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Communication time delay estimation for load frequency control in two-area power system

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A B S T R A C T

Due to increased size and complexity of power system network, the stability and load frequency control (LFC) is of serious concern in a wide area monitoring system (WAMS) having obtained signals from phasor measurement unit (PMU). The quality of services (QoS) for communication infrastructure in terms of signal delay, packet loss probability, queue length, throughput is very important and must be considered carefully in the WAMS based thermal power system. However, very few studies have been presented that includes QoS for communication infrastructure in load frequency control (LFC) of power system. So this paper presents LFC for two area thermal power system based on estimated time delay and packet loss probability using the Markovian approach. The delay and packet loss probability are modeled by different math functions. Normally, frequency deviation signal is transmitted from remote terminal unit (RTU) to control center and from control center to individual control unit of plants. The delay incurred is located in the forward loop of PSO based PI/PID controller in the form of transport delay. To verify the efficacy of controller performance, the estimated constant delay and time varying delay are applied to the controller in the two area thermal–thermal power system with and without governor dead band (GDB) and generation rate constraints (GRC) for various loads conditions. The study is further demonstrated for time delay, being compensated by 2nd order Padé approximation. The results show that frequency deviation is minimum in terms of stability and transient response.

1. Introduction

LFC is one of the major issues in a power system in terms of stability. It has been extensively investigated in past years [1–2]. The basic objective of LFC in integrated power system area is to require the balancing between total generations against total load demand, including system losses. The power system operating point experiences a change, subsequently causing deviation in nominal system frequency and scheduled tie-line power flow to other areas [3]. The area control error (ACE) is used in LFC schemes to achieve the power balance between interconnected areas and thereby maintain the system frequency very close to its nominal value and tie-line power to its schedule value [4].

1.1. LFC in smart grid application

The basic principle of smart power grid forms the networked control system, which interconnects PMUs, actuators and controllers over a communication network to exchange data for monitoring, and control of generators spread geographically in the power system. Consequently, the stable operation of power system relies heavily on the performance of the communication infrastructure. The diversification in data transmission demands a robust and reliable information and communication technology (ICT) infrastructure.

A typical smart grid (SG) wide area network would mainly have two interconnected networks: the core network using

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fiber optics for connecting head offices and substations, and distribution network handling the broadband connectivity to neighborhood networks, automation and monitoring devices. In the case of unavailability of fiber optics, worldwide interoperability for microwave access (WiMAX) technology has its option. The WiMAX is featured with inherent support to different levels of quality of services (QoS). The traditional communication technologies suffer from issues like latency, bandwidth, security, coverage, etc.

On the other hand, cognitive radio (CR) is a promising technology in providing the more advanced communication infrastructure for SG applications. In an SG application, field sensors send real-time voltage and phase observations to remote power generators which estimate the real voltage and take certain actions in order to stabilize it within some desired range [5]. However, due to operating constraints like, bandwidth, interferences, and channel fading, signal transmission usually undergo packet losses and delay which impose strict requirements on the communication protocols as well as estimation and control policies [6–7].

It is well known that communication infrastructure, especially CR which is wireless network, is unreliable because of time delay, packet loss and the communication failure. The existing communication infrastructure, originally developed to address the needs of a regulated electricity industry, cannot address majority of the new challenges to meet the desired objectives in operation of SG. As a result, adequate implementation of modern control and protection schemes cannot be ascertained [8]. Further a detail survey on the Cognitive Radio Networks (CRN) for communication infrastructure in SG, including the system architecture, communication network compositions, applications, and CR-based communication technologies and its potential application of CR based SG is given in [9]. Authors [10] have discussed the system architecture, algorithms and hardware test bed for the CRN based SG system. The cross-layer framework employs CR communication to avoid the unfriendly propagation conditions in power systems and supports QoS for SG applications [11]. Further the authors [12] have presented fundamental challenges in data communication for SG along with CR based communication architecture having three layers of networks; Home Area Network (HAN), Neighborhood Area Network (NAN) and Wide Area Network (WAN) respectively. The use of CR technology in machine to machine (M2M) communication for technical application, industry supports and standardization prospective for SG is presented in [13].

1.2. Motivation and approach

Following a load disturbance, the system frequency deviation/control signals are transmitted in the form of time stamped data packets via dedicated communication infrastructure. Efficient models that provide understanding of communication network in SG are important. The analysis of throughput and delays for communication infrastructure is performed based on M/M/1 queuing theory. The system response degrades if communication channels exhibit delays. Heavy congestion (malicious attack) of communication channel results into constant/random packet delays. Due to congestion in network channel, queue lengths become very large, buffer overflows, packets get delayed during transmission, resulting in incomplete information accesses of a communication network. In addition, the communication channel quality of services (QoS) also deteriorates. This issue opens research challenges with the proposal of wide area monitoring based controller implementation. The challenge exists to integrate computing, communication, and control into appropriate levels of power system operation and control functionalities in a new environment.

Modeling the uncertainties, in terms of time delay, packet loss probability, queue length and throughput is greatly highlighted to confirm that communication infrastructure remains robust under malicious attack. So, it is essential to build an appropriate communication infrastructure, otherwise, system may introduce potential degradation of dynamic and static performance of power system and result in system instability [14–15]. In LFC, due to use of open communication infrastructure and phasor measurement units (PMU) in the wide-area monitoring systems (WAMS), communication delays have become assured and raise concerns about the system steady state and dynamic response [16–17].

Basically, in respect of time delays introduced in control action performed, there are two types of delays encountered in power system. The first one is the direct method based on tracing critical eigenvalues. However, the direct method can handle only constant delays in the system. The method is incapable to cope with time varying delays. The second one is the indirect method based on H-infinity robust synthesis, Lyapunov stability theory and linear matrix inequalities (LMIs) techniques to evaluate the delay margin of the controller. Although in spite of some of its limitation, these techniques could deal with both time-varying and constant delays.

Recently, time delay and packet loss estimation in data communication have drawn much attention in network control system [18]. The researchers [19–23] have reported LFC issue with communication delay based on the linear matrix inequality (LMI) technique, the robust decentralized method and PI type controller. A network delay and communication model for third party LFC strategy is discussed in [19]. Furthermore, the study [24] reported time delay in design of LFC in deregulated environment.

Open communication network is preferred over dedicated ones due to its low cost, simple structure and flexibility. However, these have serious concerns in respect of time varying and random delays. Random delays have varying magnitude usually caused by packet drop out in communication channel [19]. Data packet loss takes place in the wide area monitoring system (WAMS) due to adoption of multiple paths for transmission from source to its destination. Different packets may experience different delays depending upon its path length [25–27]. Recently authors [28–29] have designed an optimal output feedback controller for Automatic Generation Control (AGC) integrated with a doubly fed induction generator (DFIG). The performance of LFC with DFIG for frequency link pricing is reported in [30]. Further the performance of LFC in deregulated environment with the superconducting magnetic energy system (SMES) and DFIG is presented in [31].

Most of the LFC studies in the past have been reported considering constant/random delays with known lower and upper bounds and did not estimate the delay and packet loss probability in their studies. However the above study presents the following shortcomings and given in next paragraph.

Authors [2] have discussed an optimal feedback controller for AGC. The impact of communication delay on LFC problem in deregulated environment is reported in [19]. Authors [20] have proposed an LMI based design of LFC for communication delay. The delay dependent stability for LFC for constant and time varying delay is presented in [22]. The Multi-agent based AGC of isolated stand-alone power system is presented in [23]. The LFC problem for multi area power system using the fuzzy PID controller in deregulated environment is presented in [24]. Further delay dependent study in deregulated environment for LFC is discussed in [32]. Authors [33] have discussed the application of layered ANN technique in AGC of power system. Furthermore, the AGC problem for design of variable structure controller in isolated power plant is discussed in [34].

The above discussion suggests that the QoS for communication infrastructure in terms of time delay, throughput and queue length in LFC problem is not reported in [2,19–20,32]. The authors [22,24,32,33] do not present the general framework in WAMS based LFC in the power system. Time delay estimation and packet loss probability have not been considered in the analysis of LFC [2,23,24,33,34]. Further packet drop out or packet disordering is not reported in [20,22,33,34].

The major contributions towards the control design for LFC problem considering QoS for communication infrastructure are the followings:

- Communication delay and packet loss probability estimation using the Markovian model approach
- Packet drops representation by different mathematical functions.
- Estimation of time delay and packet loss probability investigation over wide range of queue length.
- Assessment on deviation in frequency profile, with the design of PSO tuned controller, considering estimated time delay and comparison against GA tuned and conventionally PI tuned controller.

The rest of the paper is organized as follows. Section II briefly describes the system configuration and model of two area system; Section III is devoted to implementation of CR network and control strategy for estimation of time and packet loss probability and the design of controller, followed by CR network for LFC and effect of communication in LFC. Section IV describes simulation results for frequency deviation with time delays estimated for various load conditions. Finally, concluding remarks are drawn in Section 5.

