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Distributed Multi -Agent System Based Load Frequency Control for Multi- Area Power System in Smart Grid

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***Abstract*—** This paper presents an intelligent controller for "Load Frequency Control (LFC)" application in "smart grid (SG)"environment having changes in communication topology via multi agent system (MAS) technology. In study, network induced effects, time delay and change in communication topology (CT) have been addressed to examine the system performance in closed loop. An event triggered control method is used to reduce the communication burden in a network. An intelligent controller based on reinforcement learning consists of two levels estimator agent and controller agent in each multi-area system. Particle swarm optimization (PSO) is used to tune the controller parameters. Further proposed control strategy and system architecture as MAS for LFC in smart grid is analyzed in detail, verified for various load conditions and different network configurations. In addition, mean square error of power system states with CT is also analyzed. The results of this study validate the feasibility of the proposed control, as well as the capability of the MAS for the operation of LFC in SG with changes in CT.

Index Terms **Communication topology, Load frequency control, Multi agent Reinforcement learning, Smart grid**

I. INTRODUCTION

Load Frequency Control (LFC) problem is one of the most critical issues in large scale power systems due to imbalance between generation against the load demand and system losses. So, monitoring and maintenance of a large interconnected power system is more demanding than before. In recent years, LFC issue has gained significant importance due to its distributed characteristics and necessities of advance control capability in smart grid (SG) environment. Traditional centralized LFC structures encounter many difficulties due to limitations in exchanging information with large-scale, geographically expansive control areas along with their increased computation and storage complexities. Developing decentralized/distributed LFC structures can be an effective way of solving this problem. Distributed control is more feasible, reliable, simple and cost effective [1]. A distributed control approach is better than centralized counterparts for implementation of monitoring/control robustness in SG application [2]. To accomplish this however, the SG requires reliable communication systems. Its smartness relies on their ability to take advantage of the huge amount of data flow across the electrical power grid. The communication technologies and their impact on power system operation need a closer study to implement the control strategy. The power systems rely on control algorithms having information exchanged via communication networks. Any deteriorating network effects jeopardize failure rate of control itself. With availability of bi-directional flows of energy in the interconnected areas, and coordination through communication mechanisms, a smart grid should help balance supply and demand [3].

There is a continuous interest in designing of LFC problem in smart grid operations with better performance using several decentralized, robust and optimal control methods [4-6]. In [4], communication time delay estimation for LFC in two area power system using Markovian approach is presented. A decentralized proportional integral derivative control (PID) using PSO is used to tune the controller parameters. In [5], a delay dependent stability in deregulated environment of LFC in multi-area system is presented. Further modelling and stability analysis of automatic generation control (AGC) in smart grid is presented using cognitive radio (CR) network [6]. The exact method for computing the delay margin in LFC problem with communication delays is presented in [7]. Impact of the delay dependent study considering constant and time varying communication delay in deregulated environment for LFC in single area and multi area power system is presented in [8]. The impact of communication delay on secondary frequency control for islanded microgrid is presented in [9].

Recently, researchers have reported coupling of power system and communication networks as discrete-event systems. The combined system operates in a variable and uncertain environment. The performance of communication infrastructure considering the network induced effects such as delay, packet loss and throughput is presented in [10]. In [11], the performance of communication infrastructure in wide area power system for IEEE-118 bus network is investigated for both centralized and decentralized topology. The authors of [12] have discussed the impact of change in communication topology (CT) in smart grid for LFC problem.

In recent years, multi-agent reinforcement learning (MARL) technique, capable of solving complex and distributed problem in electrical power grid has been reported. The MAS technique is being investigated in variety of application in power system and widely used in system restoration [13], disturbance diagnosis [14], secondary voltage control [15], power distribution system [16-17], collaborative decision support systems, distributed control, robotic teams and

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economics, etc. Further the application MARL technique in AGC problem is reported in [18]. In [19], an adaptive nonlinear control technique with application of reinforcement learning (RL) in LFC problem is presented. The controller uses RL technique to learn and reduce the area control error (ACE) signal of every sampling time of LFC cycle.

To enable seamless integration of control, communication, and computation for rapid design and deployment of cyber-physical systems (CPS), architecture and design are essential for infrastructure. Dynamic connection and interaction between components in both physical and cyber systems through communication networks are essential. SG operates in a variable and uncertain environment, for example, communication link failure could occur at any time when there is traffic congestion [20]. Also, high security is needed so that the system has adequate means to protect itself from unauthorized access and attack to cyber systems.

