation time can occur at any point whether it is busy or not. The modeling of this is made simple by the condition of independence of the arrival processes from the number of packets already present in the system, which is assumed to hold for our system, since typically the arrival of the packets do not depend on the queue size. The situation where this does not hold, is in the case of smart routing, where, depending on the load on each node the routing protocol redirects the packet to another route. Under the independence assumption, the distribution of the number of messages in the system, exhibits a three way stochastic decomposition property at message departure time [44]. This effectively means that the number of packet present before the start of a vacation, the number of packets that arrive during a vacation, and the number of packets at any arbitrary time, are independent of each other. Thus the results of each can be calculated independently and added to give the total delay. The decomposition is

$$\Pi(z) = H\_(z)\alpha\_(z)\,\Pi_{G/G/1}(z) \tag{2.10}$$

where π_k probability of k messages in system immediately after a departure time

$\Pi(z)$ Generating function for $\{\pi_k\}$

$H\_(z)$ Probability generating function (PGF) for number of messages in the system at the beginning of vacation period

$\alpha\_(z)$ PGF for number of messages that arrive before any arbitrary message during a vacation period

$\Pi_{G/G/1}(z)$ $\Pi(z)$ for a G/G/1 system without vacations

For purposes of implementation into a load frequency control model, we need to strive for a more simplistic model. Thus, the additional assumption of the Poisson arrival rates is made. Now, the queuing model can be analyzed as a two customer class system with priority [46] or as a system with preemptive vacations with exponential ON distribution and a general OFF distribution [44]. In both cases, the results are the same. The former analysis is presented here.

Let a customer of type 1 be the higher priority class (denoting interruptions) and customer of type 2 be the lower priority class (denoting the actual data packets). Thus class 1 customer are immediately serviced on arrival, irrespective of the presence of class 2 customers in the queue.

Let $==^{\vartheta N}=$and $\Updownarrow^{O}$ denote the mean and square of the variation of the service distribution for both class of customers. The mean waiting time of customers in the lower priority class is partitioned as follows:

$$E[W] = E[W'] + E[W''] \tag{2.11}$$

where E[W'] is the mean waiting time before service and

E[W"] is the waiting time before services is resumed each time it is interrupted by a customer of higher priority.

W' can be separated into three parts:

W^0: residual waiting time for service of the customer if his priority is equal to that of the arriving customer

W^1 : the waiting time corresponding to service of customers of the higher or equal priority who are present in the queue when the customer arrives

W^2: waiting time corresponding to service times of higher priority customers who arrived during the waiting time in queue of the customer

Assuming that service is resumed at the point it is interrupted, we define:

$$\lambda = \lambda_1 + \lambda_2 \tag{2.12}$$

Where λ_1 and λ_2 are the vacation and message arrival rate respectively and

$$E[S_i] = \sum_{j=1}^{i} \frac{\lambda_j}{\mu_j \lambda} \tag{2.13}$$

$$E[\bar{S}_i] = \frac{E[S_i^{\,2}]}{2E[S_i]} \tag{2.14}$$

$\hat{\rho}_i = E[S_i]\lambda$:

which is the probability of queue being occupied by class i customer.

The mean waiting time to the end of this service is given by

$$E[S_i{}^2] = \sum_{j=1}^{i} \frac{\lambda_j(\sigma_j{}^2 + 1)}{\mu^2{}_j \, \lambda} \tag{2.15}$$

Thus

$$E[W_i{}^0] = \frac{\lambda E[S_i{}^2]}{2} \tag{2.16}$$

Now, $E[W^1]$ is the mean waiting time corresponding to the number of individuals the arriving customer finds and $E[W^2]$ is the mean service time of customers with the higher priority who arrive while customer i is waiting. Little's theorem states that N=×T , All terms are in steady state values, where

N: is the number of customers in the system

× is the arrival rate

T is the average time delay for a customer.

Thus applying Little's theorem we get:

$$E[W_i{}^1] = \sum_{j=1}^{i} \rho_j E[W_j'] \tag{2.17}$$

$$E[W_i{}^2] = \hat{\rho}_{i\text{-}1} E[W_i'] \tag{2.18}$$

combining 2.16-2.18 we get:

$$E[W_i'] = \sum_{j=1}^{i} \rho_j E[W_j'] + \hat{\rho}_{i\text{-}1} E[W_i'] + \frac{\lambda E[S_i{}^2]}{2} \tag{2.19}$$

thus we get:

$$E[W_i'] = \frac{\sum_{j=1}^{i} \frac{\lambda_j(\sigma_j^2+1)}{\mu_j^2}}{2(1-\hat{\rho}_{i-1})(1-\hat{\rho}_i)} \tag{2.20}$$

The total time spent at the queue of priority *i* is $E[W_i'']+1/=$ By using Little's Theorem we find:

$$E[W_i''] = \left(E[W_i''] + \frac{1}{\mu_i} \right) \hat{\rho}_{i-1} \tag{2.21}$$

So:

$$E[W_i''] = \frac{\hat{\rho}_{i-1}}{(1-\hat{\rho}_{i-1})\mu_i} \tag{2.22}$$

combining (2.20) and (2.22) gives the average waiting time of the lower priority customer.

$$E[W_2] = \frac{1}{(1-\hat{\rho}_1)} \left\{ \frac{\hat{\rho}_1}{\mu_2} + \frac{\left(\frac{\lambda_1(\sigma_1^2+1)}{\mu_1^2} + \frac{\lambda_2(\sigma_2^2+1)}{\mu_2^2} \right)}{2(1-\hat{\rho}_2)} \right\} \tag{2.23}$$

2.2.3 Distributed dedicated network

A dedicated network offers a strong fault tolerance guarantee as well as low latency and variation on packet delivery. The analysis of delay is non trivial as tandem queues are correlated and hence, the assumptions of interdependence of service times and arrival times break down. Still under certain reasonable assumptions, some simplifications can be made to decompose the individual queues. Several empirical studies performed on large packet monitors have determined the arrival process for some internet traffic to be statistically self similar with a log normal distribution with a heavy tail [41]. The data signal for load following should not conform to that distribution but could be more simply modeled as a G/G/1 queue model at each intermediate queue. This is because the signals are sent every 2 to 4 seconds all at once and hence their arrival at the source queue is deterministic. This type of data has been shown to follow a more Poisson distribution characteristic [48]. As per Jackson's theorem (extended to G/G/1 queue) which says in effect, that the number of customers in a tandem and distributed queue system behave as if each queue is a G/G/1 queue and is independent of the other queues [40] and Kleinrock Independence Approximation which states that, by merging several packet streams on a transmission line has an affect akin to restoring independence of interarrival times and packet lengths, [45] the system of tandem queues can be effectively decomposed to be an independent set of G/G/1 queues. Hence, the delays can be approximated well as the summation of the delays the packet encounters during its route with each node being modeled as a G/G/1 queue. This is dependent on the route the data packet eventually takes, which cannot be ascertained before hand. Still with the signals being sent every few seconds, the path traversed should eventually resort to the shortest path to the destination and the delays determined for this particular path would hold. For the scenario where bandwidth reservation is implemented, the path is effectively a virtual circuit network and thus, the delays can be calculated effectively.

For the situation where one needs to determine the effect of server outage or denial of service at any one node, the distributed nature of the network resorts to redirecting the signal along a different path, and effectively, the delay variation should not be large. Finally, in the case when such outages occur in a large part of the network or at the source then the delays can be approximated assuming that the vacation time lends itself to decomposition.

Chapter 3

Effect of Constant and Random Delays

3.1 Background

The communications infrastructure should have redundant links to guarantee fault tolerance to link failures as the penalty for not meeting the required generation profile due to communication contingency can be steep. This is an important factor to consider when migrating to a distributed infrastructure as it inherently offers such redundancy. Bilateral contract opportunities place additional requirements on communications for meeting customer loads with adequate quality of service. Hetrogenousity of the above structure will probably be a reality as cost factors will eventually determine the quality of the communication channel subscribed to. We suggest a network structure akin to one with fast and low error backbone for connecting geographically distant units. Slower links may be used for near locations.

This is similar to LAN with slower links but the interconnection between individual LANs being achieved with fast, reliable and redundant links. We foresee a duplex connection network scheme which will enable the generating units to reply with pertinent data such as present generation levels and acknowledgement of signals. This section enumerates some security concerns of using shared, open channels for communications. It also lists the additional services and mechanisms that will be required of the communication system and the corresponding control policy. Simulations based on constant delays and random delays were performed to observe the effects of delay distribution, topology of generators, and type of secondary control. This study was carried out using fixed constant delays and random delays.

3.2 Communication service requirements

By shifting to a distributed system several issues need to be addressed. Apart from the services provided by the classical system, additional communication services will be required for proper functioning and adherence to standards, such as NERC [1], by all participating entities. These are enumerated below:

i) A well connected distributed communication system available equally and fairly to all participants.

ii) Monitoring of the generator output for all units involved in load following, regulation, and related ancillary services by the ISO/SC to ensure proper adherence to scheduling contracts.

iii) Monitoring of customer loads for bilateral contracts to meet demand.

iv)A fast configurable abstraction and policy for managing contingent situations such as failure of generating units, non response of generator to signal input, or failures of the communication system. The re-configuration or recovery schema should preferably be automatic, or should assist the system scheduler to take appropriate steps quickly.

v) Detection of communication failure by both bilateral contract players as well as the SC.

vi)Detection of security breach or intrusion detection for all participants.

vii) Privacy for participant data, as well as some form of authentication to signals received by the generator units.

viii) Contingency plans for units with bilateral contracts if unable to meet the customer demand. This will generally be applicable to small generating organizations with limited generation capability.

3.3 Higher level fault tolerant mechanism

Transactions and signal delivery should be based upon a fault tolerant and configurable layer overseeing the proper implementation for the dissemination of the signal both from the customer to the supplier and vice versa. This layer should be implemented for both bilateral contracts as well as centralized controls. Most of the additional services enumerated in the previous section can be provided by existing fault tolerant schemes [56]. These however need to be configured and tuned, with emphasis on low latency and high security guarantees, which can be easily configured for a heterogeneous communication system. From the viewpoint of higher level abstractions, requirements of the lower layer include bounded delay guarantees, bounded throughput times and a broad overview of the network topology. Under these known parameters, the higher level abstraction can then ensure a certain quality of service. The load following control scheme follows a simple deterministic signal structure, and this can be exploited to obtain a simple and effective fault tolerant solution. For the fault tolerant abstraction, we suggest using the fail stop model for the failure characterization. This is because communication or generator failure in most cases can be detected cleanly for the following reason. Control signals are sent at a predetermined time and failure to receive it within some time bounds can be considered as a failure event. For the generator failures, one can do so by low cost heartbeat messages. Thus, an efficient way to monitor availability of the communication system as well as the generating units is through the use of heartbeat signals. Furthermore, the signal data can be piggybacked on these heartbeats, as the frequency of sending these messages will generally be greater than the data signals. These heartbeat signals can be further utilized to determine network latencies and sufficient routing and fault tolerance parameters can be updated automatically.