2. System configuration and its modeling

In this section, the state-space modeling of a two area thermal–thermal (non-reheat type) power systems is given by Eqs. (1)–(9).

$$\Delta\dot{f}_1 = -\frac{1}{T_{p1}}\Delta f_1 + \frac{K_{p1}}{T_{p1}}\Delta P_{t1} - \frac{K_{p1}}{T_{p1}}\Delta P_{tie(1,2)} - \frac{K_{p1}}{T_{p1}}\Delta P_{D1} \tag{1}$$

$$\Delta\dot{P}_{t1} = -\frac{1}{T_{t_1}}\Delta P_{t1} + \frac{1}{T_{t_1}}\Delta P_{g1} \tag{2}$$

$$\Delta\dot{P}_{g1} = -\frac{1}{R_1 T_{g_1}}\Delta f_1 - \frac{1}{T_{g_1}}\Delta P_{g1} + \frac{1}{T_{g_1}}u_1 \tag{3}$$

$$\Delta\dot{f}_2 = -\frac{1}{T_{p2}}\Delta f_2 + \frac{K_{p2}}{T_{p2}}\Delta P_{t2} - \frac{K_{p2}}{T_{p2}}\Delta P_{tie(1,2)} - \frac{K_{p2}}{T_{p2}}\Delta P_{D2} \tag{4}$$

$$\Delta\dot{P}_{t2} = -\frac{1}{T_{t_2}}\Delta P_{t2} + \frac{1}{T_{t_2}}\Delta P_{g2} \tag{5}$$

$$\Delta\dot{P}_{g2} = -\frac{1}{R_2 T_{g_2}}\Delta f_2 - \frac{1}{T_{g_2}}\Delta P_{g2} + \frac{1}{T_{g_2}}u_2 \tag{6}$$

$$\Delta\dot{P}_{tie} = 2\pi T^0\Delta f_1 - 2\pi T^0\Delta f_2 \tag{7}$$

$$ACE_1 = B_1\Delta f_1(t-\tau_d) + \Delta P_{tie(1,2)} \tag{8}$$

$$ACE_2 = B_2\Delta f_2(t-\tau_d) - \Delta P_{tie(1,2)} \tag{9}$$

The Eqs. (1)–(9) can be arranged in a state-space form as:

$$\dot{x} = Ax + Bu + \Gamma d \tag{10}$$

where A (9×9) is the state matrix, B (9×2) is the control matrix and Γ (9×2) is the disturbance matrix.

The states; Δf_2deviation in area frequency, ΔP_{t1} ΔP_{t2} generator mechanical output, ΔP_{g1} ΔP_{g2} valve position, ΔP_{D1} ΔP_{D2}, load disturbance in a two area system. The parameters; T_{ti}, T_{gi} & R_i are the moment of inertia of generator unit, damping coefficient of generator unit, governor time constant, turbine time constant and speed droop respectively.Here, $\frac{1}{K_{pi}} = D_i$ & $\frac{T_{pi}}{K_{pi}} = M_i$, subscript i refers to area 1 and 2. B_i Frequency bias factor,ACE_i the area control error (ACE), the tie-line power exchange and is tie-line synchronizing coefficient between area 1 and area 2. The ACE for each area is defined as linear combination of tie-line power exchange between two areas and frequency deviation. The generators are assumed to be equipped with non-reheat type turbine but can be modeled in similar way. Eqs. (8) and (9) include the delay in transmission of frequency deviation signal between the plant and controller. The ACE signal combined with the delayed area frequency deviation and the net tie-line power exchange is used as the input to the controller. The delay incurred in the forward loop of controller is considered in the form of transport delay$e^{-s\tau_d}$. The block diagram of system in study is depicted in Fig. 1. The parameters of conventional two areas LFC system [32] are given in Table 1A in Appendix section.

Governor dead band (GDB): The inherent nonlinearity in the dynamics of power system is included in the model. The GDB is represented as:

$$GDB = 0.8x_i - \frac{0.2}{\pi}\dot{x}_i$$

where x_i is the state-variable and i stands for an area-1 & 2.

The valve position remains unchanged during the sustained speed change in governor. The backlash nonlinearity trends to produce a continuous sinusoidal oscillation of a natural period of about 2 s [33].

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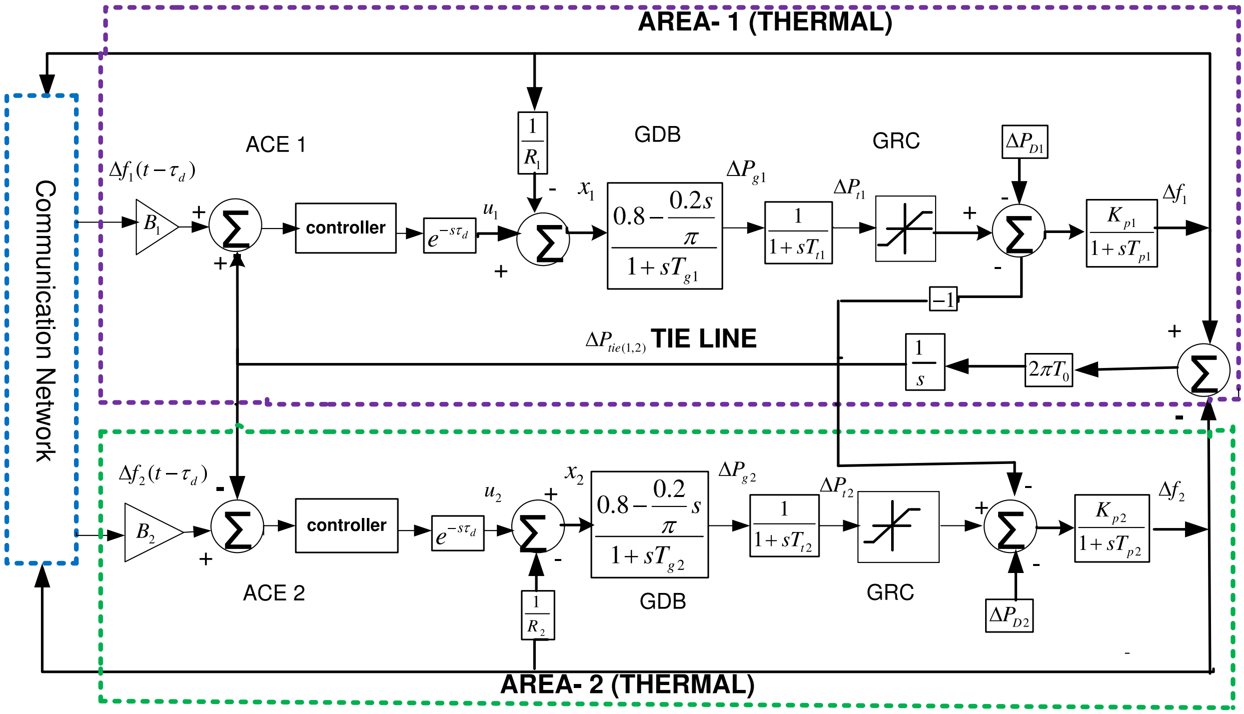


Fig. 1. Proposed LFC scheme for two area thermal–thermal power system with communication infrastructure.

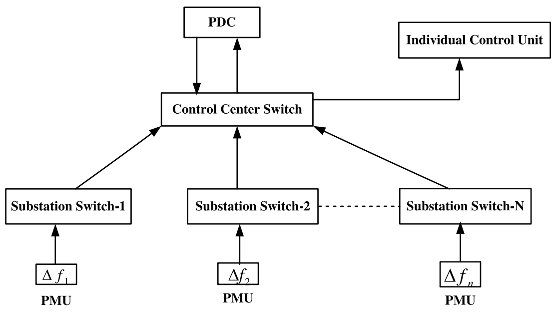
***Generation rate constraints (GRC)*:** With GRC included in the model, the dynamic response is affected in terms of settling time and larger overshoot as compared to without GRC in the system [34]. The generation rate 0.1 p.u.MW/min i.e. 0.00017 pu MW/s [34] is considered in study.

3. Implementation of cognitive radio network and control strategy

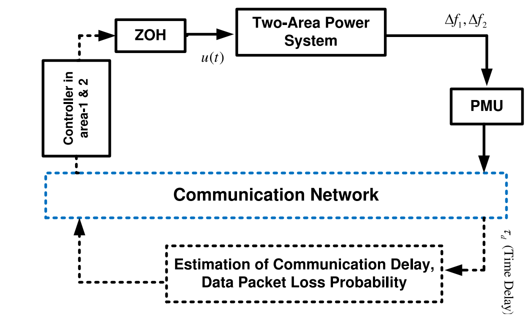
The communication delay in wide-area power system arises from communication channels during transmission of signals from RTU to control center and again from control center to individual units [32]. This needs systematic embedding of cyber technologies capable of monitoring, communicating, and controlling the physical components of power system [35]. The modeling strategy should include the impact of communication networks and cyber components with respect to the significant information of the physical system [36]. The communication delays are not constant and depend on the information system loading [37]. The wide area monitoring application and the adverse effect of signal delay is considered for the analysis of DFIG based wind farms in [38]. So it is essential to build a suitable networked control system (NCS), defining a new paradigm for operation of power system. The functionality of NCS depends on capabilities of communication information technology [39]. Further a detail literature review of synchrophasor measurement technology in power system is presented in [40]. In WAMS, for power system applications, PMUs and other data sources of every substation are linked to each other via a communication network as illustrated in Fig. 2. The block diagram of a PMU-PDC communication network for the *i*th area- power system is illustrated in Fig. 2(a). The network sends the measurement and control signals in the form of packets. The PMUs are time driven and sends periodically measured packets to control center. The control center switch will route the packets from PMUs to phasor data concentrator (PDC). A data packet traveling via network suffers not only transmission delay, but also possibly packet loss. Packet losses occasionally occur due to node failures or message collisions in network. Thus, packet dropout is another factor affecting the NCS's performance. The compensation required for packet loss in NCS can be achieved through its accurate prediction or computation of packet loss rate [41]. Fig. 2(b) illustrates the NCS scheme having estimation of time delay and packet loss probability for two area power system. In the said figure, PMU and other devices such as PDC are time driven while ZOH is event driven. Dashed and solid lines represent the discrete-event and continuous-time domain signal respectively. The frequency deviation data of each control area is sampled by PMUs and then sent via communication network in the form of packets. This follows the packet loss probability and time delay estimation. Subsequently, control action in two control areas of the power system is performed.