There are many multi-area systems whose operating mode and power output often is uncontrollable because they are subjected to changes in communication topologies. As a result, there are situations, wherein area's information exchange via communication network is ON or OFF. That is, some areas may connect into network or disconnect form network at any time. Therefore, the controller design in SG environment must have a large degree of intelligence and flexibility to face CT and uncertain environment. Nevertheless, the CT changes in smart grid environment with multi-area AGC schemes as MAS have not been yet considered.

In this study, an intelligent controller for LFC in SG with CT changes using multi-agent system (MAS) technique is presented. This paper deals with an intelligent controller for LFC problem in a power system that has the frequency bias coefficient β_{est} is as one of its functionalities and its implementation issues in smart grid are discussed in detail. An intelligent controller consist two agents which communicates with each other to provide complete information of the system. The first agent is the estimator agent which based on frequency bias coefficients provides the area control error (ACE) signal, and the second agent is controller agent provides ΔP_{ri} signal according to ACE signal obtained from estimator agents, incorporating reinforcement learning RL algorithm to compensate the power imbalance between generations against the load demand. Further PSO technique is used to tune the controller gains. The network is modelled considering different network configurations, i.e. change in CT using MAS technique. Physically adopting such scheme indicates the performance of communication system in maintaining the exchange of information within the power system.

The major contribution towards an intelligent control design for LFC problem in SG, considering change in communication topology are highlighted below:

• To improve the dynamic performance A MARL technique is applied in multi-area power system as CT changes in smart grid.

• A time varying communication matrix is included in power system to model the CT changes in smart grid.

• The LFC for power system with event triggered control method is used to reduce the amount of communication required for data transmission and hence improve the dynamic performance of system.

• In order to check the dynamic performance of system, mean square error of power system states are computed and compared with other method available in literature.

The rest of the paper is organized as follows. Section II briefly describes the system configuration and model of multi-area power system. Section III is devoted to MARL technique and its implementation in LFC problem, followed by an event -triggered control scheme for four area power system is considered in section IV. Section V discusses the simulation results for frequency deviation with time delays for various load conditions. Finally, concluding remarks are drawn in Section VI.

II. MODELING OF POWER SYSTEM IN SMART GRID

The basic objective of LFC in integrated power system area is to require the balancing between of total generation against total load demand, including system losses and maintain a tie-line power at a scheduled value. The AGC via communication network in a smart grid is shown in Fig.1.

The Power system dynamics is modelled as a continuous time simulation while communication network as a discrete-event due to its inherent nature. The information for frequency deviation of each area and tie-line power between two areas is transmitted via communication network through local/control center, to each area for respective control action.

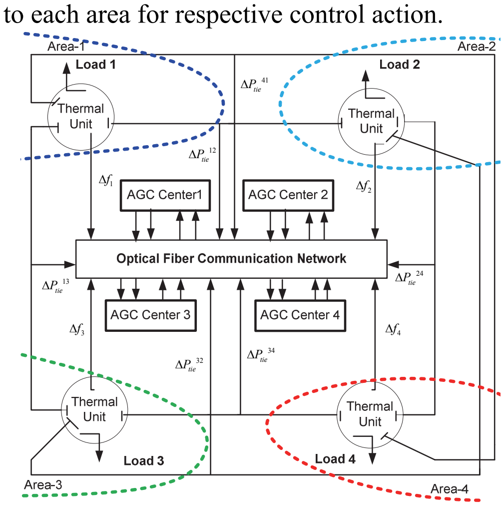

Fig.1 Framework structure of multi-area power system having communication network

The state-space modeling of thermal power system is presented. In LFC problem, our aim is to keep the frequency close to its nominal value by adjusting the balance between generation set point and load demand. The frequency deviation of each area is governed by

$$\Delta \dot{f}_i = -\frac{1}{T_{pi}}\Delta f_i + \frac{K_{pi}}{T_{pi}}\Delta P_{ti} - \frac{K_{pi}}{T_{pi}}\Delta P_{tie}{}^{i} - \frac{K_{pi}}{T_{pi}}\Delta P_{Di} \tag{1}$$

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where, Δf_i frequency deviation of individual area is, ΔP_{ti} is generator mechanical power deviation, $\Delta P_{tie}^{\ i}$ is tie-line power deviation of between two areas, ΔP_{Di} is load deviation of each unit, $\frac{1}{K_{pi}} = D_i$ is the damping coefficient of each area and $\frac{T_{pi}}{K_{pi}} = M_i$ is equivalent inertia of each area.