Typically, fault tolerant abstraction layers incorporating some form of security are dependent on time synchronization for guaranteeing services, such as, failure detection, intrusion detection or for tuning throughput parameters. They also use time synchronization to check for timeliness and causal ordering. Hence, virtual synchrony schemes may also be needed to be implemented. One way this can be simply done is by the use of timestamps or sequence numbers on each packet, which allows existing virtual synchrony protocols to use and guarantee synchrony with known bounds [57]. Additionally, delays can be determined and appropriately used for tuning and reconfiguration. It is suggested further to send a window of the history of the signals previously sent with each signal data. This provides several benefits, namely in detecting malicious or replayed data packets, and in assisting generating units to take effective remedial actions during communication failures. Time stamping with additional history of data can also allow detection and recovery from certain types of Byzantine communication failures. Byzantine failures are failures which are difficult to detect, an example is, if a router randomly fails and recovers, as a result of which data packets get delayed, dropped or altered.

3.4 Data Security

Data and information security are clearly a requirement given the critical role of the energy infrastructure. Of particular importance is a simple type of malicious attack known as the denial of service attack. From the earlier simulations, it was seen that attacks of such nature on the ISO or any bilateral contract units can make the AGC system fail. Both random or malicious data can lead to an unfulfilled contractual schedules or to misoperation of the generator units. This is especially true for small players with limited generating capacity. Such forms of malicious data can be easily induced by competitors or malevolent parties in an open distributed communication system. Additionally, the signal data can be monitored by outside parties and used for personal or nefarious purposes. Therefore, data authentication as well as confidentiality need to be maintained. Contemporary fault tolerant protocols incorporate these in their middleware abstraction. Confidentiality of the data can be provided using any of a number of good encryption techniques. Strong encryption is not a requirement as the security expiry time is on the order of a few seconds or possibly minutes at the most. Still, there may be situations where competitors may monitor a sequence of data if not encrypted strongly and this may lead to a competitive advantage. Some form of authentication of the data signals should be implemented to determine the source of the data before making the appropriate change in generation. Authentication can be provided by signing the signal packet with the source's given and known signature or by using public key schemes. Authentication should be based on a strong scheme, as compared to that of the confidentiality issue, due to its usefulness over an extended period of time. Before security mechanisms are implemented, a strong security policy, defining the level of security requirment for each entity involved in the load frequency control, needs to be made and adhered to by all parties and necessary action to be taken in case of malicious activity detection.

Ordering of messages can be trivially provided by time stamps, which should guard one against replay of messages. In case a generator receives an old packet, it can simply ignore the data. In many cases, this might be preferential to responding to the old command. Redundancy for availability must be provided by the system operator to guard against denial of service attacks, which by far is the simplest to perpetrate and the most easy to succumb to, for the load frequency control system. This can be achieved by keeping several layers of redundancy. The option of shifting to manual control should be incorporated in case of situations where the communications system cannot recover. In case of malicious failures with no possibility of recovery, the system operator may need to switch from automatic to manual control to restore adequate power system response. There may be other possibilities for stabilization by isolating offending signals or shifting to agreed upon control measures in the case of widespread communication failures. Later, it will be shown that bilateral contract generators are highly susceptible to delays in the signal and this must be a fundamental consideration in the communication system infrastructure.

3.5 Simulation Results

Simulations for both the classical LFC as well as models including bilateral contracts were performed using Matlab. Constant delays were modeled by delaying the control signals to each generator by a fixed time interval. Different delay distributions were simulated by independently incorporating a predetermined delay time for each individual generator. Random delays were simulated using random signal packets from a history of signals. This allowed simulations of scenarios involving both random delays and malicious replaying of captured signal packets. Simulations involving different generators distributed amongst three control areas (CA) were performed. The relevant output from these simulations are summarized in Table 3.2. Situations where the LFC system fails completely is depicted throughout the thesis as a system frequency instability. However the system does not become unstable, as limits placed on the generators as well as control logic prevents such situations.

3.5.1 Constant delays

The load frequency control models all consist of three CAs interconnected via tie lines. Simulations were carried out with sets of 9, 17 and 50 generators respectively. Here, CA 1 is considered a small area, CA 2 a medium area and CA 3 a large area to represent several possible different scenarios. Several simulations with the generators configured to accept the classical AGC signals, pure bilateral configuration [6], and a mixture of the two standard simplified models for the prime mover and governor were used [17].

The area control error (ACE) and generator control error (GCE) signals were sent every four seconds as is normally done in the US. Participation among the generators involved in the AGC service was divided equally. In the case of a mixture of AGC and bilateral contract, participation under bilateral contracts was made higher than those of the traditional units. For the delays, simulation based on constant packet delays as well as random delays, involving both individual generators as well as that induced at the source itself (disseminator for AGC signals) were conducted. The constant delays denote a heavily congested network or a denial of service type attack at the respective site. The random delays denote Byzantine failures as well as malicious attacks. For the load variation, a step load increase is used. Below we supply typical parameter values used for simulations:

	D	M	Tg	Tch	R	B	T	Participaton factor	GCE participation
CA 1	3.6	80	0.5-1	0.3-0.5	0.05	1/R+D	7.55	0.5-1.2 / no.of gen	0.3-0.7
CA 2	2.2	220	0.5-1	0.3-0.5	0.05	1/R+D	3.77	0.5-1.2 / no.of gen	0.3-0.7
CA 3	3.7	1500	0.5-1	0.3-0.5	0.05	1/R+D	7.55	0.5-1.2 / no.of gen	0.3-0.7

Table 3.1 Values used for a typical simulation of 50 generators

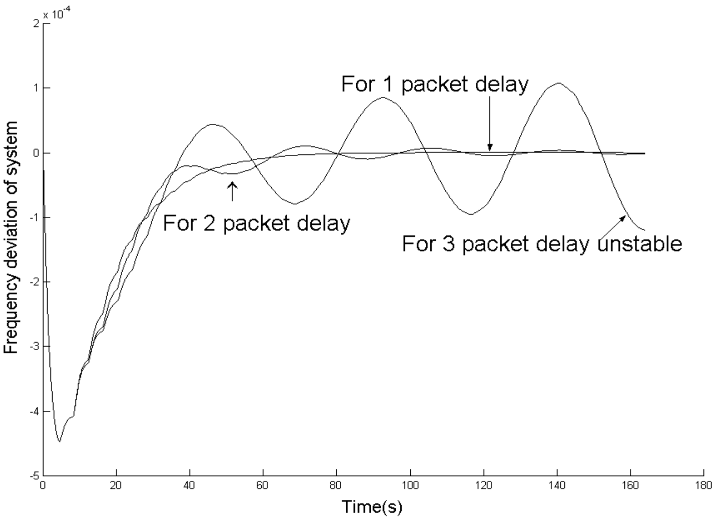

Fig 3.1 Instability caused by constant delays in a Control Area for pure AGC

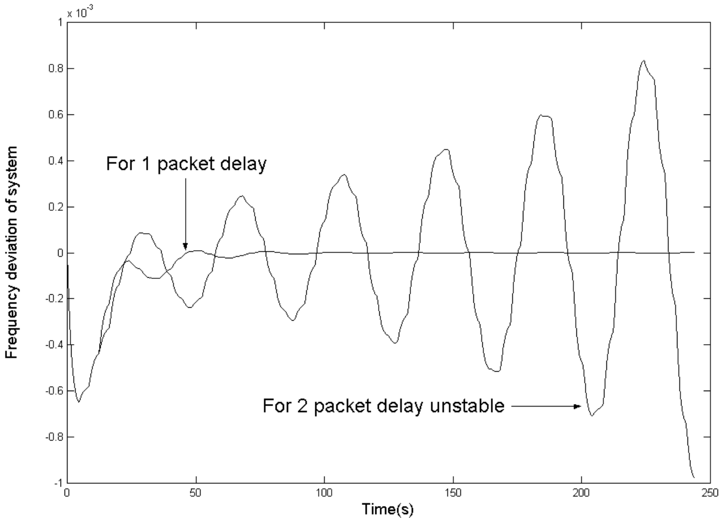

Fig 3.2 Failure of LFC caused by constant delays in a bilateral contract generator unit

From the Figs. 3.1-3.4, we see that bilateral contract channels and the ISO communication channels are a point of potential concern, as they are very susceptible to delays in signal. Thus, they must to guarantee a high level of fault tolerance in their communication links. Fig 3.1 shows that the bilateral generator is susceptible to a delay of only 2 packets, for our model, and this in turn may make the LFC system fail. The value is, of course, system dependent and also contingent on the generator parameters. Hence, it is of utmost importance for the bilateral contract entity to utilize a low latency communication channel with fault tolerance built into the control scheme.

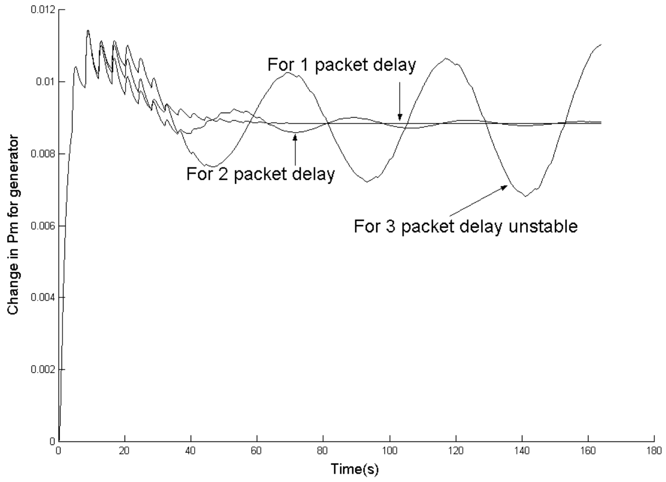

Fig.3.3 Deviation of mechanical power output for generator

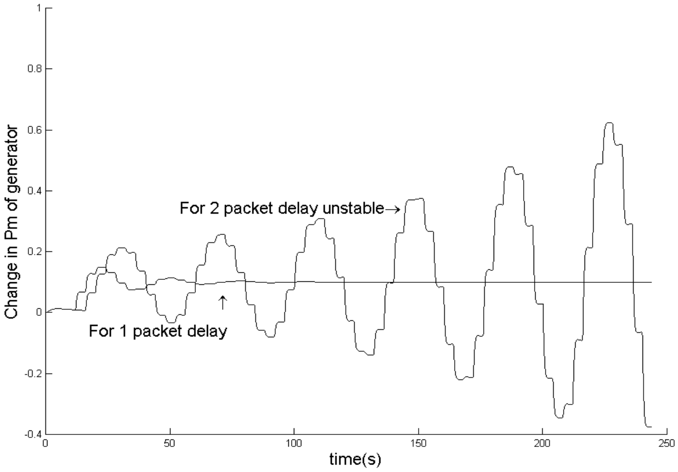

Fig.3.4 Deviation of mechanical power output of bilateral generator unit

3.5.2 Random Delays

Load following ancillary service is typically robust to signal delays, if the delays are present in a minority of the communication channels. However, if a majority of the channels exhibit delays in communication then the LFC system may fail. This is illustrated in Fig. 3.1 and 3.3, which show the LFC system becoming failing in the case of a 3 packet delay occurring in at least 66% of the AGC channels. This makes the source of the AGC signals (ISO) susceptible to any denial of service, or network congestion. As the controlling authority is typically the center for most data (both sending and receiving), this becomes a serious concern. Appropriate measures must be taken to decrease the possibility of any such occurrence. This will become more aggravated for more critical and speed dependent applications, such as emergency control signals. Even though the load following signals are typically not considered critical a relatively simple denial of service attack perpetrated by any individual on this service can lead to instabilities.