3.1. Estimation of delay and packet loss probability using the Markovian approach

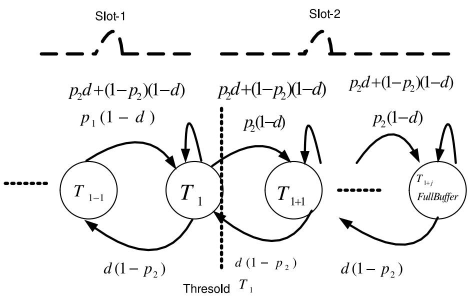
In WAMS based monitoring and control of large power system, a communication infrastructure is indispensable. Since PMUs generates data at a constant rate, it is assumed that interval times of packets from PMUs is constant. If the packet is either not received by pre-defined dead line or received later, it is treated as packet loss. To compensate packet



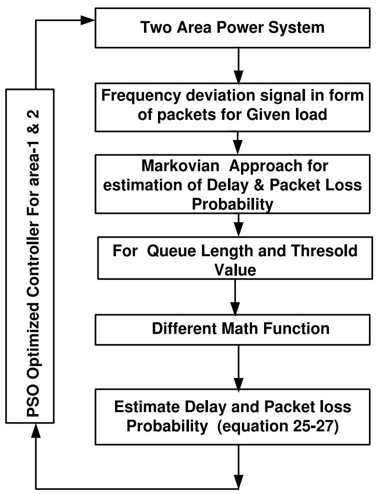
(a) PMU-PDC communication network for ith area power system



(b) NCS for two-area power system control with estimation of time delay and packet loss



(c) Markovian chain state transition diagram with thresold value



(d) Flow chart of Markovian approach for estimation of time delay and packet loss probbaility

Fig. 2. Architecture for WAMS with communication infrastructure.

loss, the basic idea of queuing modeling is adopted. Parameters such as throughput, time delay and probability of packet loss can be used as performance measures for communication infrastructure. Discrete-time Markov chain transition offers a procedure to estimate the amount of time delay introduced during the transmission of signal.

The stochastic packet loss is called the Markovian packet loss if it is conducted by discrete time homogeneous Markov chain on a complete probability space (Ω, R, P) and takes the value in finite sequence with following transition probabilities [18].

$$\pi_{ij} = P_r\left[\zeta_{k+1} = \frac{j}{\zeta_k} = i\right] \geq 0 \forall i, j \in R \tag{11}$$

where for each $I \in R$, N is the upper bound.

The transition probability matrix is defined as:

$$\pi = \begin{bmatrix} \pi_{11} & \pi_{12} & \dots & \pi_{1N} \\ \pi_{21} & \pi_{22} & \dots & \pi_{2N} \\ \vdots & \vdots & \vdots & \vdots \\ \pi_{N1} & \pi_{N2} & \dots & \pi_{NN} \end{bmatrix} \tag{12}$$

In this approach, the frequency deviation signal of each area in terms of packets is transmitted via communication infrastructure to controller. During transmission of signal from RTU to control center, packet loss and time delay are incurred in the system. Therefore it is indispensable to model time delay and packet loss during controller design of a system. Further for analysis purpose it is assumed that probability of packet (in terms of frequency deviation signal) arrival is described by p_1 before the threshold value T_1 and p_2 after the threshold value T_1, where d is the probability of packet departure. The probability of no packet arrival and no packet departure is described by $(1 - p_1)$ and $(1 - d)$ respectively. The probability of no packet arrival at the threshold value greater than or equal to is given by$(1 - p_2) = (1 - p_1(1 - D))$. The Markov chain state transition diagram for frequency deviation signal as packets with threshold value is shown in Fig. 2(c).

In case, if the buffer level capacity to accommodate packets reaches to a value greater than or equal to threshold value, some of the packets are dropped with some amount of probability and represented by a mathematical function D. The packet arrival rate from T_1 upto T_1+J is p_2, represented by $p_1(1 - D)$. When packets are dropped with some amount of probability, the packet loss is given by $(1 - D)$. The following steps are required to obtain the estimation of delay and packet loss probabilty for frequency deviation signal using markovian approach.

Step-1: From the state transition diagram, the following equiliburim probablity equation is derived assuming $p_1 < d$ for the stable system.

$$\pi_0 = \pi_0(1 - p_1) + \pi_1(d(1 - p_1)) \tag{13}$$

$$\pi_1 = \pi_0(p_1) + \pi_1[p_1 d + (1 - p_1)(1 - d)] + \pi_2(d(1 - p_1)) \tag{14}$$

So for genreal case,

$$\pi_i = \pi_{i-1}[p_1(1-d)] + \pi_i[p_1 d + (1-p_1)(1-d)] + \pi_{i+1}(d(1 - p_1))\text{for}i = 2, 3 \ldots \text{T}_1 - 2 \tag{15}$$

$$\pi_{T_1-1} = \pi_{T_1-2}[p_1(1-d)] + \pi_{T_1-1}[p_1 d + (1-p_1)(1-d)] + \pi_{T_1}[d(1-p_1)(1-D)] \quad (16)$$

Similarly π_{T_1} and π_{T_1+1} can be computed as above from (16)

Step–II: Solve the above equilibrium probability Eqs (13)–(16) for each value of π_i for $i = 1, 2, \ldots, T_1 + J$ with respect to π_0 using the mathematical value for π_1, $\pi_2, \ldots, \pi_{T_1+J}$

Step–III: From the normalized equation $G(Z) = \sum_{i=0}^{T_1+J} \pi_i z^i$ and the results in step II, solve the value for π_0:

$$\pi_0 = (1-d)(1-\gamma_1)(1-\gamma_2)(1-p_1(1-D))/Q \quad (17)$$

where Q is given by (18)

$$Q = (1-\gamma_2)(1-p_1(1-D))(1-{\gamma_1}^{T_1} - d(1-\gamma_1)) + {\gamma_1}^{T_1}(1-\gamma_1)(1-p_1)(1-{\gamma_2}^{J+1}) \quad (18)$$

where

$$\gamma_1 = p_1(1-d)/d(1-p_1) \quad (19)$$

$$\gamma_2 = p_2(1-D)(1-d)/d(1-p_1(1-D)) \quad (20)$$

Step–IV: For given queue length using the probability generating function obtained in step (II), to calculate the value of $G(Z)$.

$$G(Z) = \sum_{i=0}^{T_1+J} \pi_i z^i \text{ For } i = 1,\ 2, \ldots, T_1 + J. \quad (21)$$

Step–V: To calculate the mean queue length (MQL), find the first order derivative of (21) by substituting$Z = 1$, which is given as:

$$MQL = G'(1) \quad (22)$$

Step–VI: To find the average time delay in transmission of frequency deviation signal of each area in forms of packets to control center. This can be computed on the basis of queuing theory concept as discussed below.

Little's rule: With help of little's rule [42] average time delay of packet can be calculated:

Let us assume that $F(t)$ is number of frequency deviation packet in the system at time t. And $\alpha(t)$ is the total number of packets which reached in the interval$[0, t]$.T_i is the time spent by the ith packet in the system.

$$F_t = \frac{1}{t}\int_0^t F(\tau)d\tau \quad (23)$$

where F_t is the average time of $F(\tau)$ up to time t. Eq. (23) varies with time but for most of the cases of system interest, F_t tends to steady state F, where $F = \lim_{t\to\infty} F_t$

Similarly, limit exists for arrival process of packets

$$\lambda = \lim_{t\to\infty} \frac{\alpha(t)}{t} \quad (24)$$

The steady state time of average packet delay,

$$T = \lim_{t\to\infty} \frac{\sum_{i=0}^{\alpha(t)} T_i}{\alpha(t)} \quad (25)$$

The quantities F, λ, T are related as $F = \lambda T$ known as Little's rule.

Throughput is the total number of successful transmission of frequency deviation signal in the form of packet to control center and given as

$$S = (1-\pi_0)/d \quad (26)$$

Step-VII: The probability of packet loss (PL) is defined as the fraction of frequency packet that arrives to find no waiting place to accommodate them. This is true when waiting place in the system is finite. The PL is given by:

$$PL = D\sum_{i=L_1}^{T_1+J-1} \pi_i + D\pi_{T_1+j}d + \pi_{T_1+j}(1-d) \quad (27)$$

where $i = T_1, T_1+1, \ldots, T_1+J$

D is the packet dropping function introduced to determine the probability of packet loss and delay. The probability of packet loss is increased from 0 to $1-D$.

In this study, a step reduction in frequency packet arrival rate from p_1 to $p_2 = p_1(1-D)$ is considered by dropping some of the packets, once the packet reaches a threshold value greater than or equal to T_1. The reduction in packet rate is modeled by following different packet dropping functions (D):

Function 1 (F1): Exponent Function $(a)^f$, $0 < a < 1$
Function 2 (F2): Logarithmic function $\log(f)^a$, $a < 0$
Function 3 (F3): Multiplication of function by constant $(a^* f)$ for all real value.
Function 4 (F4): Power of function $(f)^a$, $a < 0$

The flow chart illustrating the transmission of frequency deviation signal in form of packets through PMUs to control center and estimation of delay and packet loss is shown in Fig. 2(d). In the scheme, first measure the frequency deviation caused due to load disturbance, followed by estimation of packet loss probability and time delay using the Markovian approach with different math functions for given queue length, threshold value of data, arrival and departure of packet data. Next, with estimated time delay, control action is applied to the power system in order to minimize the frequency deviation.

3.2. Cognitive radio (CR) network for load frequency control

CRN is a promising technology in the development of future SG. In CR network, there are two types of users, i.e. primary and secondary user. Primary users have licensed spectrum in the existing network, while secondary users may have the access to the spectrum without compromising QoS delivered to primary users. The major challenge is to maintain desirable QoS at primary users while providing sufficient level of transmission rate to the secondary users.