The turbine dynamics is represented as

$$\dot{\Delta P}_{t_i} = -\frac{1}{T_{t_i}}\Delta P_{t_i} + \frac{1}{T_{t_i}}\Delta P_{gi} \tag{2}$$

Where, T_{t_i} is turbine constant of each area and ΔP_{gi} is turbine valve position deviation of each area.

The governor equation is given by

$$\dot{\Delta P}_{g_i} = -\frac{1}{R_i T_{g_i}}\Delta f_i - \frac{1}{T_{g_i}}\Delta P_{g_i} + \frac{1}{T_{g_i}}\Delta P_{ri} \tag{3}$$

Where, R_i is droop coefficient of individual area and ΔP_{ri} is load generation balance point.

The net tie-line deviation between two different areas is represented as

$$\dot{\Delta P}_{tie}^{\ i} = \sum_{j=1, j\neq i}^{N} 2\pi T_{ij}(\Delta f_i - \Delta f_j) \tag{4}$$

Where T_{ij} is synchronization coefficient, Δf_j is the frequency deviation of area j and N is the total number of interconnected areas.

The state space modelling of i th area is given by (5).

$$\dot{x}_i = A_{ii}x_i + B_i u_i + \sum_{j=1, j\neq i}^{N} A_{ij}x_j + \Gamma_i \Delta P_{di}, \tag{5}$$

where, $x_i = \begin{bmatrix}\Delta f_i & \Delta P_{ti} & \Delta P_{gi} & \Delta P_{tie}^{\ ij}\end{bmatrix}^T, u_i = \Delta P_{ri}$

$$A_{ii} = \begin{bmatrix} -\frac{1}{T_{pi}} & \frac{K_{pi}}{T_{pi}} & 0 & -\frac{K_{pi}}{T_{pi}} \\ 0 & \frac{-1}{T_{ti}} & \frac{1}{T_{ti}} & 0 \\ -\frac{1}{R_i T_{gi}} & 0 & -\frac{1}{T_{g_i}} & 0 \\ \sum_{j=1, j\neq i}^{N} 2\pi T_{ij} & 0 & 0 & 0 \end{bmatrix} \quad A_{ij} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -2\pi T_{ij} & 0 & 0 & 0 \end{bmatrix}$$

$$B_i = \begin{bmatrix} 0 & 0 & \frac{1}{T_{g_i}} & 0 \end{bmatrix}^T \quad \Gamma_i = \begin{bmatrix} -\frac{1}{M_i} & 0 & 0 & 0 \end{bmatrix}^T$$

In simulation study, the initial condition of frequency deviation for all the four areas is assumed as 0.5 Hz, while the initial conditions of other states as zero.

$A_{ii}, B_i, u_i, \Gamma_i$ and ΔP_{di} are system matrix, system input, control input matrix, disturbance and load disturbance of i th area respectively , whereas A_{ij} represents the system matrix of interconnected areas.

If communication infrastructure is completely reliable, the control inputs of controller can be given as:

$$u_i = -K_i x_i - \sum_{j=1, j\neq i}^{N} K_{ij}x_{ij}, i \in \{1 \ \ \dots \ \ N\} \tag{6}$$

where, K_i, K_{ij} is the controller gain obtained from PSO algorithm.

The other areas' states are linked with communication infrastructure in ACE signal. The continuous-time domain simulation of power system as discrete event, its network impact on control and stability is important to be analyzed. A time varying communication matrix is included in the design of controller, which depends upon type of CT selected. It is obvious that communication network for transmission of data is either ON or OFF. So, we can consider a communication matrix as an ON–OFF switch. Here '0' and '1' represents the OFF and ON state respectively in the CT matrix. So, communication matrix can be defined as:

$$C(t) = [C_{ij}(t)]_{N\times N} \tag{7}$$

Next, diagonal elements of $C(t)$ will always be 1, indicating communication channel for diagonal elements is always ON.