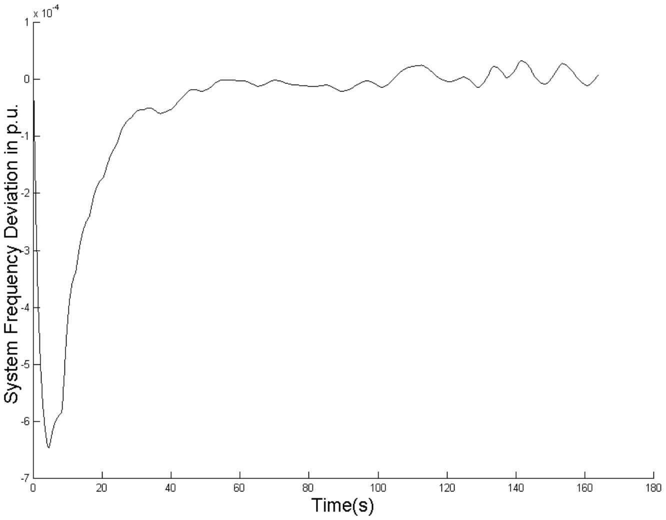

Fig.3.6 System frequency response with random delays for bilateral system

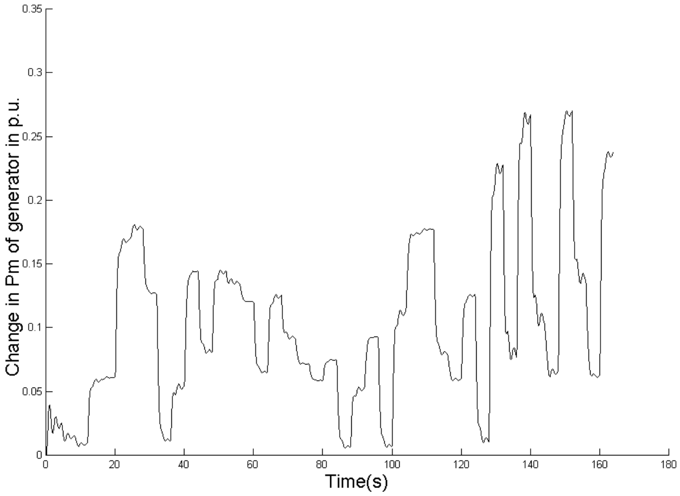

Fig 3.7 Unfulfillment of contract due to random delays in a bilateral contract

Fig. 3.7 shows that for random delays the bilateral contract cannot meet the contractual obligation to customer, although the effect on the system is not large Fig 3 b. This contractual failure may be very detrimental to both players. Random delays can be introduced by Byzantine failures of the communication channel or by malicious parties. The delay models suggested here act as a way to ascertain whether a given network structure introduces sufficient delay to cause instability in the system. Thus, one must incorporate the appropriate communication delay model in further simulations of load frequency control, to include the effects of communication delays.

Scenario	**Traditional AGC**	**Bilateral**	**Mixed AGC and Bilateral**
Fixed delay	Fails for 15 packet delay in single generator. Fails for 3 packet delay in all generators.	Fails for 2 packet delay in any generator.	Fails for 2 packet delay in a bilateral generator. Fails for 3 packet delays in in all AGC generators, or a 7-8 packet delay in majority of the generators. Delays tend to degrade system response.
Random delay	Fails in certain situations with random delay in all generators. No adverse affects from random delay in single generator.	Fail to meet customer demand and may lead to failure of the LFC.	System not adversely affected if in bilateral units only but those parties cannot meet the contractual schedule.
Both fixed and random delays	--	--	LFC system may fail for small delays.

Table 3.2: Summary of simulations

Chapter 4

Network Simulation Results

4.1 Background

4.1.1 Network Simulator

The network simulator (ns) is a discrete event simulator targeted at networking research. Ns provides substantial support for simulation of TCP, routing, and multicast protocols. Ns began as a variant of the REAL network simulator in 1989 and has evolved substantially over the past few years. The ns development effort is now an ongoing collaboration with the VINT project. REAL is a network simulator originally intended for studying the dynamic behavior of flow and congestion control schemes in packet-switched data networks. It provides users with a way of specifying such networks and to simulate their behavior. It provides around 30 modules (written in C) that precisely emulate the actions of several well-known flow control protocols (such as TCP), and 5 research scheduling disciplines (such as Fair Queueing and Hierarchical Round Robin). The modular design of the system allows new modules to be added to the system with little effort. Source code is provided so that interested users can modify the simulator to their own purposes. Ns was used in addition to gt-itm's network topology generator to create random connected graphs to denote a communication network.

4.1.2 Modelling the Communication Network

Modelling of the communication network was performed using otcl scripts for ns. For the radial topology, intermediate nodes were used to depict either ISP or other routing equipment. From Fig 4.1, node 1 and 8 depict such intermediate nodes. The centralized AGC authority is shown by nodes 0 and 7 which are interconnected by fast links, as depicted by the link between 0 and 7. The rest of the nodes depict the generating unit nodes. Thus, Fig. 4.1 depicts a 2 CA scenario with each CA containing it own central authority. Generators subscribing to the centralized AGC were connected directly to the CA, as depicted by nodes 2-6 which subscribe to the AGC centre denoted by node 0. Traffic was simulated by including traffic agents at the various nodes depicting traffic generated by participants involved.

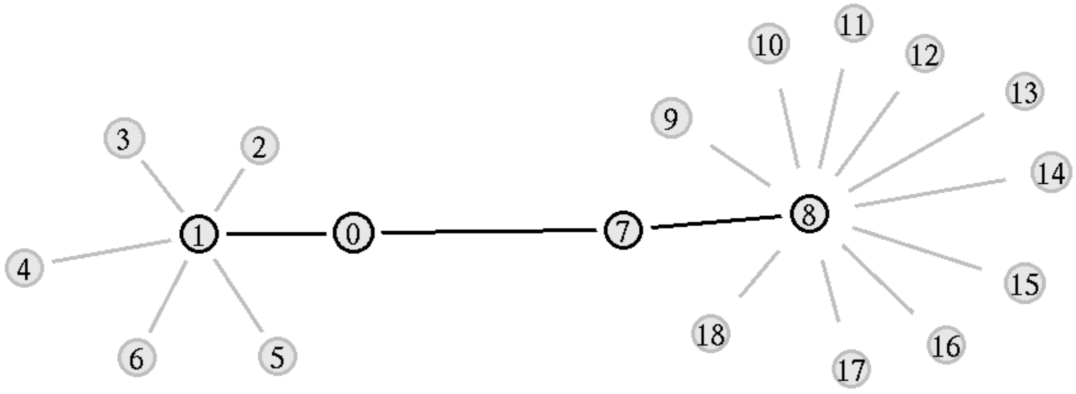

Fig. 4. 1 Radial Network 2 CA(output using nam)

The typical distributed topology is show in Fig 4.2. Here, the square nodes depict generators involved in the AGC. The circular nodes depict the intermediate nodes which could denote ISP or other intermediate routers. All nodes are fully connected as the topology was generated using gt-itm which guarantees connectivity. The graph is of a hierarchical nature as is the situation in any real network with TCP MAN/WAN networks, being formed with a virtual hierarchy scheme. Additionally, we allow for inter stub connections for the topology [39] depicting geographically distant generating units under the same company and connected by an internal dedicated link. Traffic source and sinks were allocated randomly as this denotes a shared network and hence the location of these pairs is random. Bilateral contract entities of load and generation pairs were distributed randomly as this allows for contracts to span across various CA's and geographical boundaries.

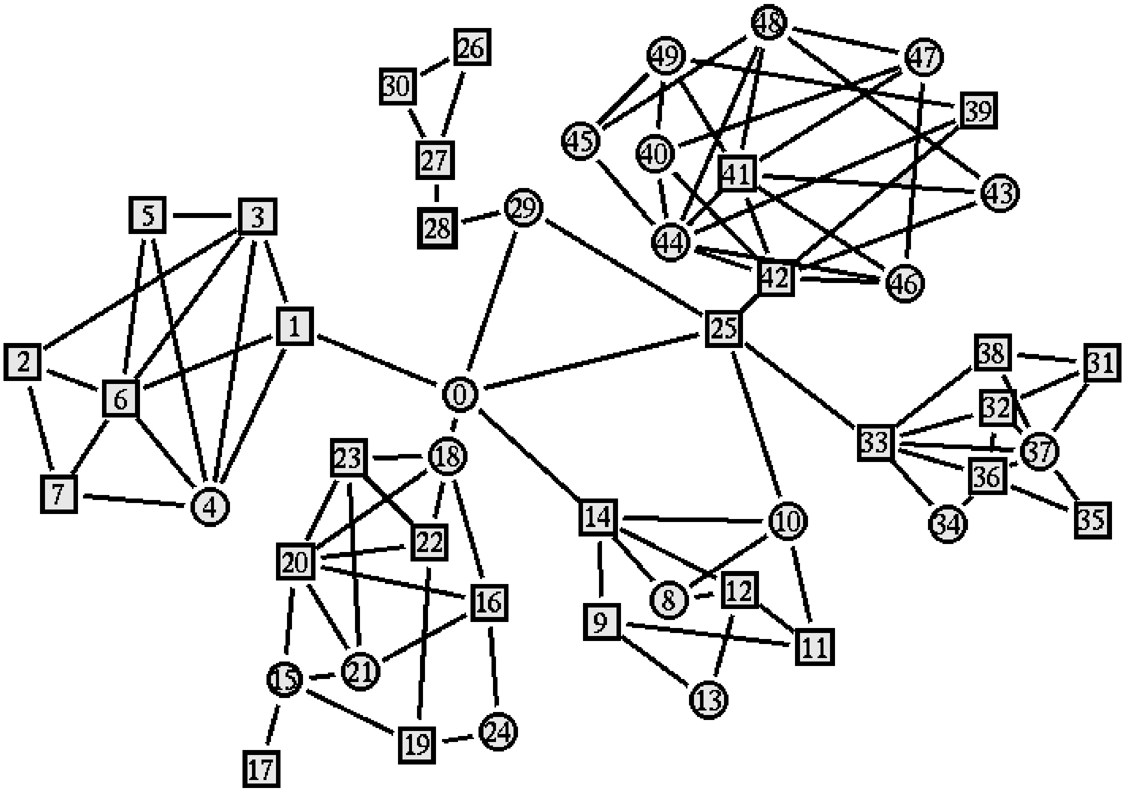

Fig. 4. 2 Distributed 50 node network (output using nam)