So communication infrastructure can be used as CR network for monitoring and controlling of power system. The

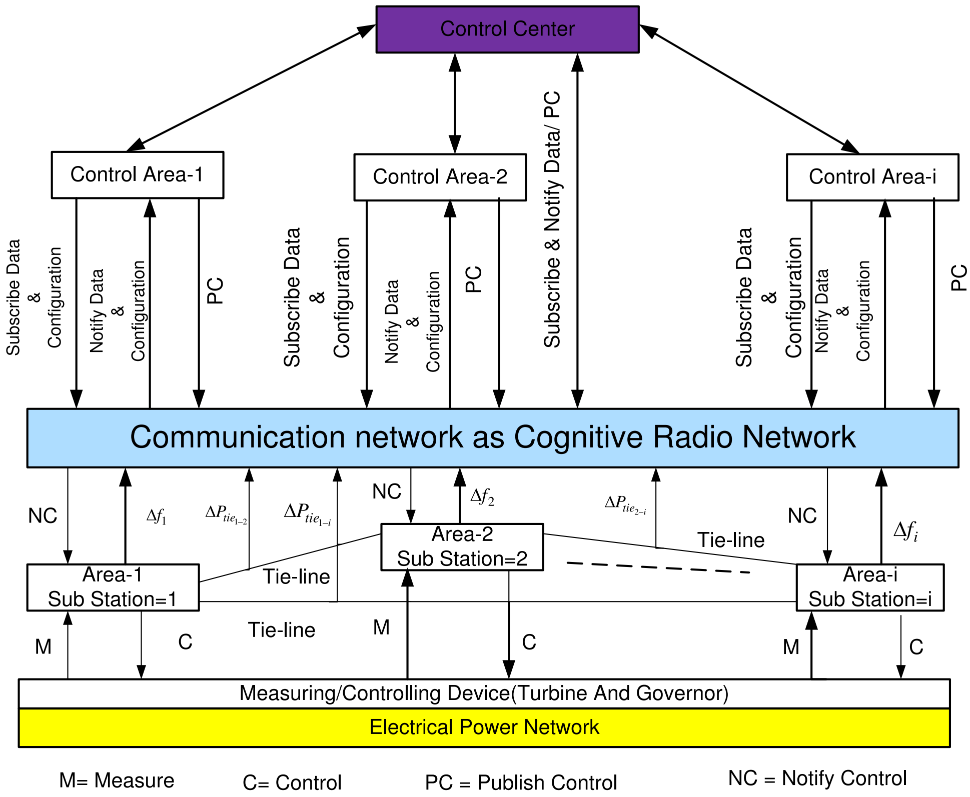


Fig. 3. Illustration of CR network for ith area power system.

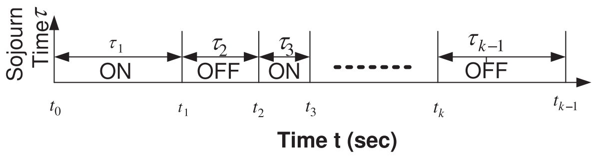


Fig. 4. Cognitive channel model for arbitrary sojourn time.

main objective of CR network is to utilize the licensed spectrum efficiently in a current network and design an optimal CR network protocol for enhancement of Quality of services (QoS) including maximum time delay and success rate of delivered packet. The random interruption of secondary user data will cause packet loss and delay. Due to incur of packet loss, time delay introduced have significant impact on the control performance in power system. Therefore, it is important to establish a systematic approach to take into account the time delays in power system control.

The illustration of CR network for automatic generation control (AGC) is given in Fig. 3. From the said figure, we can observe that there are two loops of data transmission, first one is control center to RTUs and second one is data transmission from RTUs to control center over CR network. In a communication network during transmission of control signal from remote terminal unit to control center and then from control center to individual unit some amount of packet loss and delay is incurred in transmission of signal.

Recently, the authors [43] have reported that the wireless local area network channels exhibit a semi-Markovian property during transition between the idle and busy states. Accordingly, this model concept is utilized to characterize the primary user channel activities. The primary user activity is driven by an ON-OFF process such that each primary user generates data only during the ON-periods. On the other hand, secondary users are assumed to generate data packets in each slot according to a Poisson distribution. The communication with arbitrary sojourn time for CR network is given in Fig. 4. It is clear that communication network for transmission of data is either ON or OFF. So we can consider a communication channel as an ON/OFF switch, where 0 and 1 represents the OFF and ON state of communication channel respectively. So from above discussion it is obvious that we can model the AGC as a switch models. If the disturbance matrix of Eq. (10) is zero then we can represent the system as:

$$\dot{x} = Ax + Bu \tag{28}$$

Above equation can be converted into sampled discrete time system

$$x(k+1) = A_p x(k) + B_p u(k) \tag{29}$$

where $A_p = e^{Ah}, B_p = \int_0^h e^{A\tau} Bd\tau$,where h is the sampling period.

Further channel state at kth instant is described as $\alpha_k = \{0\ \ 1\}$

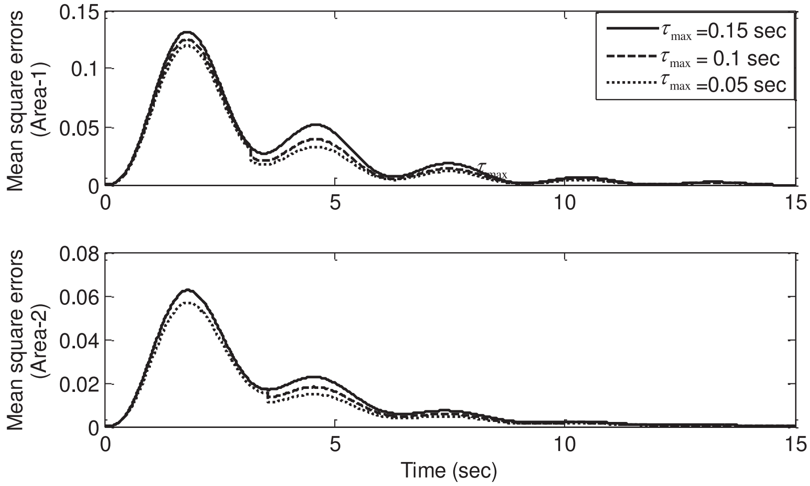
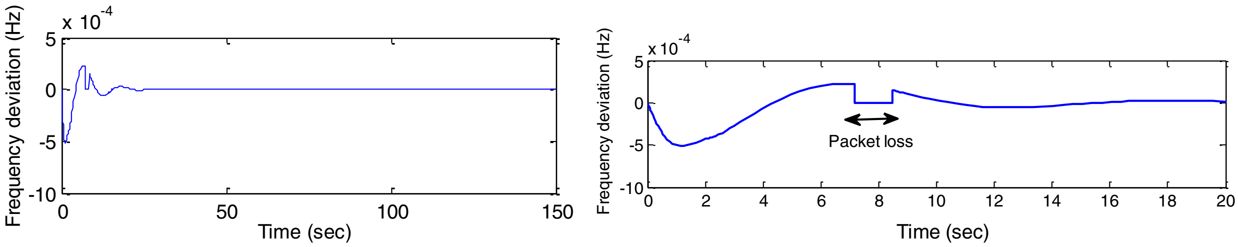


Fig. 5. Mean square error of power system states for arbitrary sojourn time.



(a)Detail Plot (b) Zoomed Plot

Fig. 6. Frequency deviation of area 1 with packet loss and delay.

Again considering the time interval between two consecutive instant$l \in [t_k, t_{k+1})$, the state feedback controller in a switch form can be represented as

$$u(l) = \begin{cases} Kx(l), & \alpha t_k = 1 \\ Kx(t_k), & \alpha t_k = 0 \end{cases} \tag{30}$$

By substitution of value $u(l)$into Eq. (29), the power system state can be represented in switch form during time interval $l \in [t_k, t_{k+1})$

$$x(l+1) = \begin{cases} (A_p + B_pK)x(l), & \alpha t_k = 1 \\ A_px(l) + B_pKx(t_k), & \alpha t_k = 0 \end{cases} \tag{31}$$

The sojourn time is time dependent, and can be represented as $\{\tau_1 \quad \tau_2 \quad \ldots \quad \tau_i \quad \ldots \quad \tau_{k+1}\}$, where $\tau_i = t_{i+1} - t_i$

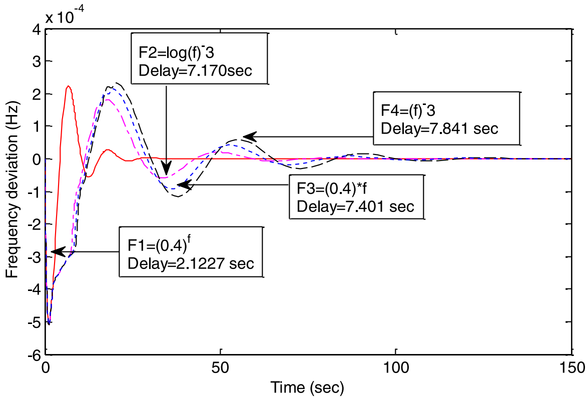
Theorem 1. [44]: *The power system (31) is globally asymptotically stable for arbitrary sojourn time $\tau_i \in [\tau_{\min}, \tau_{\max}]$, $i \in \{0 \quad 1 \quad 2 \quad 3 \quad \ldots \quad k+1\}$ if all eigenvalues of the matrices $(A_p{}^{\tau_i} + \sum_{r=0}^{\tau_i - 1} A_p{}^r B_p K)$ are inside unit circle.*

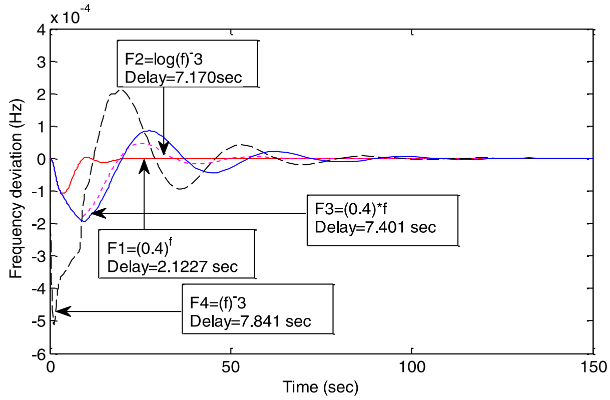
From above theorem, we can find the largest value of sojourn time $\tau_i \in [\tau_{\min}, \tau_{\max}]$, where $\tau_{\max}$ is the maximum value of τ_i having maximum eigenvalue lying outside the unit circle for the first time.