Further the power system dynamics including CT is given as

$$\dot{x}_i = A_{ii}x_i + B_i u_i + \sum_{j=1, j\neq i}^{N} c_{ij}A_{ij}x_j + \Gamma_i \Delta P_{di}, \tag{8}$$

Again the control inputs including CT can be represented as

$$u_i = -K_i x_i - \sum_{j=1, j\neq i}^{N} c_{ij}K_{ij}x_{ij}, i \in \{1 \ \ \dots \ \ N\} \tag{9}$$

Putting the value of u_i in eqn. (8), the closed loop dynamics of system can be represented as

$$\dot{x}_i = \hat{A}_{ii}\, x_i + \sum_{j=1, j\neq i}^{N} c_{ij}\hat{A}_{ij}\, x_j + \Gamma_i \Delta P_{di} \tag{10}$$

where $\hat{A}_{ii} = A_{ii} - B_i K_i$, $\hat{A}_{ij} = A_{ij} - B_i K_{ij}$

Often, communication structure modelling refers to the reconstruction of state and/or output specific paths. But, if the structure to be modeled is subject to large uncertainties, it is better to include several topologies of structure rather than the exact path. Mainly, these topologies are based on a multi-model representation of the structure, because of the large degree of uncertainty in the establishment of communication link. The one possible illustration of CT of power system is shown in Fig. 2(a). The perfect CT (Case A) is shown in Fig.2(a) wherein, each thermal area is connected to each other establishing direct one-to-one link. The remaining topologies in Fig. 2(a) (Case-B to case F) are considered as imperfect CT, wherein the communication link between two or more than two areas fails. For example in case B, there is no direct link established between area 4 & area 3 and area 4 & area 2. So, in this study it is assumed that at least one direct or indirect link should exist between any two agents i.e. system have connected link. These types of configuration convey incomplete inter area state information to its neighborhood area to AGC control center, resulting potential degradation of data flow in the communication network. The five imperfect CT is triggered by random Markov process, one sample of whose is presented in Fig.2 (b). In Fig.2 (b), modes 1-5 represents the imperfect CT as given in Fig.2 (a), (Case B to Case F), correspondingly.

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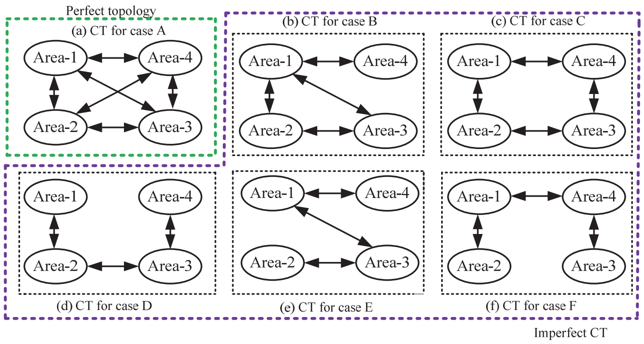
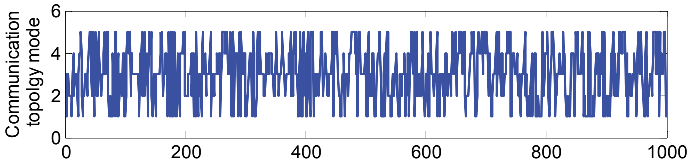


(a) Illustration of possible CT for multi-area power system



(b) One sample CT modes using markov process [11]
Fig. 2 CTs between the agents (4 areas)

III. IMPLEMENTATION OF MARL TECHNIQUE

In this section, MARL technique is implemented for multi-area power system with communication network. The complex hybrid behaviours are caused due to frequent switching between different modes of CTs as the logic relation operation and operating modes of interconnected area. Therefore, interactive hybrid control strategies should be designed to effectively control the complex hybrid behaviours. The modeling of multi-area power system with MAS is given in Fig. 3(a). From Fig. 3(a), it is clear that that MAS agent will collect data of multi-area power system through communication network and then send it to estimator agents. Next, estimator agents will estimate the available signal and provides an average ACE signal to controller. Further at each instant controller agents observe the current state of system and takes an action of the signal. The controller agent uses MAS technique to compensate the power imbalance between generations against the load demand in which PSO is used to tune the system parameters. The block diagram of multi-agent model for i th area power system is shown in Fig. 3(b). The details of MARL technique is given in subsequent section.