4.2 Simulation Results

Simulations were carried out for both the traditional radial communication system as well as one depending on a distributed network for communication. Simulations for the load frequency control were carried out using Matlab's Simulink toolbox, and the network dynamics was simulated using ns. An offline version of ns was used since the signal is deterministic. For both bilateral as well as central secondary control, a signal rate of four seconds were assumed. One result of the simulations was that,at least for most load variation profiles, a signal rate of four seconds for bilateral contracts, could meet the customers need. The following network parameters were investigated:

- Bandwidth (bandwidth ranging from 64Kbps to 10 Mbps were used to denote phone links to ethernet connections respectively)
- Losses introduced in links or nodes
- Delays introduced in the links apart from transmission delays
- Effects of dynamic routing (specifically use of distance vector algorithm to calculate the routing path to be taken dynamically)
- Effects of link/node failures

4.3 Radial network simulations

Simulations were performed for a radial communication system, with the number of generators of 17, 50, 150 and 300. This was done to determine the effects of scale on the communication system. The generators were divided amongst 2 CA's in the ratio of approximately 1/3 to 2/3 to simulate a small control area connected to a large control area. Parameters of the load frequency were kept similar to that illustrated in Table 3.1. The only exception was the use of a larger load damping constant for area 2 (D) to denote the larger CA. From chapter 3, it was seen that it is unsuitable to accommodate bilateral contracts unless redundant links are provided for each connection. Still, this case is interesting in that a rough scheme for sending the signals were obtained. Additionally, the effects of bandwidth, lossy links and link delays were also performed. The effects of link failures can be extrapolated from the results of simulations in chapter 3. For denoting the heterogeneous communication link bandwidths, bandwidths were allocated randomly for each connection ranging from 56.6Kbps to 100Mbps. This takes into consideration phone lines and RF links up to high speed T3 lines. The link from the central control authority was always assigned the highest bandwidth, keeping in mind that these connections have to be fast and reliable links in order to guarantee high data transfer.

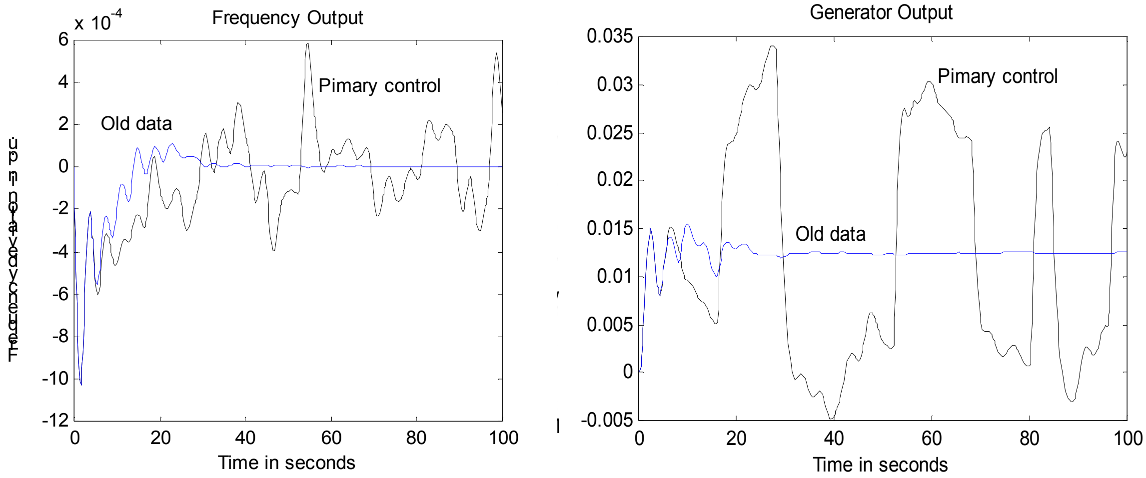

Fig 4.3 (a) (b)Comparison of control approaches for missing data

For these simulations, it is necessary to assume default control actions in the event of not receiving a signal packet. From Fig 4.3 a and b, it is clear that using data from the previous packet is much better. In this scenario, medium level lossy links were used (i.e. losses with uniform probability 10 %). In the case of reverting to primary control, the system response is unsuitable for correct operation of the LFC. For lower losses, the system response is stable but the frequency deviation does not return to zero quickly. Thus subsequent simulations use old data values in case of missing data as it leads to a more robust system. If a signal is not received for a long period of time, then the generator reverts to primary control. Note in the case of radial communication structure, for a large control area with numerous generators under central control, sending signal data all at once can introduce instability (Fig 4.4.a and b) or may result in a fraction of the generators not receiving the signal (4.5 a and b). This is because sending the signals in bulk results in overloading the queues, and subsequently to packets being dropped. If the packets dropped become large then it leads to instability. In these simulations, droptail queues were used. Thus, it is suggested to stagger sending the signals in batches with the time between each batch send being of the order of a few microseconds (depending on the central link). Also, it is prudent to send the signals to large participating generators, or slow reacting generators, first.

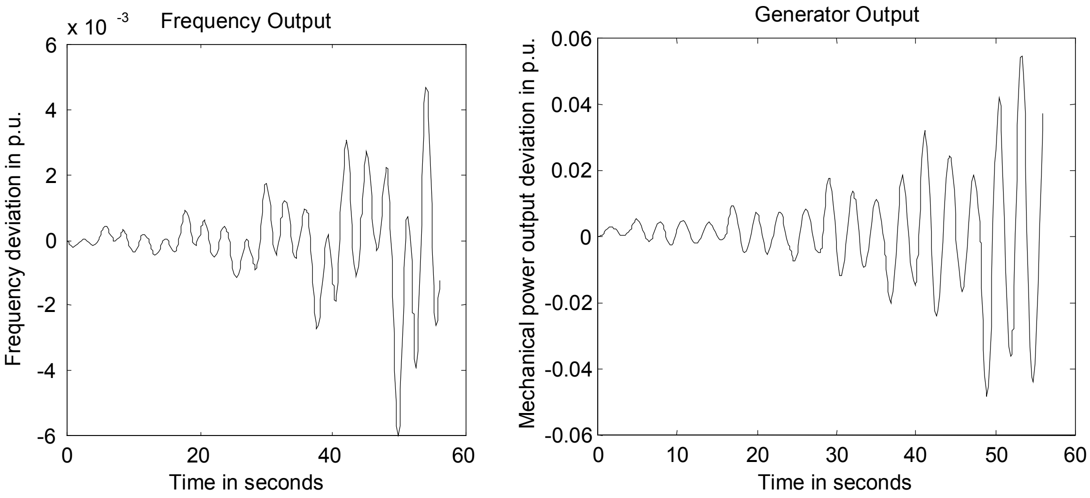

Fig 4.4 (a) (b): Signal sent simultaneously (300 Generators)

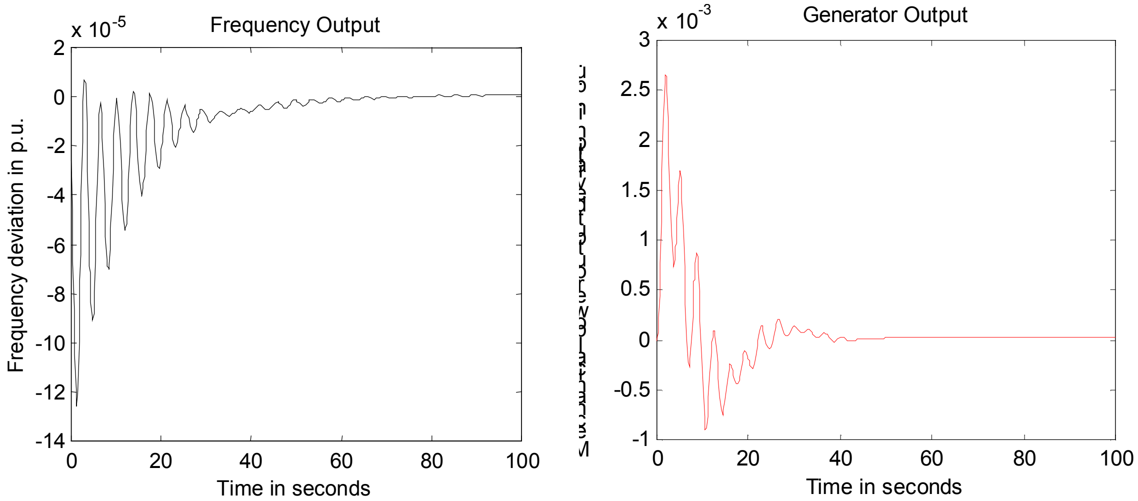

Fig 4.5 (a) (b): Signal sent simultaneously (150 Generators)