Maximum eigenvalues of matrices with different sampling period are given in Table 1B in Appendix. From the table we can find largest value of sojourn time over wide range of sampling period for which the power system remains stable. Bold-faced value in table suggests the first time instance when maximum eigenvalues of system lies outside of unit circle.Since the state estimation relies on the information received from PMUs, packet losses in data transmission strongly affect the estimation performance [45]. In order to investigate the estimation performance, mean square error (MSE) is computed with maximum sojourn time considered as shown in Fig. 5. We can observe that system state estimation becomes sluggish with selection of higher value of maximum sojourn time.

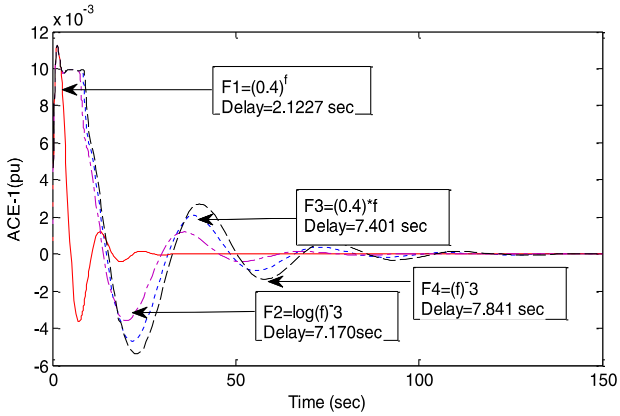
3.3. Compensated communication time delay

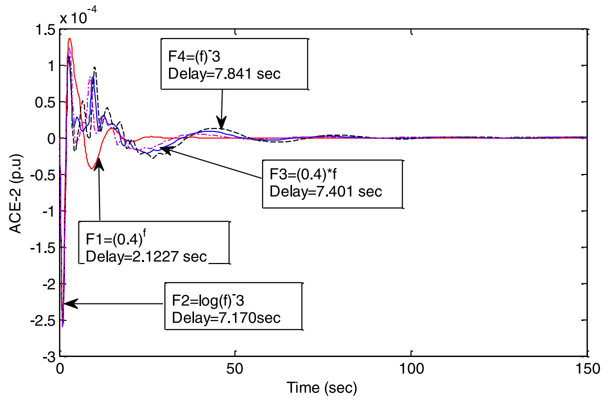
The conventional LFC model is reformed to include communication delays. The communication delay can be expressed by the exponential function $e^{-s\tau}$ where τ defines the estimated communication delay time. These delays are considered on two main communication links. First is the time delay introduced in the measured frequency and power flow through RTUs/WAMS up to control center and second delay lies in between control center output to individual



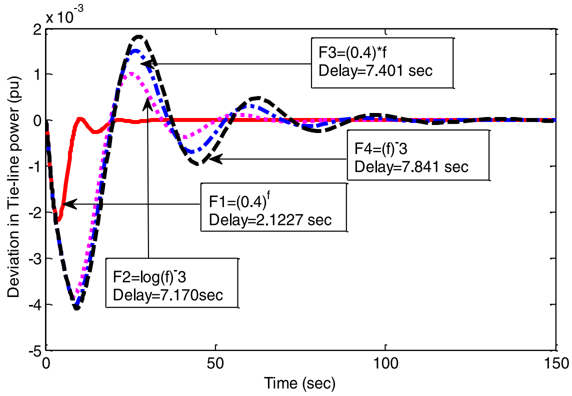


(a) Frequency deviation: (i) Area 1 (ii) Area 2





(b) Area control error: (i) Area 1 (b) Area 2

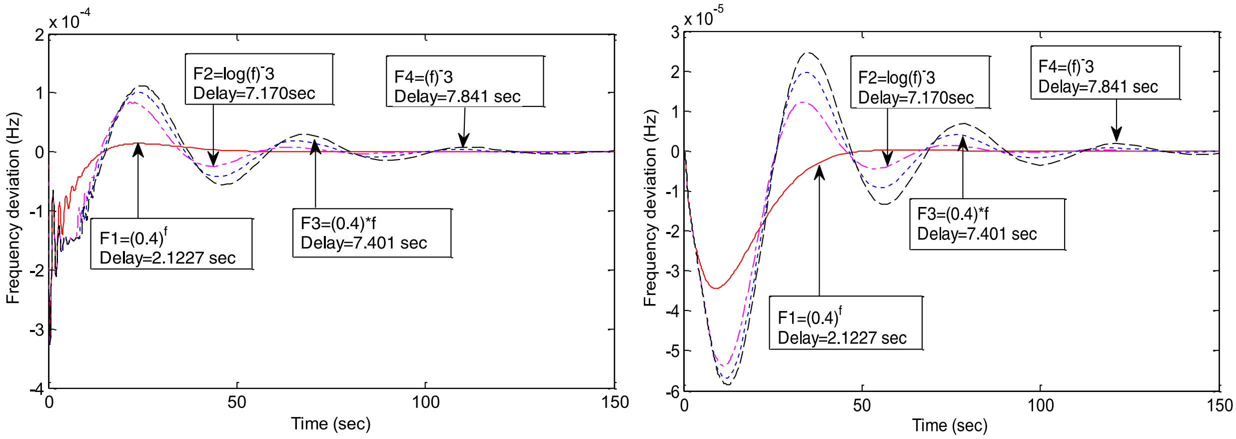


(c) Tie-line power deviation

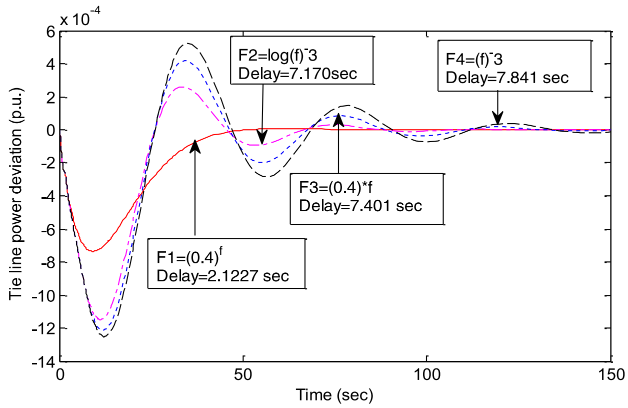
Fig. 7. System response optimized by the PI controller, with time delay estimated by different functions.

generation units. Following a load disturbance with in the control area, the system frequency undergoes a transient change and the feedback mechanism acts to generate appropriate control signal to make generation output follow the load demand. The balance between the control areas is achieved by measured frequency and power deviation via communication link to generate the signal optimized by particle swarm optimization (PSO) based the PI controller. The PSO technique is applied to obtain optimized PI controller gains. The PSO algorithm and analytical calculation of PSO are not discussed in his paper and can be referred from [46]. The optimized parameters of PSO based PI control, GA based PI control and conventional PI controller are given in Table 1C in Appendix. After optimization the value of controller gain is computed for area 1 and area 2.

$$u_1(t) = \left[k_{p1}ACE1 + k_{i1}\int (ACE1)dt\right] \quad (32)$$



(a) Frequency deviation: (i) Area 1 (ii) Area 2



(b) Tie-line power deviation

Fig. 8. System response optimized by the PID controller, with time delay estimated by different functions.

$$u_2(t) = \left[k_{p2}ACE2 + k_{i2}\int (ACE2)dt\right] \tag{33}$$

Objective function for the PSO based PI/PID controller is given as

$$PI = \frac{1}{2}\int_0^{150} (B_i{}^2\Delta f_i^2 + \Delta P_{tie}^2) \tag{34}$$

where i=1, 2 for area 1 and area 2.

4. Simulation results and discussion

In this section, numerical simulation results are discussed for different load conditions with estimated packet loss probability and time delay. The parameters of PI controllers are optimized by the PSO algorithm. The delay and packet loss probabilities are first estimated with discrete Markovian approach using different math functions. Later, the estimated time delay is used in the simulation with controllers for the minimization of frequency deviation profile, area control error and tie line power deviation. Different case studies have been applied to system and their responses are given in following sections.

4.1. Case-I: step change in load

A 0.01 pu step change in load is applied to two area thermal–thermal power system and frequency deviation is obtained to estimate time delay and packet loss probability using the Markovian approach. The frequency deviation of area 1 with time delay (2.12 s) and packet loss for function (F1) is shown in Fig. 6. The frequency deviation of area 1 and area 2, with time delay estimated by different functions perturbed by 0.05 pu step load change is shown in Fig. 7. The delay computed from different functions is also indicated. It is determined to be maximum (7.841 s) for function (F4) and minimum (2.1227 s) for function (F1). The maximum time delays determined from F2 and F3 is 7.170 s and 7.401 s respectively (Fig. 7(a)). It is found that estimated time delay varied in wide range with different math functions. The area control error is shown in Fig. 7(b). The PSO tuned PI controller is able to control the controlled variable having a large time delay. Tie-line power deviation is illustrated in Fig. 7(c). Overall frequency deviation in both areas is minimum in terms of settling time with different delays present in the system. Next, the frequency deviation and corresponding tie-line power deviation obtained by optimized PID controller is