A. Multi-agent reinforcement learning

The main objective of MARL technique is how to maximize the reward signal by taking some action in a particular situation. The main task of MARL technique is to solve a problem by interacting with a system. Learner is called an agent and system that interacts with it is known as environment. Further, agent will interact with environment and take the action a_t from the set of action at a time t sec and brings the system state s_t to new system state s_{t+1}. So, agent is provided with the corresponding reward signal r_{t+1}. This interaction process between agent and environment is repeated until the desired aim is achieved. In this study, Markov decision process (MDP) is used that will contain all relevant information of state signal enabling to predict the next system state using some action with expected reward signal. Further in MDP, the aim is to maximize the sum of returned reward over time, and expected sum of discounted reward [18] is presented by

$$R = \sum_{k=0}^{\infty} \lambda^k r_{t+k+1} \tag{11}$$

Where λ is a discount factor lies between $0 < \lambda < 1$, which provides the maximum preference to recent rewards.

The value function of each state is expressed as the expected reward when starting at system state s_t having following policy $\Omega(s,a)$

$$V^{\Omega}(s) = E_{\Omega}\left\{ \sum_{k=0}^{\infty} \lambda^k r_{t+k+1}) \middle| s_t = s \right\} \tag{12}$$

The optimal policy of value function can be given as

$$V^*(s) = \max_{\Omega} V^{\Omega}(s), \forall s \in S \tag{13}$$

Further action value is found using eqn. (14)

$$Q^{\Omega}(s,a) = E_{\Omega}\left\{ \sum_{k=0}^{\infty} \lambda^k r_{t+k+1}) \middle| s_t = s, a_t = a \right\} \tag{14}$$

To find the optimal action value, Bellman's equation is used and given in eqn. (15).

$$Q^*(s,a) = \max_{\Omega} E_{\Omega}\left\{ r_{t+1} + \lambda \max_{a'} Q^*(s_{t+1}, a') \middle| s_t = s, a_t = a \right\} \tag{15}$$

Next, a temporal difference method is used which learns the model of system under control. The only information available is the expected reward for each action taken for transition of state s_t to new state s_{t+1}. This algorithm, called Q-learning, will approximate the Q value function. The structure of Q-learning algorithm is given in Fig. 3(c). The detail of learning process of controller is shown in Fig. 3(d). In next subsection proposed control formulation is presented.

B. Proposed control formulation

In this section, an intelligent controller for LFC in SG environment having changes in CT using MAS technique is presented. The main objective of proposed method is to control the potential degradation of dynamic performance of power system on CT changes in the smart grid environment. An intelligent controller consist two levels in each multi-area system. The first level, i.e. estimator agent will be responsible for estimating the frequency bias coefficients, and provides the area control error (ACE) signal, whereas the second level, i.e. controller agent to compensate the power imbalance between generation and the load demand in which particle swarm optimization (PSO) is used to tune the controller parameters.

B.1 Controller agent

Conventional PI control in LFC problem may be replaced by intelligent controller for improvement in frequency deviation. In this regard, the design of LFC problem operates in discrete mode and performance of system are more flexible. Further at every time step ($k = 1,2,3......$) the controller agent observe the current state of system s_k and take an action a_k in order to bring the new state of system. It is already described in above section (Fig. 3(b)) that area control error and ΔP_D signals are available as state vector for every LFC execution period and used as input to the controller agent. It is assumed that all

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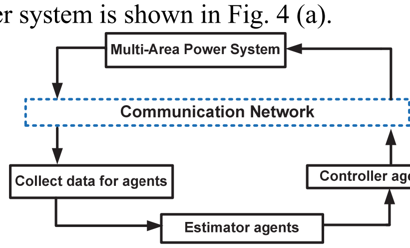
possible states are finite. Here PSO algorithm is used to compute discretized state vector value. In this paper, RL algorithm is used to estimate the Q^* value function and optimal policy. The complete details of the algorithm can be found in [19].