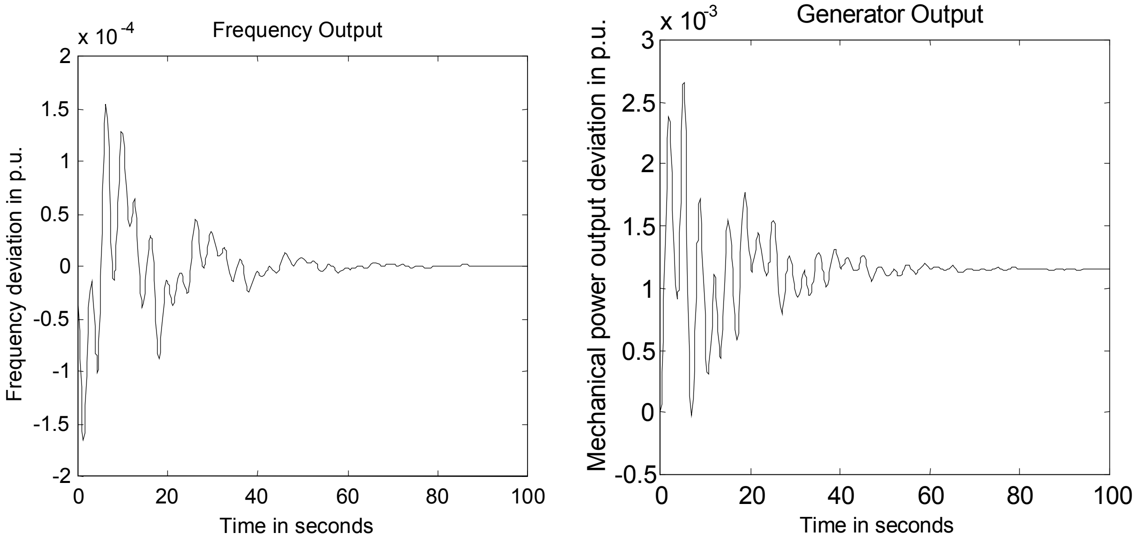

Fig 4.6 (a) (b): Signal staggered (300 Generators)

4.3.1 Effect of Bandwidth

Low bandwidth links (below 256 Kb), especially around the vicinity of the central authority, tends to degrade the performance of the load frequency model. Thus, subscribing to phone lines or low RF links is not a good choice as can be seen from Fig 4.7 a and b where even though the whole LFC system does not fail some generators are unable to fulfil their participating output generation. This obligation is met by the rest of the generators. The assumption made here is that all generators have no constraints on the surplus output power limit. In case there are constraints on the generators output, this may lead to failure of the secondary control to bring the frequency deviation back to zero, and in some cases cause failure of the LFC system. One strategy would be to connect large generators (or generators with large surplus) to fast links and thus ensure that in case of small generators unable to meet their requirement (due to network congestion, packet drop), the system still is able to perform well. In the case of quality of the load frequency control service low bandwidth degrades the performance. Presently the only criteria this service has to adhere to is that the ACE has to return to zero or its pre-disturbance level within 15 minutes following the start of the disturbance [1]. A network consisting of bandwidths greater that 1.5 Mb with some low bandwidth links, has been found to be sufficient for most purposes.

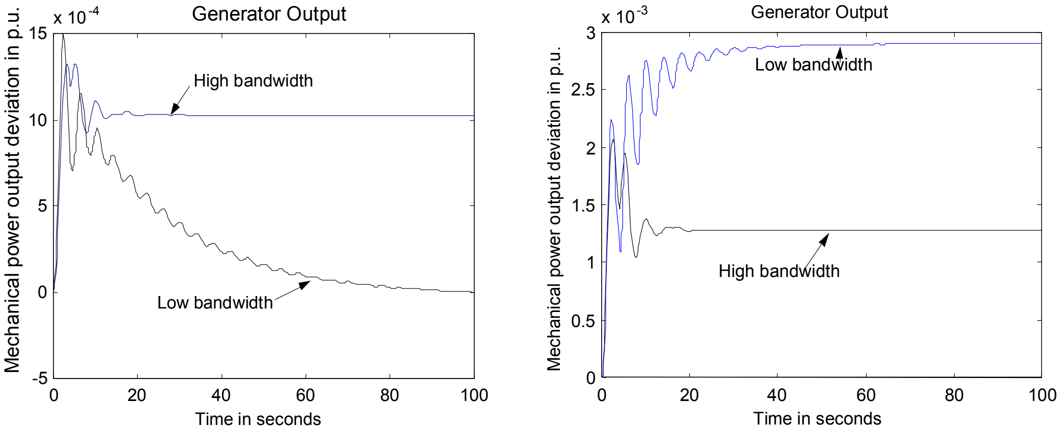

Fig 4.7 (a) (b): Effect of bandwidth on power output of generators (300 generators)

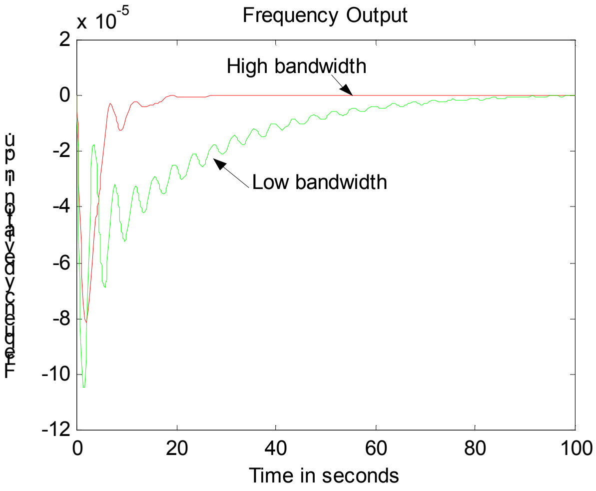

Fig 4.8 (c) Effect of bandwidth on frequency deviation (300 generators)

4.3.2 Effect of Traffic:

Additional traffic was generated by using telnet, ftp, web, and mail client server pairs. These form most of the internet traffic. While the former three traffic agents use TCP for transport, mail clients use UDP as their transport protocol. In addition, bulk UDP traffic from and to the central authority was included to simulate the effect of database update of the central authority, that is required by the network monitoring responsibility. Even under heavy load (and fast links) the effects on the load frequency model is minimal (Fig 4.8 and 4.9 a and b). High load was simulated by using an equal amount of traffic generators as the number of nodes in the system.

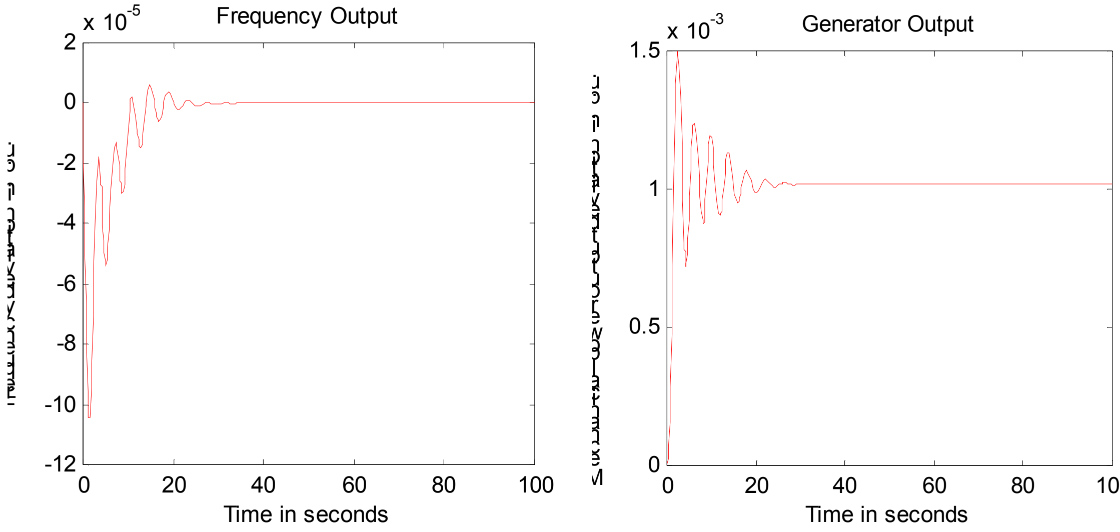

Fig 4.9 (a) (b):Effect of medium traffic

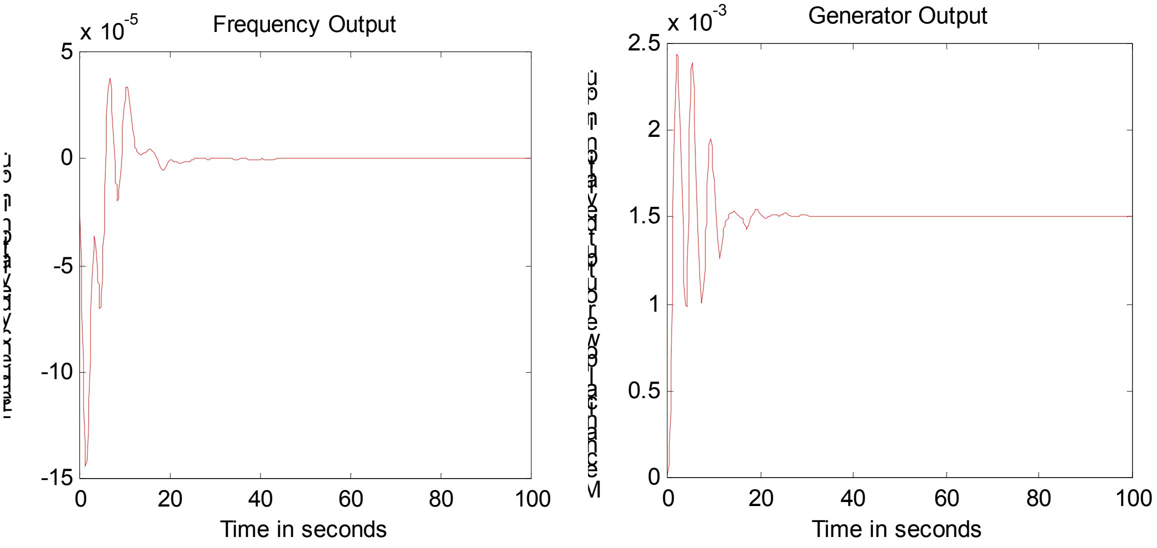

Fig 4.9 (a) (b): Effect of high traffic

4.3.3 Effect of packet losses

Losses were introduced at random links using a uniform probability of dropping packets due to the errors. Thus, the assumption that the errors introduced in the packets could not be corrected by the error correction mechanism at both the physical and data link layer, was made. The case where packets could be corrected is akin to an uncorrupted packet with slight delays (in the order of microseconds). From Fig 4.10 -11 a and b we see that lossy links are indeed very detrimental to the proper working of the LFC model. It is drastically affected by losses and the LFC system may fail. Thus, links which are generally lossy in nature such as RF links are not appropriate to support the transport of the ACE signals. Again, note that the effect of load on the outcome is minimal. The the system functions approximately the same in high traffic as well as low traffic conditions.