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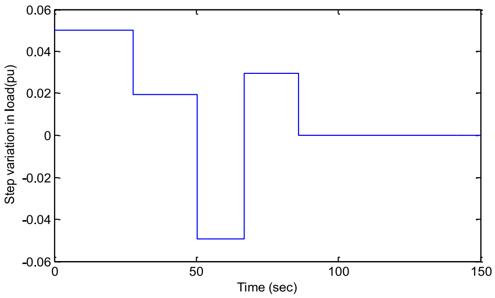
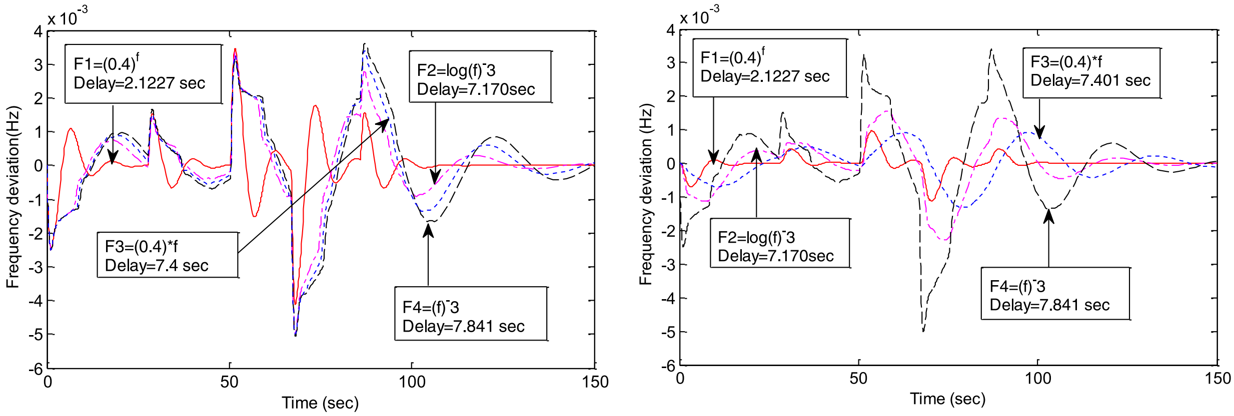
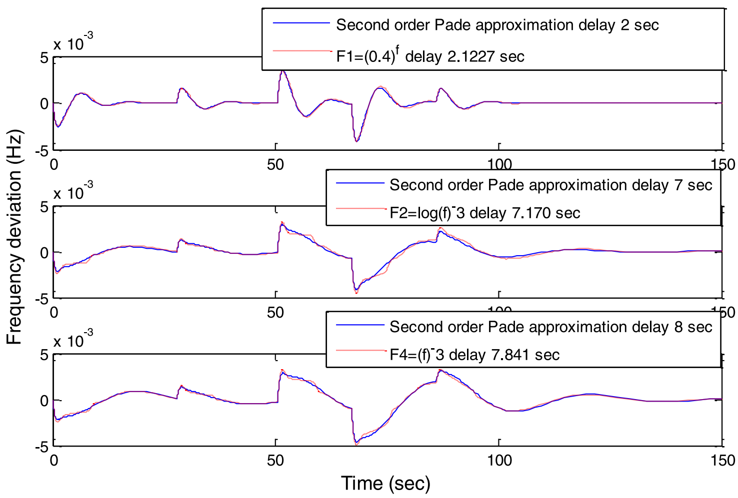


(a) Step variation in load



(b) Frequency deviation: (i) Area 1 (ii) Area 2



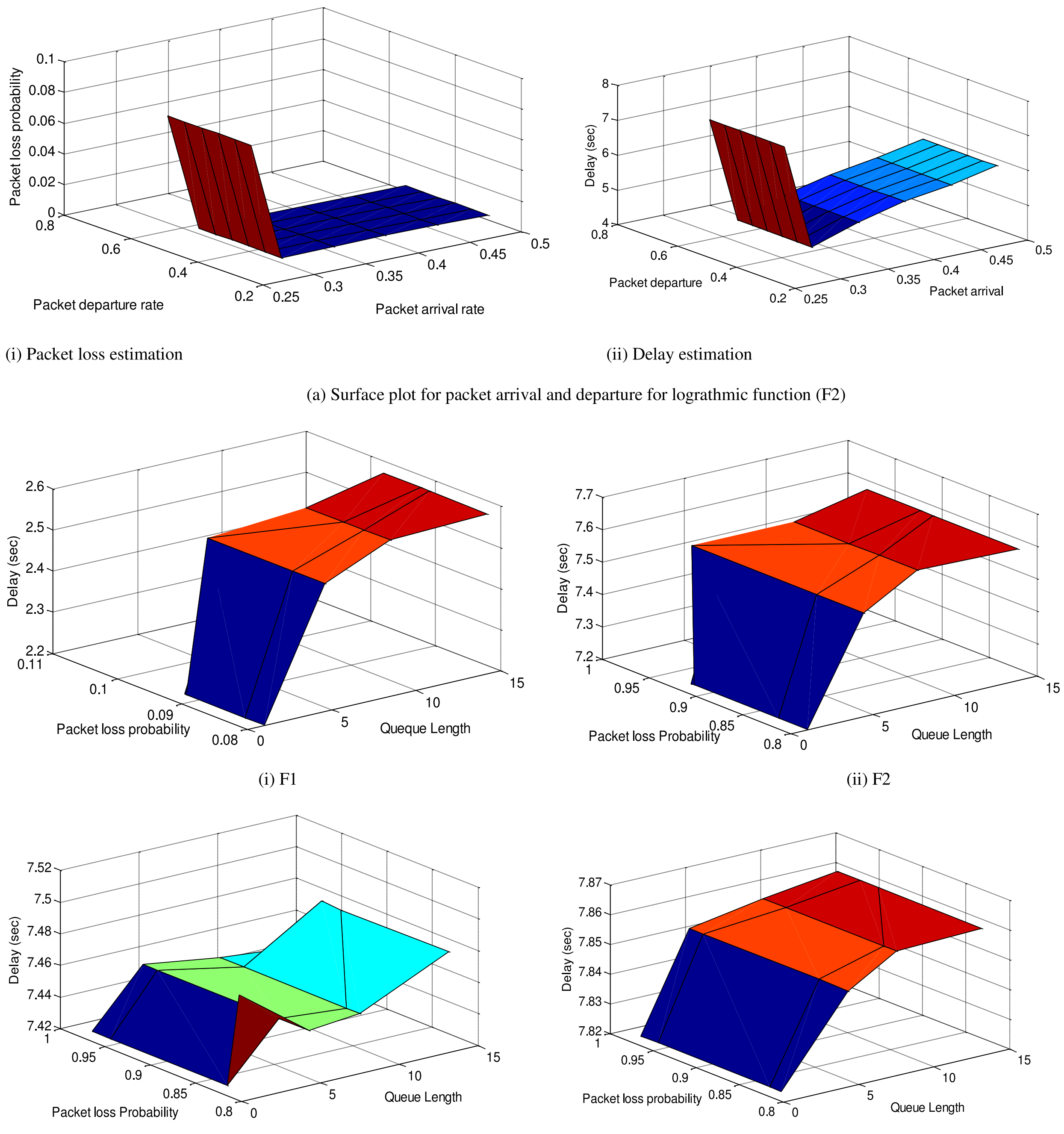
(c) Comparative frequency deviation in Area 1

Fig. 9. Frequency deviation with random load change.

illustrated in Fig. 8(a) and (b) respectively. It can be seen that responses achieved by two controllers are satisfactory.

4.2. Case-II: random step change in load

The system performance is demonstrated for random load present in power system with estimated delay. The estimated delay is incorporated with system controller to minimize the frequency deviations. The step variation in load is given in Fig. 9(a). Their corresponding frequency deviation is given in Fig. 9(b). It can be observed that frequency deviation associated with small time delay, i.e. 2.1227 s estimated by function F1 undergoes reduced undershoot/overshoot. On the other hand while those obtained by other functions; F2–F4 is accompanied with predominantly large overshoot/undershoot



(i) Packet loss estimation

(ii) Delay estimation

(a) Surface plot for packet arrival and departure for lograthmic function (F2)

(i) F1

(ii) F2

(iii) F3

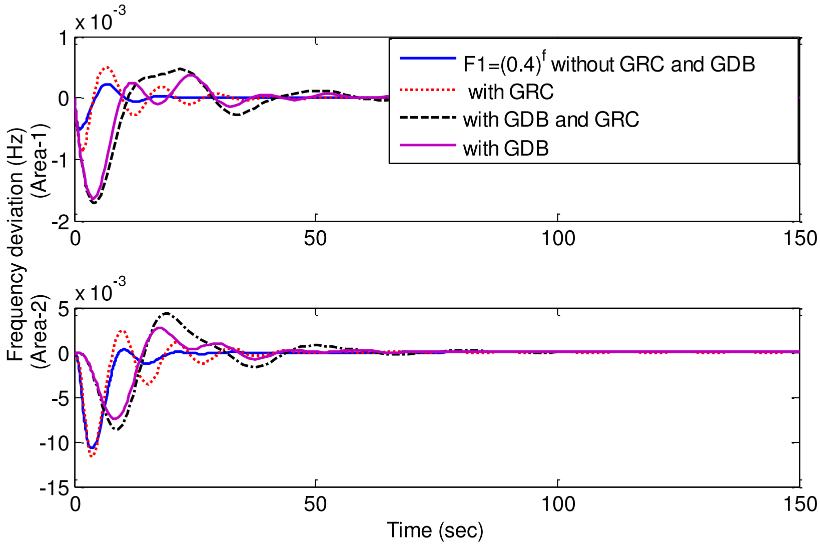
(iv) F4

(b) Surface plot for time delay estimation

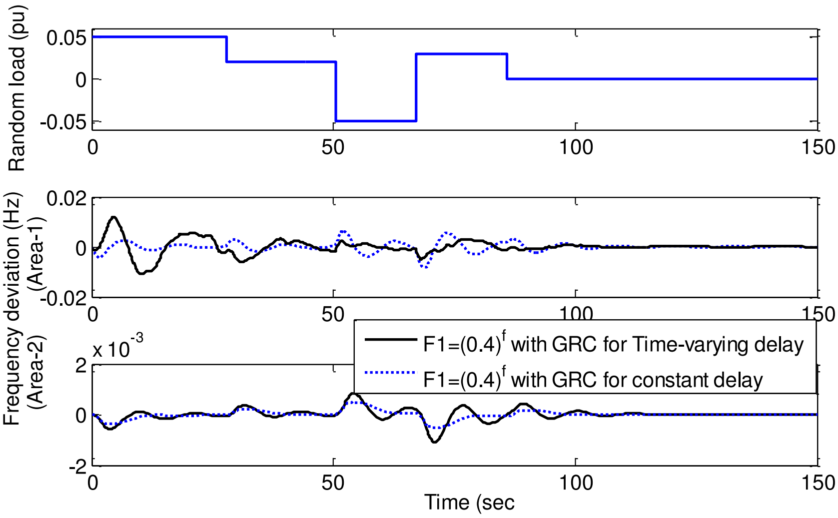
Fig. 10. Investigation of packet loss and time delay estimation by different functions.

for same pattern of load disturbances. Furthermore, as observed, the primary function of controller is performed effectively.