Let us take a sequence of sample or training set (s_k, s_{k+1}, a_k, r) where, $(k = 1,2,3......)$ is LFC execution period. For each sample, transition of state s_k to new state s_{k+1} requires some action a_k. Where $r_k = f(s_k, s_{k+1}, a_k)$ is called a consequent reinforcement. For estimating of Q^* value function above sequence is used in simulation. Let us assume that for kth iteration Q^k is the estimate of Q^*. So Q^{k+1} can be obtained as follows

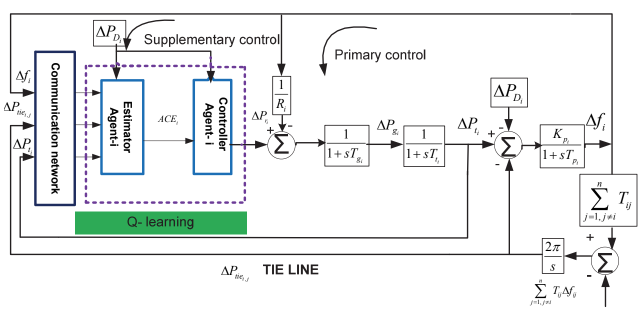
$$Q^{k+1}(s_k,\alpha_k) = Q^k(s_k,\alpha_k) + \alpha[g(s_k,s_{k+1},\alpha_k) + \lambda \max_{\alpha\in A} Q^k(s_{k+1},\alpha^*) - Q^k(s_k,\alpha_k)] \quad (16)$$

Where, $0 < \alpha < 1$ is constant referred as step size of learning algorithm. In this algorithm, exploration probability for selection of action for different state is used. Each state action is selected on the probability distribution over action space.

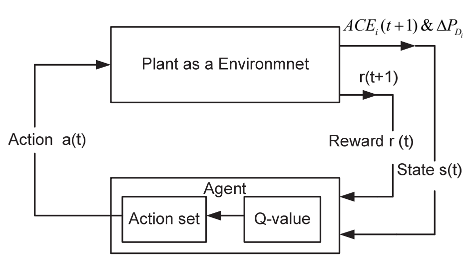
Further, Q-value is used as objective function for PSO algorithm. The Q-value of each particle insures the performance of particle for controlling the system. The learning of controller proceeds to a new generation until a predefine stop criteria is achieved. The parameters of PSO includes, population size =100, maximum generation =100, cognitive coefficient ($C_1 = C_2 = 1.2$) and inertia weight ($W = 0.3$). The simulated results using PSO of area-1 for four-area power system is shown in Fig. 4 (a).



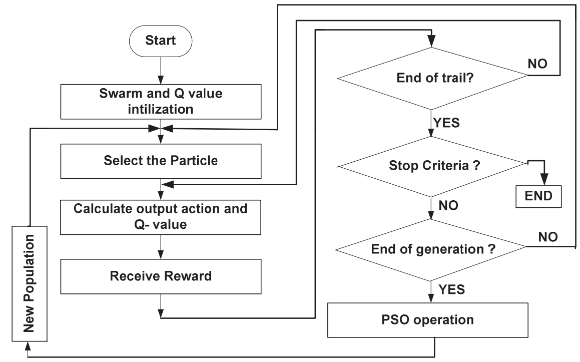
(a) Flow chart of modelling of multi area power system with MAS



(b) Proposed multi agent model for ith area of thermal power system



(c) Q-learning algorithm structure



(d) Block diagram of learning process with Q-value based PSO

Fig.3 Architecture for proposed multi area power system with communication infrastructure

B.2 Estimator agent

The ACE of system can be represented as a linear combination of tie-line power and frequency deviation of each area given by

$$ACE_i(t) = B_i \Delta f_i(t) + \Delta P_{tie(i,j)}(t) \quad (17)$$

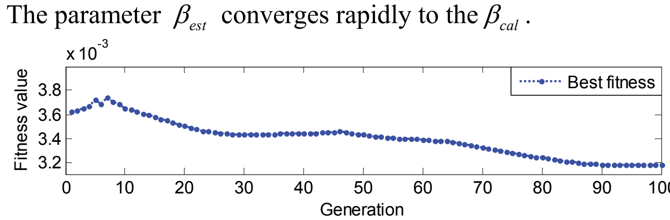
To determine the ACE, it is obvious to know the frequency bias coefficient (β). Conventionally, the value of β is usually considered as $-10B$ i.e. a constant value. Thus, the ACE signal will only react to internal disturbance, not to the external disturbance. Further to improve the dynamic performance of system, the estimator agent will estimate the β parameters and determine the ACE signal accordingly. It is clear that for each LFC execution period, estimator agent will receive the $\Delta P_{tie_{i-j}}$, Δf_i, ΔP_{t_i} and ΔP_{D_i} signal as a inputs, then determine the β parameter, the ACE signal and feed to the controller accordingly (Fig. 3(b)). The power balance of system (pu) for i th area can be represented as

$$\sum_{j=1}^{n} \Delta P_{t_{ji}}(t) - \Delta P_{D_i}(t) - \Delta P_{tie_{i-j}}(t) = \frac{T_{p_i}}{K_{p_i}}.\Delta \dot{f}_i(t) + \frac{1}{K_{p_i}}\Delta f_i(t) \quad (18)$$