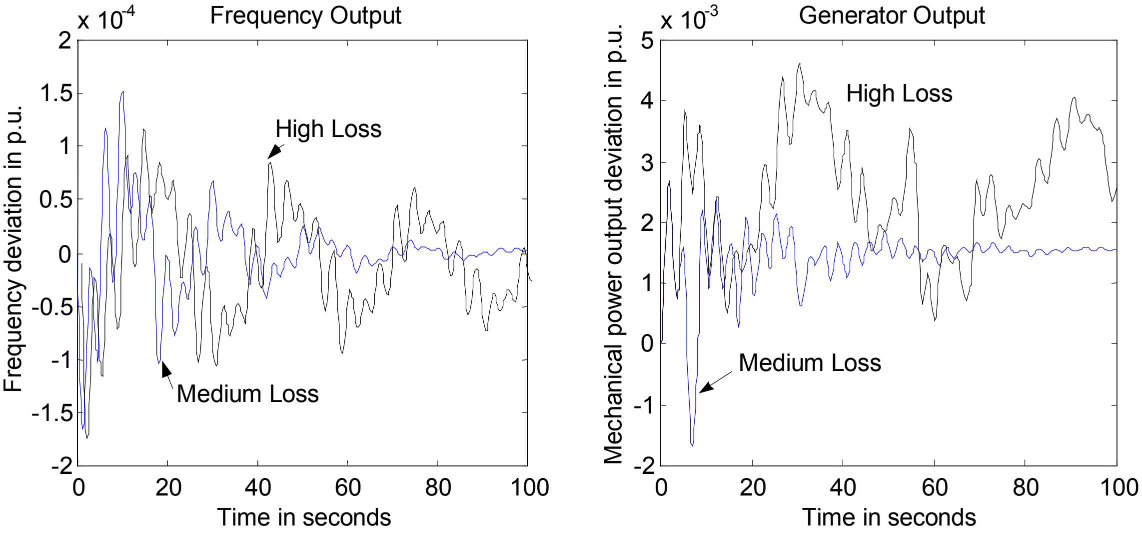

Fig 4.10 (a) (b) 300 generators medium traffic with high and medium losses

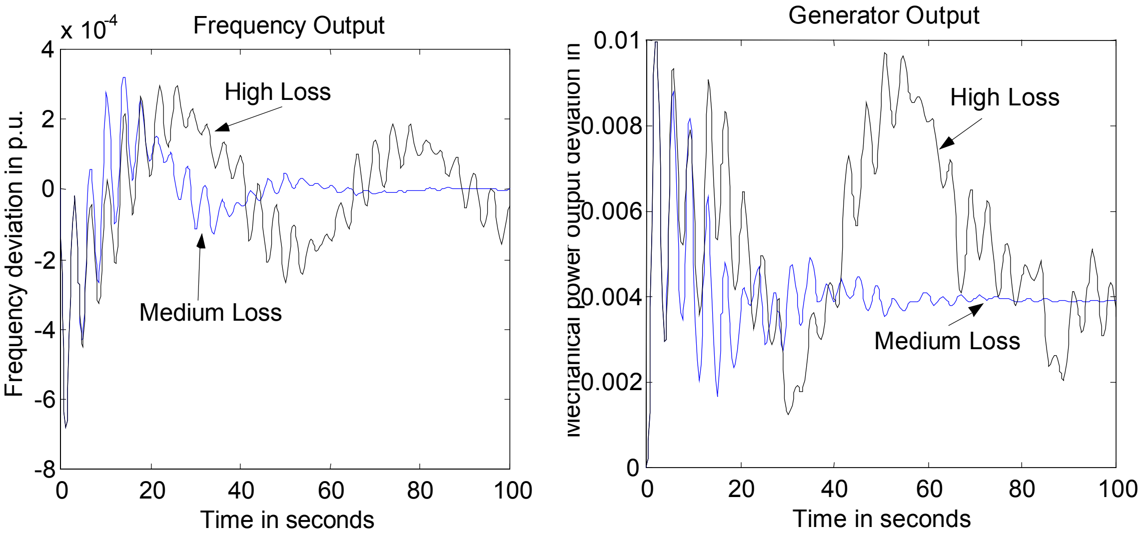

Fig 4.11 (a) (b) 300 generators high traffic with high and medium losses

4.4 Simulations for distributed communication network

4.4.1 Pure Central AGC

Simulations using only pure central AGC is performed for a distributed communication network. Bandwidths are assigned randomly for the distributed network ranging from 128.8K to10Mb. This also assumes that the routing path is fixed and the best path (lowest cost path) is calculated beforehand, which applies to the scenario in which virtual circuit switching or bandwidth reservation is used to route the signals.

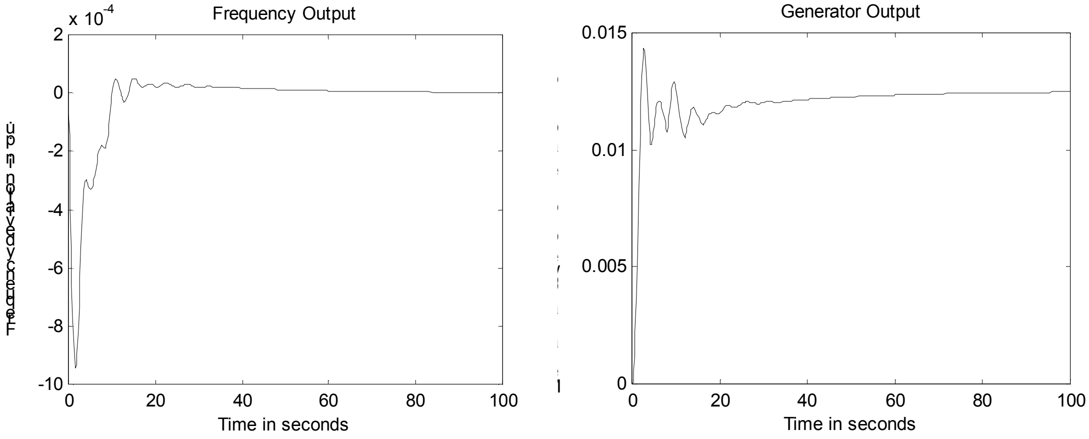

Fig 4.13 (a) (b) Base case no load, no loss, no link dynamics

4.4.2 Effect of Trafiic and Packet Loss

This is also consistent with the simulations involving dedicated links. The effects of network traffic load is still minimal on the LFC as can be seen from Fig 4.13 a and b.

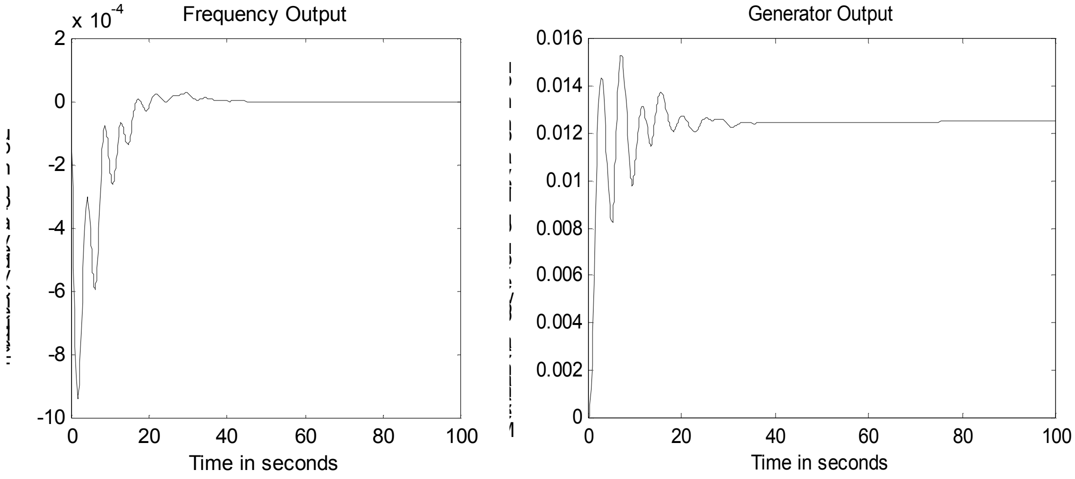

Fig 4.14 (a) (b)Effect of high traffic

The effects of lossy links are much more prevalent. From Fig 4.14 a and b, it can be seen that the LFC system may fail even for very low percentage of loss probability, even more so than the dedicated links. Here, the effects of network load also comes into play with the LFC system failing with a medium network traffic. From Fig 4.15 a and b, note that the for any higher probability of loss in signal packets the LFC system does indeed fail unpredictably.

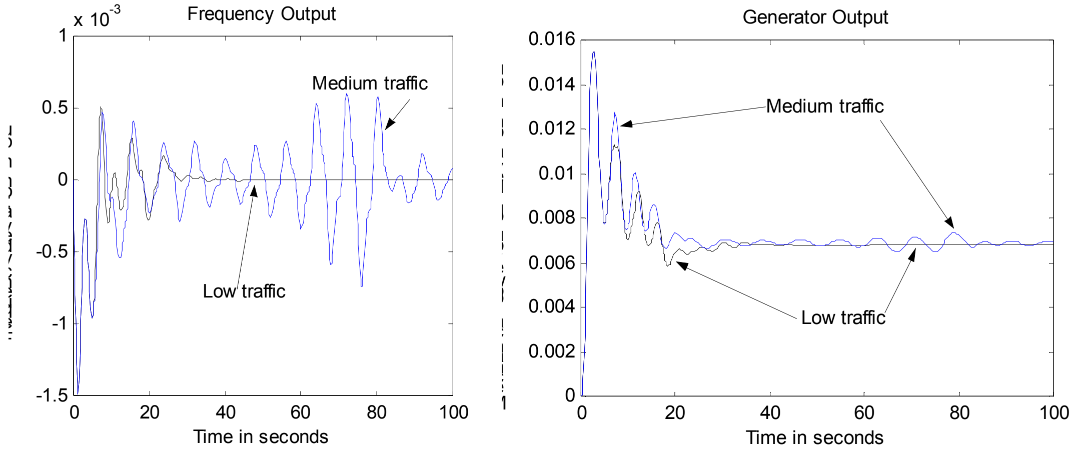

Fig 4.15 (a) (b): Effect of low losses

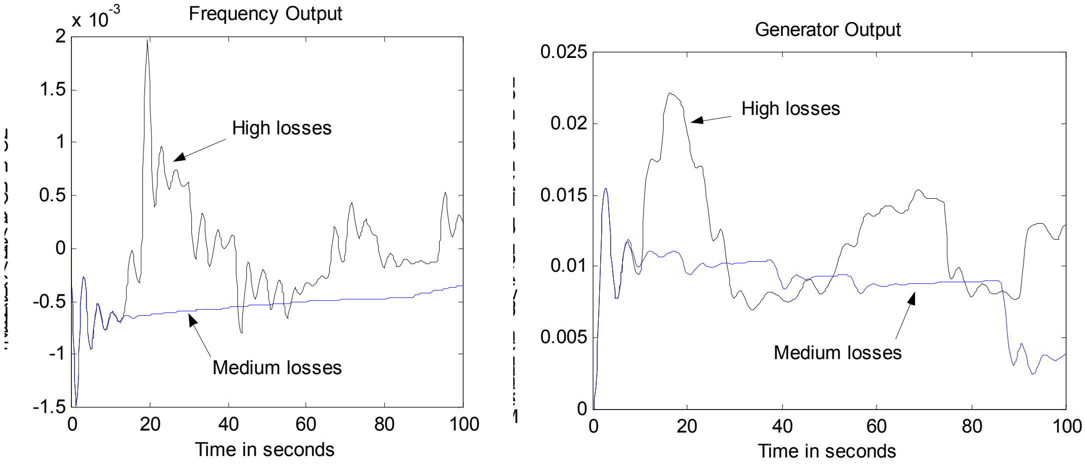

Fig 4.16 (a) (b): Effect of medium and high losses with low traffic

4.4.3 Inclusion of Bilateral Contracts

Scenarios including bilateral contract generators were performed to observe the effects of communication system on the bilateral contract response. Chapter 3 established that the bilateral contract generators are more suspect to constant delays in the communication network. From these simulations, we see that on the whole for small to medium contingencies in the communication network the inclusion of bilateral contract does make the system more robust. When there are large contingencies in the links to the bilateral contract generator, then the system is more unreliable. Thus, we again emphasize the importance of ensuring that the central authority and each bilateral generator unit be connected using reliable fast connections. High traffic load is shown to cause minimal effect for scenarios involving bilateral generators.