In most practical cases, it is impractical to compute the time delay up to 3 decimal places as computed analytical by these functions. The delay associated with transmission of wide-area signals expressed as $e^{-s\tau_d}$ can be also modeled by 2nd order Padé approximation [40]. To evaluate the comparison, different values of $\tau_d = 2,\ 7,\ 8$ *sec* are considered in simulation. This is shown in Fig. 9(c) for frequency deviation in area 1. The comparative simulations suggest that the frequency deviation responses obtained by the controller are nearly similar. In other words, time delay according to packet loss probability in remote signal, being estimated by



(a) GDB and GRC for estimated constant delay



(b) GRC with constant and time varying delay

Fig. 11. Frequency deviation with nonlinearites included in the system.

different functions; F1–F4, and one the approximated by 2nd order Padé approximation resemble each other. This in turn validates the estimated time delay corresponding to packet loss probability by these functions.

4.3. Case III: packet loss and time delay estimation by different mathematical functions

The impact of packet arrival/departure rate of frequency deviation signal on packet loss probability (i.e. packet dropping)/delay is investigated for load disturbance of 0.05 p.u. The maximum queue length = 20 and threshold $T_1 =$ [1, 2… max queue length] for function F2 is considered. Fig. 10 shows the variation of loss probability and delay. The probabilities of packet loss decrease, i.e. lower packet loss is achieved for a wide range of packet arrival rate as observed in Fig. 10(a)(i). The variation in estimated time for given packet arrival rate is illustrated in Fig. 10(a)(ii). The estimated time delay follows similar trend as packet loss probability for a low range of packet arrival rate, i.e. upto. 0.35. On the other hand, as time of arrival of packet is increased, the corresponding delay also increases.

Next, the performance measures of communication infrastructure in terms of probability of packet loss, queue length and delay by introducing different packet dropping functions; F1–F4 is analyzed. The variation of queue length affects the packet arrivial and departure rate for the different function and hence some amount of packet loss probability and delay incurred in the system. In case, if the system buffer level capacity to accommodate packets reaches to a value greater than or equal to queue length, some of the packets are dropped with some amount of probability and transition

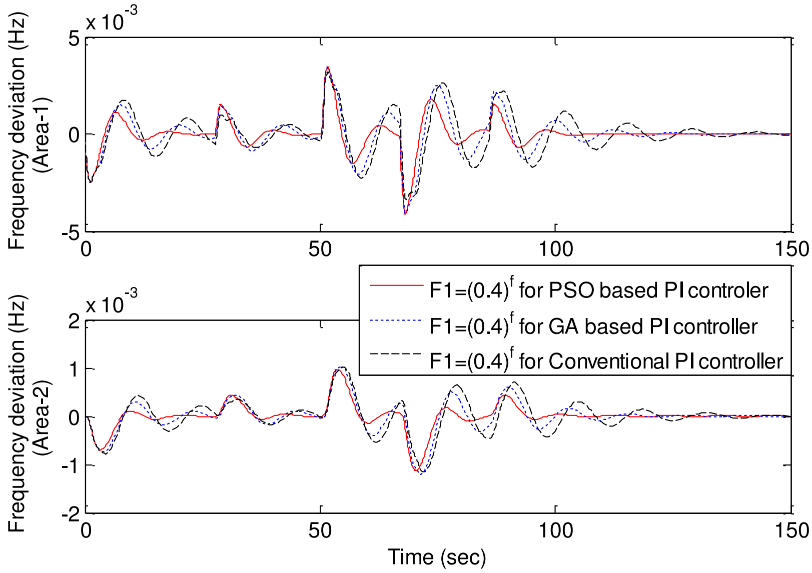


Fig. 12. Frequency deviation with random load for function F1.

of packets form one stage to next stage cause some amount of delay . As observed in Fig. 10(b), packet dropping function F1 does not sufficiently represent the time delay (i.e. a low value); however it models the delay well for queue length above 5. The function F2 captures higher packet dropping probability and delay with respect to function F1 for queue length varied from 1 to 15. This is shown in Fig. 10(b)(ii). The variation in delay follows similar trend as suggested from function F3, shown in Fig. 10(b)(iii). Similarly, the function F4 achieves same range of loss probabilities as above functions, but delay varies significantly with queue length. This is depicted in Fig. 10(b)(iv).

4.4. Case-IV: effect of GDB and GRC with constant and time varying delay on system performance

In this subsection, the study is demonstrated for power system having non-linearties imposed by GDB and GRC. In a large power system, such as two areas, due to generation rate limiter, a slower dynamic behavior would be expected [47]. The estimated delay (i.e. 2.27 s) obtained from function F1 is considered and frequency deviation response for different cases is shown in Fig. 11(a). For the case without GRC and GDB in the system, it is obvious, the response is fast in settling down to steady state condition. Furthermore, the frequency deviation response is sluggish with time delay including GDB and GRC in the system. Further, system dynamic performance is affected in terms of larger overshoot.

In order to study the impact of time varying delays in the range of 0-3 s, the simulation is shown in Fig. 11(b). The communication delay is estimated by function F1. The system is perturbed by a random step load disturbance as illustrated in upper subplot. It can be seen that the frequency deviation undergoes more dynamic variation for time varying delay as compared to constant delay case during the period of load disturbance conditions. In other words, during the period lets say, $t = 100 - 150$ *sec*, the response for both constant and time varying delay are very similar to each other. Further, it is to mention that the controller performance remained consistent with the analytical results presented in above sections.

4.5. Case-V: comprative analysis of prosed method with other optimization techniques

In this section in order to show the efficacy of our proposed method, we have performed the comprative analysis with other optimization techniques such as genetic algortgim (GA) based PI controller and conventional PI controller. The estimated delay by function F1 is used in simulation for frequency deviation of both areas for random load as shown in Fig. 12. It is depicted that the frequency deviation of both areas is minimum for proposed PSO based PI controller with respect to other controllers; GA based PI and conventaional PI controller in terms of overshoot and settlling time.

5. Conclusion

In this paper a novel frame work is proposed to interlink power system, QoS for communication infrastructure and control on LFC application in power system.The proposed design scheme included estimation of delay and packet loss probability using the Markovian model in power system. The probability of packet loss was modeled using different math functions. The deviation in frequency profile was assessed by design of PSO tuned controller, with estimated time delay taken into account. The results were simulated at different load conditions and compared to other optimization technique, which shows that frequency deviation of system remained minimum and performance of power system remained stable inspite of communication delay and packet loss present in the system. Furthermore, the efficacy of proposed method for estimation of time delay was investigated over wide range of queue length.The LFC implementation with a cyber physical modeling approach allows well to characterize with the dynamic behavior of each component of the system, unlike assumed values of upper and lower bound of delay reported in the past. Thus this paper highlights the impact of QoS for communication infrastructure and its control on LFC. Using proposed control scheme reduced frequency deviation and stability of study power system was suggested.

Appendix

Table 1A, Table 1B, Table 1C

Table 1A
Parameters of two area LFC scheme [25].

Sr.no.	Area-1	Area-2	Description	Value	
				Area-1	Area-2
1	T_{t_1}	T_{t2}	Turbine time constant	0.30 s	0.40 s
2	T_{g_1}	T_{g2}	Speed governor time constant	0.10 s	0.17 s
3	B_1	B_2	Frequency biasing coeffient	21 p.u./Hz	21.5 p.u. /Hz
4	R_1	R_2	Speed regulation	.05 Hz/p.u.	.05 Hz/p.u.
5	T_{12}		Tie –line synchronizing power coefficient,	0.1986	
6	K_{p_1}	K_{p_2}	Power system gain	1 Hz/p.u.	0.6611 Hz/p.u
7	T_{p_1}	T_{p_2}	Power system time constant	10 s	7.92 s
8	a_{12}		Area size coeffient	−1	

Table 1B
Maximum eigenvalues of matrices with different sampling periods.

S.No.	$\tau_i = t_{i+1} - t_i$ (time steps)	$\lambda(\tau)$ for $h = 0.05$	$\lambda(\tau)$ for $h = 0.1$	$\lambda(\tau)$ for $h = 0.15$
1	1	0.8362 + 0.134i	0.7935 + 0.3547i	−0.4257 + 0.68547i
2	2	−0.7254	0.7542 + 0.5564i	−0.324 + 0.5425i
3	3	0.6925 + 0.4257i	0.6547+0.4258i	−0.4256
4	4	−0.7854	**−1.1254**	−0.65248
5	5	−.0.94254	−1.35426	−.0921 + .4687i
6	6	**−1.2428**	−2.12654	.062587 + 0.36247i
7	7	−2.54781	−2.65478	−0.0254
8	8	−5.42147	−5.3647	−0.4567
9	9	−7.2564	−6.782	−0.9817
10	10	−9.3245	−6.925	**−1.0145**

Table 1C
Parameters of PSO /GA tuned PI control.