By using eqn. (17) and (18), we can get

$$\sum_{j=1}^{n} \Delta P_{t_{ji}}(t) - \Delta P_{D_i}(t) + \beta_i \Delta f_i(t) - ACE_i(t) = \frac{T_{p_i}}{K_{p_i}}.\Delta \dot{f}_i(t) + \frac{1}{K_{p_i}}\Delta f_i(t) \quad (19)$$

From eqn. (19), we can find the ACE signal. Using the ACE signal and other variables, the β value can be estimated for corresponding LFC execution period. Since the value of β vary according to system condition, so these system parameters have to be updated regularly using a recursive least square algorithm. Fig. 4(b) shows the estimated and calculated value of β over 50 sec of area-1. As depicted, for this simulation, the β_{cal} is set to $-10B$ of the target control area. The parameter β_{est} converges rapidly to the β_{cal}.



(a) Fitness value vs generation for PSO algorithm of area-1

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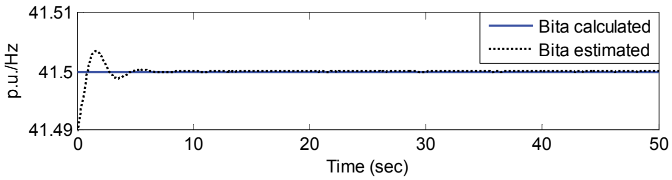

(b) Estimation of β value with calculated over 50 sec

Fig.4 Fitness value vs. generation and estimation of β value

IV. EVENT TRIGGERED COMMUNICATION METHOD

Recently, the application of LFC considering communication delay has been investigated and presented in [21-22]. In smart grid power system; it is desirable to reduce the communication usage between sensor and controller nodes [23]. Further, to reduce the required control effort, LFC scheme may be used in digital operating platform [24].

This trend motivates the researchers to work more on event–triggered communication scheme for LFC. Recently, researchers have reported coupling of power system and communication networks as discrete-event triggering systems for LFC in multi-area power system with communication delays [25]. To improve the dynamic performance of system, it is advisable to design an event-triggered control scheme to minimize the communication delays. In this paper, Markovian jump system under event triggered approach is applied in LFC scheme for perfect communication topology scheme given in Fig.2 (a) for CT (Case A) [26].

$$\begin{aligned}\dot{x}(t) &= A(m(t))x(t)+B(m(t))u(t)+B_w(m(t))w(t)\\ y(t) &= C(m(t))x(t)+D(m(t))u(t)+D_w(m(t))w(t)\end{aligned} \tag{20}$$

Matrices $A(m(t))$, $B(m(t))$, $C(m(t))$, $D(m(t))$, $B_w(m(t))$ and $D_w(m(t))$ is known real matrices with appropriate dimension. $w(t)$ is external disturbance and $(m(t))$ is the finite homogeneous finite state Markov jump process taking discrete value in finite set $S=\{1 \quad 2 \quad \cdots \quad m\}$ according to following transition probabilities.

$$\Pi = (\mu_{ij})(i, j \in S)$$

$$\mathrm{P}\,m\left\{m(t+\Delta t)=j \,\middle|\, r(t)=i\right\} = \begin{cases}\mu_{ij}\Delta t + o(\Delta t), i \neq j\\ 1+\mu_{ii}\Delta t + o(\Delta t), i = j\end{cases} \tag{21}$$

$$\lim_{t\to 0}\frac{o(\Delta t)}{\Delta t} = 0, \mu_{ij} \geq 0 (i \neq j)$$

$$\mu_{ii} = -\sum_{j=1, j\neq i}^{N} \mu_{ij}$$

In this scheme following assumption is considered; (i) the states are sampled for a given sampling rate and sensor is time driven, (ii) the sampled signal is transmitted to communication infrastructure is decided by event triggered approach. So average communication period under event triggered scheme is given as $T_{c_{av}} = \dfrac{\sum_{k=1}^{v} t_k}{v}$ Where, $T_{c_{av}}$ is average communication period and v is total number of sampled signal transmitted to the controller and decided by event triggered method.