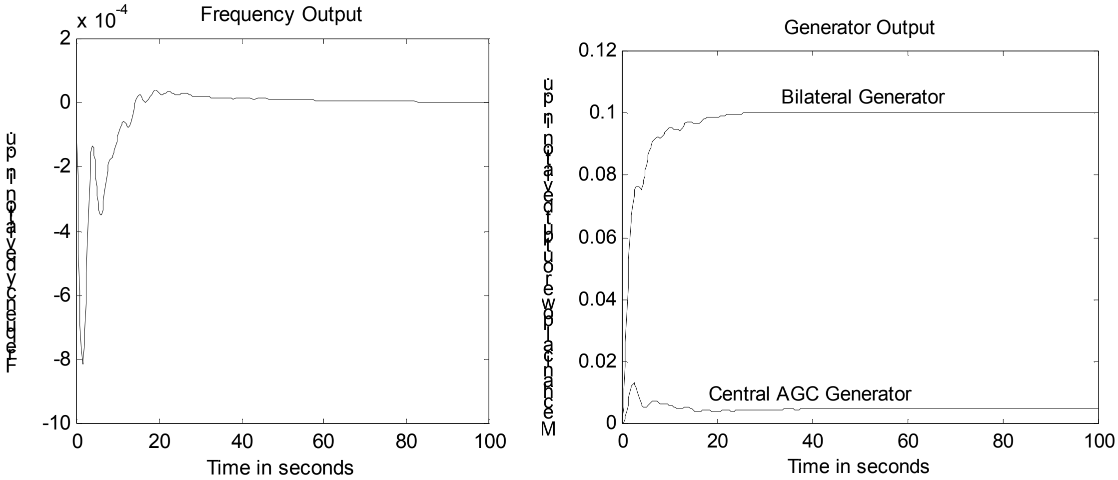

Fig 4.17 (a) (b): Base case

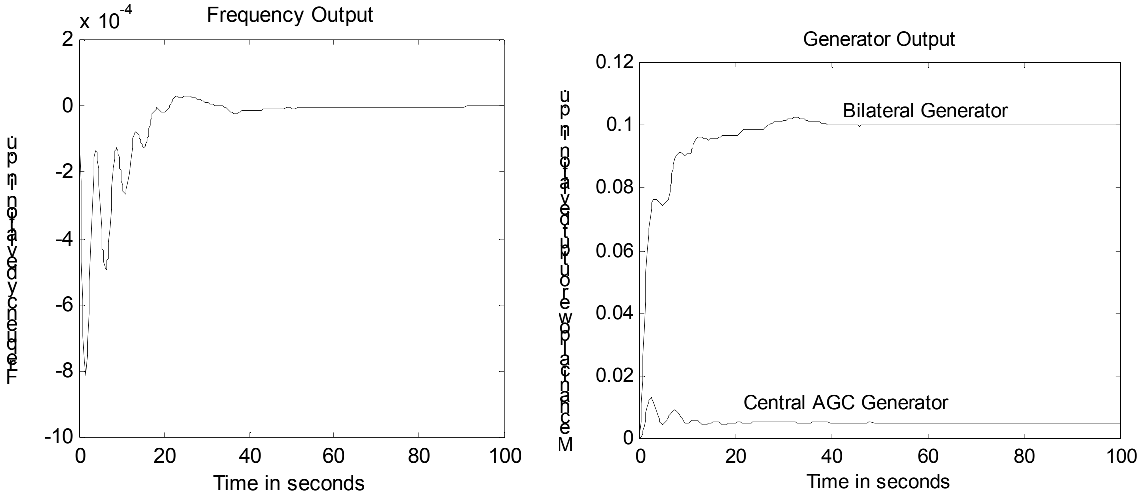

Fig 4.17 (a) (b) Effect of high traffic

4.4.4 Effect of Losses

Comparing with the pure central AGC scenario we notice that the topology including bilateral contracts perform better Fig 4.18 a, b and c, for low losses. However for medium and high losses the results are about the same as that of the pure central AGC scenario.

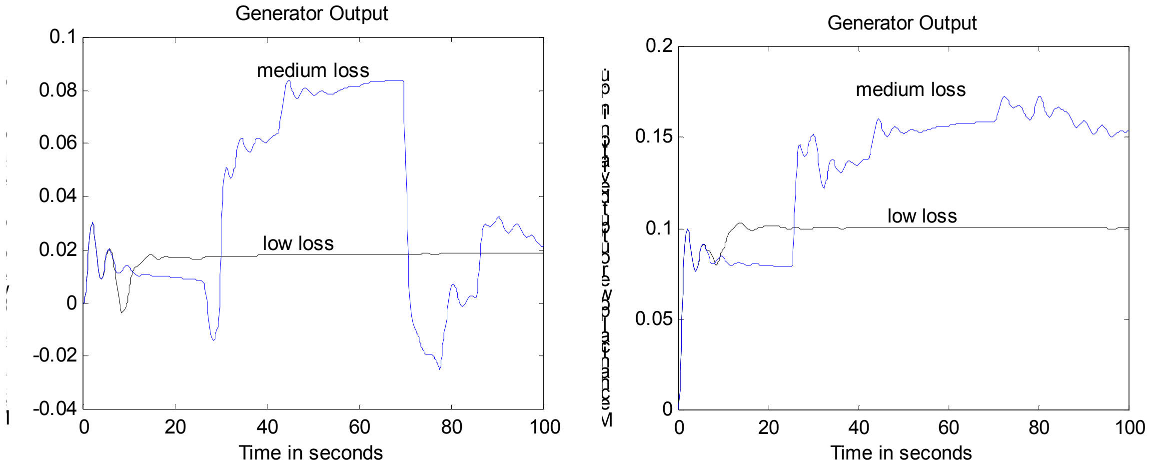

Fig 4.18 Effect of losses (a) Output of Central AGC grenerator (b) Output of bilateral generator

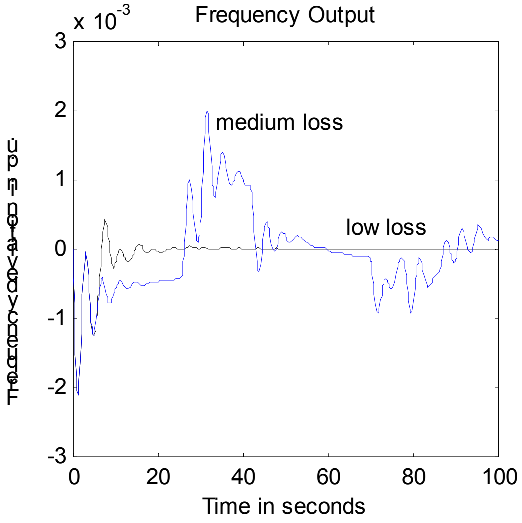

Fig 4.18 (c) Frequency deviation

4.4.5 Effect of Link dynamics and dynamic routing

The location of the link dynamics impacts the system performance. At locations distributed on the intermediate links, the system remains stable albeit with a slow performance. In addition, the bilateral contract approximately meets the demand of its load. However for link dynamics in the vicinity of the bilateral contract (Fig 4.20 a and b), the complete LFC system fails and the bilateral generator cannot meet the load demand. This is consistent with the previous results from chapter 3.

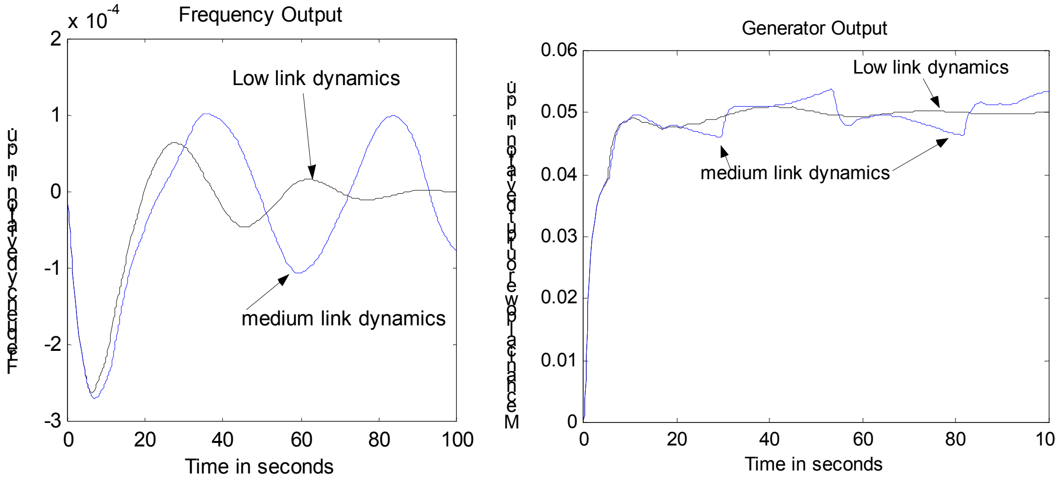

Fig 4.19 (a) (b) Low loss link dynamics, distributed in network with bilateral power output