Description	Value	Area-1		Area-2	
		k_{p1}	k_{i1}	k_{p2}	k_{i2}
Parameters of particle swarm optimization					
Population size, maximum generation, cognitive coefficient & inertia weight	100,50,1.4,0.74	0.2019	0.1362	0.019	0.0668
Parameters of genetic algorithm					
Crossover, mutation probability, population size & maximum generation	0.42, 0.53,100 & 50	0.4524	0.3425	0.3941	0.2542
Parameters of PI controller		0.6452	0.8422	0.5495	0.7453

References

[1] P. Kundur, Power System Stability and Control, McGraw- Hill, New York, 1994.
[2] E. Charles, J.R. Fosha, Olle I. Elgerd, The megawatt-frequency control problem: a new approach via optimal control theory, IEEE Trans. Power Appar. Syst. PAS-89 (4) (April 1970) 563–577.
[3] D.P. Kothari, I.J. Nagrath, Modern Power System Analysis, 3rd ed., McGraw-Hill, Singapore, 2003.
[4] H. Bevrani, Robust Power System Frequency Control, 1st ed., Springer, NewYork, 2009, pp. 15–37.
[5] H. Li, L. Lai, H. Vincent Poor, Multicast routing for decentralized control of cyber physical systems with an application in smart grid, IEEE J. Sel. Areas Commun. 30 (6) (July 2012) 1097–1107.
[6] C.L. Robinson, P. Kumar, Optimizing controller location in networked control systems with packet drops, IEEE J. Sel. Areas Commun. 26 (4) (May 2008) 661–671.
[7] S.L. Dai, H. Lin, S.S. Ge, Scheduling -and- control co design for a collection of networked control systems with uncertain delays, IEEE Trans. Control Syst. Technol. 18 (1) (Jan. 2010) 66–78.
[8] Li. Weilin, M. Ferdowsi, M. Stevic, A. Monti, F. Ponci, Cosimulation for smart grid communications, IEEE Trans. Ind. Inform. 10 (4) (Nov. 2014) 2374–2384.
[9] A.A. Khan, M.H. Rehmani, M. Reisslein, Cognitive radio for smart grids: survey of architectures, spectrum sensing mechanisms, and networking protocols, IEEE, Commun. Surv. Tutor. (99) (Sep. 2015), doi:10.1109/COMST.2015.2481722.
[10] R.C. Qiu, Zhen Hu, Zhe Chen, Nan Guo, R. Ranganathan, Shujie Hou, Gang Zheng, Cognitive radio network for the smart grid: experimental system architecture, control algorithms, security, and microgrid testbed, IEEE Trans. Smart Grid 2 (4) (Dec. 2011) 724–740.
[11] G.A. Shah, V.C .Gungor, O.B. Akan, A Cross-Layer QoS-Aware communication framework in cognitive radio sensor networks for smart grid applications, IEEE Trans. Ind. Inform. 9 (3) (Aug. 2013) 1477–1485.
[12] Rong Yu, Yan Zhang, S. Gjessing, Chau Yuen, Shengli Xie, M. Guizani, Cognitive radio based hierarchical communications infrastructure for smart grid, IEEE Netw. 25 (5) (September-October 2011) 6–14.
[13] Yan Zhang, Rong Yu, M. Nekovee, Yi Liu, Shengli Xie, S. Gjessing, Cognitive machine-to-machine communications: visions and potentials for the smart grid, IEEE Netw. 26 (3) (May-June 2012) 6–13.
[14] M.S. Mahmoud, Robust Control and Filtering for Time-Delay Systems, Marcel Dekker, New York, 2000.
[15] J. Aweya, D.Y. Montuno, M. Ouellette, Effects of control loop delay on the stability of a rate control algorithm, Int. J. Commun. Syst. 17 (2004) 833–850.
[16] B. Naduvathuparambil, M.C Valenti, A. Feliachi, Communication delays in wide area measurement systems, in: Proceedings of the Thirty-Fourth Southeastern Symposium on System Theory, 2002, pp. 118–122.
[17] Xiaorong Xie, Yaozhong Xin, Jinyu Xiao, Jingtao Wu, Yingduo Han, WAMS applications in Chinese power systems, IEEE Power Energy Mag. 4 (1) (Jan.-Feb. 2006) 54–63.
[18] X. Ye, S. Liu, P.X. Liu, Modelling and stabilization of networked control system with packet loss and time-varying delays, IET Control Theory Appl. 4 (6) (June 2010) 1094–1100.
[19] S. Bhowmik, K. Tomsovic, A. Bose, Communication models for third party load frequency control, IEEE Trans. Power Syst. 19 (1) (Feb. 2004) 543–548.
[20] Yu. Xiaofeng, K. Tomsovic, Application of linear matrix inequalities for load frequency control with communication delays, IEEE Trans. Power Syst. 19 (3) (Aug. 2004) 1508–1515.
[21] Xu. Shengyuan, J. Lam, On equivalence and efficiency of certain stability criteria for time-delay systems, IEEE Trans. Automat. Control 52 (1) (Jan. 2007) 95–101.
[22] L. Jiang, W. Yao, Q.H. Wu, J.Y. Wen, S.J Cheng, Delay-dependent stability for load frequency control with constant and time-varying delays, IEEE Trans. Power Syst. 27 (2) (May 2012) 932–941.
[23] T. Hiyama, Zuo Dunding, T. Funabashi, Multi-agent based automatic generation control of isolated stand-alone power system, in: Proceedings of the International Conference Power System Technology, PowerCon, 13-17 Oct 2002, pp. 139–143.
[24] H. Shayeghi, H.A. Shayanfar, A. Jalili, Multi-stage fuzzy PID power system automatic generation controller in deregulated environments, Energy Convers. Manag. 47 (18) (Nov. 2006) 2829–2845.
[25] Wei Zhang, M.S. Branicky, S.M. Phillips, Stability of networked control systems, IEEE Control Syst. 21 (1) (Feb 2001) 84–99.
[26] Huijun Gao, Xiangyu Meng, Tongwen Chen, Stabilization of networked control systems with a new delay characterization, IEEE Trans. Autom. Control 53 (9) (Oct. 2008) 2142–2148.
[27] Yun-Bo Zhao, Guo-Ping Liu, D. Rees, Design of a packet-based control framework for networked control systems, IEEE Trans. Control Syst,. Technol. 17 (4) (July 2009) 859–865.
[28] Ibraheem, K.R. Niazi, G. Sharma, Study on dynamic participation of wind turbines in AGC of power system, Electric Power Compon. Syst. 43 (1) (2014) 44–55.
[29] G. Sharma, Ibraheem, K.R. Niazi, Optimal AGC of asynchronous power systems using output feedback control strategy with dynamic participation of wind turbines, Electric Power Compon. Syst. 43 (4) (2015) 384–398.
[30] Y.P. Verma, Ashwani Kumar, Participation of doubly fed induction generator based wind turbine in frequency regulation with frequency linked pricing, Electric Power Compon. Systems 40 (14) (2012) 1586–1604.
[31] P. Bhatt, S.P. Ghoshal, R. Roy, S. Ghosal, Load frequency control of interconnected restructured power system along with DFIG and coordinated operation of TCPS-SMES, in: Proceedings of the Joint International Conference Power Electronics, Drives and Energy Systems (PEDES) & Power India, 20-23 Dec. 2010, pp. 1–6.
[32] Chuan-Ke Zhang, L. Jiang, Q.H. Wu, He Yong, Wu Min, Further results on delay-dependent stability of multi-area load frequency control, IEEE Trans. Power Syst. 28 (4) (Nov. 2013) 4465–4474.
[33] Aysen Demiroren, Neslihan S. Sengor, H. Lale Zeynelgil, Automatic generation control by using ANN technique, Electric Power Compon. Syst. 29 (2001) 883–896.
[34] Wah-Chun. Chan, Sen, Yuan-Yih Hsu, Automatic generation control of interconnected power systems using variable-structure controllers, IEEE Proc. Gener., Transm. Distrib. 128 (5) (September 1981) 269–279.
[35] T.C. Yang, Networked control system: a brief survey, IEE Control Theory Appl. Proc. 153 (4) (10 July 2006) 403–412.
[36] C.A. Macana, E. Mojica-Nava, N. Quijano, Time-delay effect on load frequency control for microgrids, in: Proceedings of the 10th IEEE International Conference Networking, Sensing and Control (ICNSC), 10-12 April 2013, pp. 544–549.
[37] M. Mokhtari, F. Aminifar, D. Nazarpour, S. Golshannavaz, Wide-area power oscillation damping with a fuzzy controller compensating the continuous communication delays, IEEE Trans. Power Syst. 28 (2) (May 2013) 1997–2005.
[38] M. Mokhtari, F. Aminifar, Toward wide-area oscillation control through doubly-fed induction generator wind farms, IEEE Trans. Power Syst. 29 (6) (Nov. 2014) 2985–2992.
[39] R.A. Gupta, Mo-Yuen Chow, Networked control system: overview and research trends, IEEE Trans. Ind. Electron. 57 (7) (July 2010) 2527–2535.
[40] F. Aminifar, M. Fotuhi-Firuzabad, A. Safdarian, A. Davoudi, M. Shahidehpour, Synchrophasor measurement technology in power systems: panorama and state-of-the-art, IEEE Access 2 (2014) 1607–1628.
[41] M.S. Hasan, C. Harding, H. Yu, A. Griffiths, Modeling delay and packet drop in networked control system using network simulator NS2, Int. J.Autom. Comput. 2 (2005) 187–194.
[42] D. Simchi-Levi, M.A. Trick, Introduction to "Little's law as viewed on its 50th anniversary", Oper. Res. 59 (3) (2011) 535.
[43] S. Geirhofer, L. Tong, B.M. Sadler, Dynamic spectrum access in WLAN channels: empirical model and its stochastic analysis, in: Proceedings of the First International Workshop on Technology and Policy for Accessing Spectrum (TAPAS), Aug. 2006.
[44] Shichao Liu, P.X. Liu, A. El Saddik, Modeling and stability analysis of automatic generation control over cognitive radio networks in smart grids, IEEE Trans. Syst. Man Cybern. Syst. 45 (2) (Feb. 2015) 223–234.
[45] Xianghui Cao, Peng Cheng, Jiming Chen, Shuzhi Sam Ge, Yu Cheng, Youxian Sun, Cognitive radio based state estimation in cyber-physical systems, IEEE J. Selected Areas Commun. 32 (3) (March 2014) 489–502.
[46] Y.L. Abdel-Magid, M.A. Abido, AGC tuning of interconnected reheat thermal systems with particle swarm optimization, in: Proceedings of the10th IEEE International Conference on Electronics, Circuits and Systems, ICECS, 1, 2003, pp. 376–379.
[47] S.A. Pourmousavi, M.H. Nehrir, Introducing dynamic demand response in the LFC model, IEEE Trans. Power Syst. 29 (4) (July 2014) 1562–1572.

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