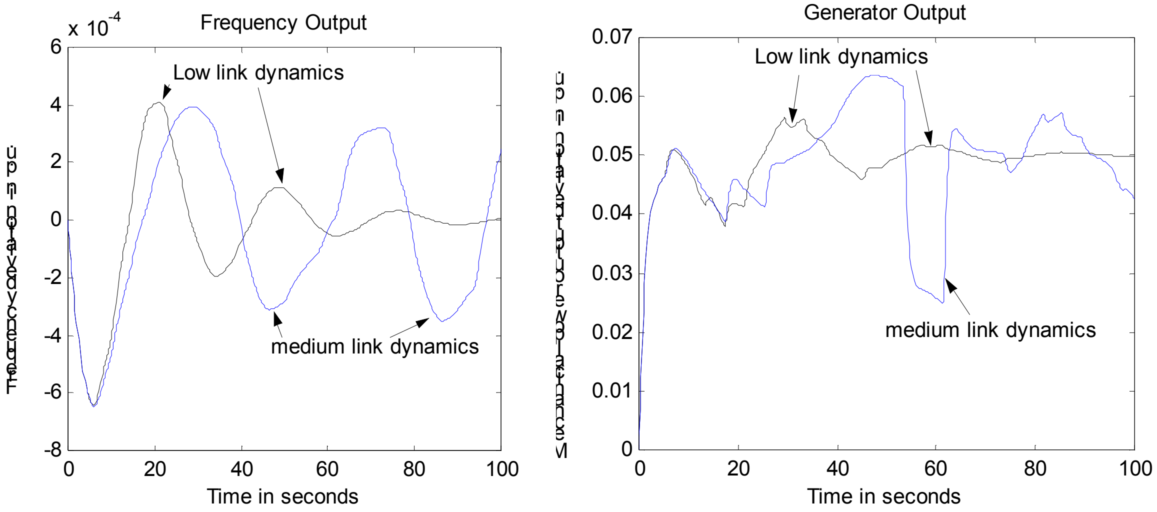

Fig 4.20 (a) and (b) Low loss and Link failures at vicinity of bilateral contract with (b) showing the output of the bilateral generator

From Fig 4.21 (a), (b), (c) notice that the use of dynamic routing significantly improves the performance of the network and in turn the performance of LFC. Comparing with Fig 4.21 (a) and (b) with fixed routes, the system withstands even large loss in the packets. This is because routing ensures multiple packets received at the destination.Although some packets are lost, duplication of the packets due to routing mechanisms ensures to some extent the receipt of the packets. Thus, even though the performance is degraded the system remains stable. Also from Fig 4.19 b some pure central AGC generators are unable to meet the scheduled demand due to losses occurring at their dedicated link.

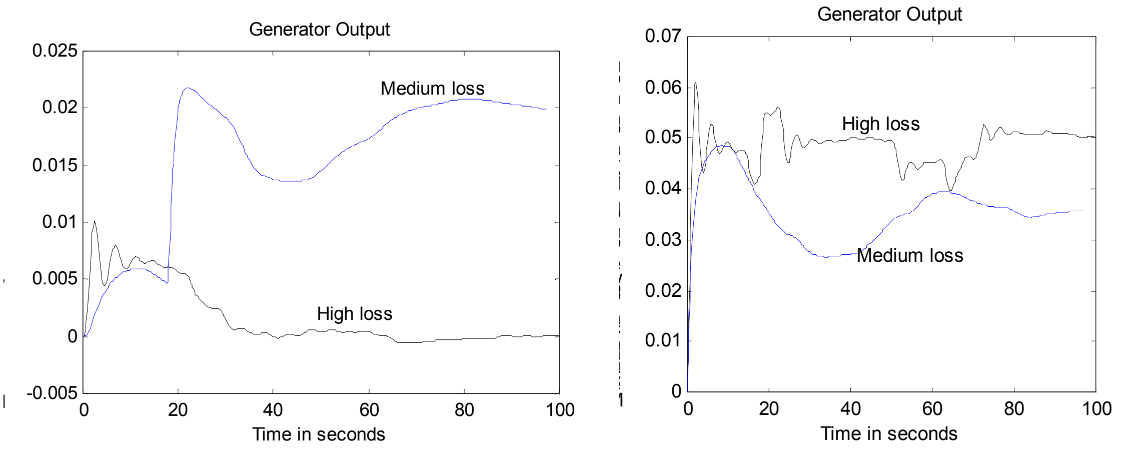

Fig 4.21 Dynamic routing with (a) Output of pure AGC generator (b) Output of the bilateral generator

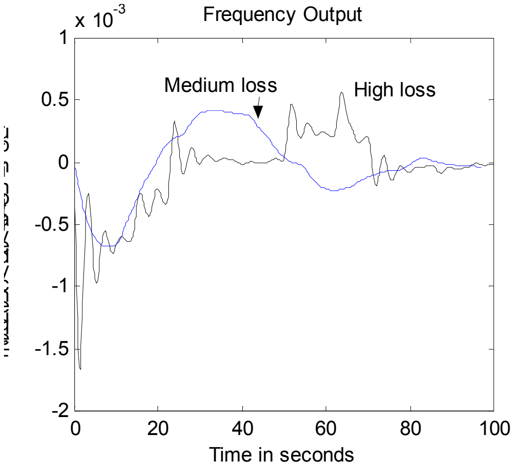

Fig 4.21 (c) Dynamic routing, frequency output

Effect of: **On**	**Traffic Load**	**Loss**	**Link/ Node dynamic**	**Dynamic Routing**
Radial Dedicated	minimal	unsuitable at high loss	-	-
Distributed Radial	minimal	unsuitable at low losses (with medium load)	unsuitable at low loss, low dynamics	Stable with medium loss and medium link/dynamics
Distributed with bilateral	minimal	unsuitable at meduim load	unsuitable at low loss medium dynamics	Depending on location of loss/dynamics performance is either better than or worse than Radial

Table 4.1 Summary of Results

Chapter 5

Conclusions

The ongoing deregulation process in the electricity market is creating a number of new challenges. One of the most urgent is the necessity to develop a widely well-distributed and interconnected communication system that can help the power and ancillary service markets become more competitive as well as to offer new and improved services. Such a communication network inevitably carries some issues related to uncertain signals both in timing and quality. This thesis presents the issues that need to be addressed for the load frequency control, in migrating to a distributed, open communication system. Furthermore, the scope for competitors to jeopardize other individual power entities is much greater, even if the disruptions are unintentional, and these effects must be addressed.

In the near future, the power system's communication system will inevitably face contingencies similar to those presented in the previous section. As shown, a problem in the communication system can compromise the system integrity. Most often the anomaly slows down the system response, but in the worst case, it can lead the system towards instability or other unacceptable behavior. Bounds and characterizations of the network layer delays on the communication system assist in modeling the system and also allows for fault tolerance guarantees to be developed based on the bounds. Delay bounds also help in providing guidelines for intrusion detection and a failure of the system used for LFC control. Bilateral contract participants can also guarantee a quality of service to their customers for their load following. These studies are germane to both the ISO and the bilateral contract participants as they are the most susceptible to delays in the communication system. A reliant and robust communication network with low delays and small delay variation is needed. Emergent technologies, such as, bandwidth reservation and cognizant routing techniques can be used to provide good quality of service for the critical data packets.

Chapter 1 presented the problem of failures in a communication system on the load frequency control service. This is geared towards the fact that the deregulation of the generation sector will bring about the additional distributed communication network requirement. Chapter 2 developed and proposed communication models to be incorporated in the traditional load frequency control model, which currently does not include any model of communication. Chapter 3 stated some additional mechanisms and concerns that need to be implemented and addressed for the proper functioning and maintenance of the load frequency service in a deregulated market. In addition to that, the effects of constant delay and random delays on different LFC topology as well as on different contractual generators was performed. Suggestions were made to incorporate various mechanisms to decrease the ill effects of network behaviour on the load frequency model. Simulations in chapter 4 involving various communication network parameters were performed and the effect on the LFC model were noted, for both a pure centralized LFC as well as scenarios involving bilateral contracts, in distributed network.

5.1 Recommendations for further research:

Several areas are in need of further investigations.

Conditions of the communication network that need to be simulated are:

1) Real LFC system with real communication network parameters
2) WAN (wide area network) simulations including satellite links for geographically distant locations, with emphasis on bilateral contracts.
3) Different protocol strategy at the transport layer for ensuring reliability in signal dissemination.
4) Fault tolerant mechanisms
5) Quality of service for bilateral generators.

6) More realistic models including generator and transmission network constraints [16]. This should put additional constraints on the communication network.

7) Lockstep behaviour of both the communication devices (for example several nodes may fail together instead of independently) and the generators (for the case where more than one generator supplies a given load for a bilateral contract).

Verification of the assumptions used for the models developed in Chapter 2. In this thesis it was assumed that the arrival traffic and vacation arrival has a Poisson distribution for the distributed model. Such an assumption is likely to be limiting

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APPENDIX

A: Glossary of terms

Area Control Error

The instantaneous difference between actual and scheduled interchange, taking into account the effects of frequency bias.

Automatic Generation Control (AGC)

Equipment that automatically adjusts a Control Area's generation to maintain its interchange schedule plus its share of frequency regulation.The following AGC modes are typically available:

Tie Line Bias Control - Automatic generation control with both frequency and interchange terms of ACE considered.

Constant Frequency (Flat Frequency) Control - Automatic generation control with the interchange term of Area Control Error ignored. This AGC mode attempts to maintain the desired frequency without regard to interchange.

Constant Net Interchange (Flat Tie Line) Control - Automatic generation control with the frequency term of ACE ignored. This AGC mode attempts to maintain interchange at the desired level without regard to frequency.

Availability

A measure of time a generating unit, transmission line, or other facility is capable of providing service, whether or not it actually is in service. Typically, this measure is expressed as a percent available for the period under consideration.

Control Area

An electric system or systems, bounded by interconnection metering and telemetry, capable of controlling generation to maintain its interchange schedule with other Control Areas and contributing to frequency regulation of the Interconnection.

B: Queueing Theory Concepts

Little's Theorm:

Let

$N(t)$= Number of customers in the system at time t

$\alpha(t)$ =Number of customers who arrived in the interval [0,t]

T_i =Time spent in the system by the i^{th} customer

$$N_t = \frac{1}{t}\int_0^t N(\tau)\ d\tau \qquad (B.1)$$

which is the time average of $N(\tau)$ up to time t. This changes with time but for most systems of interest N_t tends to a steady state N. That is:

$$N = \lim_{t\to\infty} N_t \qquad (B.2)$$

Similarly, assuming the limit exists for the arrival process

$$\lambda = \lim_{t\to\infty} \frac{\alpha(t)}{t} \qquad (B.3)$$

$$T = \lim_{t\to\infty} \frac{\sum_{i=0}^{\alpha(t)} T_i}{\alpha(t)} \qquad (B.4)$$

which is the steady state time average customer delay. The quantities N, λ, T are related by a simple formula via Little's theorem

$$N = \lambda T \qquad (B.5)$$