Now, event detector is used to determine whether the new sample data should be transmitted to controller with following judgment condition given below.

$$\left[x(kT)-x(t_kT)^T\right]\varphi(m(kT))\left[x(kT)-x(t_kT)\right] > \psi(m(kt))x^T(kT)\varphi m(kt))x(kT) \tag{22}$$

$\psi(m(kt)) \in [0 \quad 1)$ is scalar parameters which sets the threshold detection $\varphi m(kt)) > 0$ is the event matrix can be calculated and designed according to [26].

where $x(kT)$ is current sample data and $x(t_kT)$ is latest transmitted data meets the event threshold condition the output data will be stored and send it to controller for further action.

Since, a time varying delay exists over the communication network, we can transform the event based markovian jump system into delay system according to [26].

Let us define the network delay

$$\tau(t) = t - t_kT - nT, t \in \left[t_kT + nT + \tau_{i_k+n}, t_kT + (n+1)T + \tau_{i_k+n+1}\right] \tag{23}$$

where, $n = 0 \quad 1 \quad \cdots \quad q$, q is positive integer.

From above equation it is clear that $\tau(t)$ is bounded and τ_m is upper bounded $0 \leq \tau(t) \leq T + \bar{\tau} = \tau_m$

Next, the error between two samples can be given as

$$e_k(s_kT) = x(s_kT) - x(t_kT) \tag{24}$$

where, $s_kT = t_kT + nT$ represent the current sampling instant t_kT to future transmitted sampling state $t_{k+1}T$.

Now, event triggered method can be written as

$$e_k^T(s_kT)\varphi(r(kT))e_k(s_kT) \geq \psi(r(kt))x^T(s_kT)\varphi r(kt))x(s_kT) \tag{25}$$

Further, the control signal for LFC can be selected as

$$u(t) = k(m(T))x(t_kT), t \in \left[t_kT + \tau_{t_k}, t_{k+1}T + \tau_{t_k+1}\right] \tag{26}$$

where $k(m(T))$ is the controller gain of PI controller.

Closed loop system can be obtained by putting eqn. (24) and (26) in eqn. (20).

$$\begin{aligned}&\dot{x}(t) = A(m(t))x(t) + B(m(t))k(m(T))x(t-\tau(t))\\ &-B(r(t))k(m(T))e_k(s_kT) + B_w(m(t))w(t)\\ &y(t) = C(m(t))x(t) + D(m(t))k(m(T))x(t-\tau(t))\\ &-D(r(t))k(m(T))e_k(s_kT) + D_w(m(t))w(t)\\ &x(t) = \phi(t), t \in [\tau_m \quad 0]\end{aligned} \tag{27}$$

Where $\phi(t)$ is a continuous function on $[\tau_m \quad 0]$

Further in order to show the impact of data derived for different triggered parameter, the event triggered release instant and release interval is given in Fig. 5. The system state response of perfect CT configuration of LFC scheme with trigger parameter $\psi_i = .2$ is given in Fig. 6. It is obvious that dynamic performance of power system states under event triggered scheme ensures the stability under the improved LFC scheme. The simulation is performed for 10 sec, only 71 samples and 35 samples out of 100 samples are successfully transmitted to controller for triggered parameters of 0.2 and 0.5 respectively.

So, average communication period with event triggered scheme (25), controller transmit only 67.6 % for ($\psi_i = .2$) and 28.57% for ($\psi_i = .5$) of sampled data produced by event

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triggered scheme at $\psi_i = 0$. From the above discussion, it is clear that with the help of event triggered scheme, the resource utilization of communication channel is reduced by 32.4 % and 71.43 % respectively. So, for LFC scheme based on event triggered method, the cost reduction on communication can be achieved by increasing the triggered parameters. However, for too large value of event triggered parameters, the system performance may deteriorate. Further the reduction in the communication cost, transmission rates, average release period and trigger time for different value of event triggered parameter is given below in Table.1. It is clear that data transmission rates to controller and average release period have an inverse relationship which is realistic for LFC problem in SG. For higher value of event triggered parameter in LFC scheme, using longer sampled data stay, average release period of samples will increase and hence the signal transmission rate to controller is reduces and finally, cost of communication burden in SG is greatly reduced.

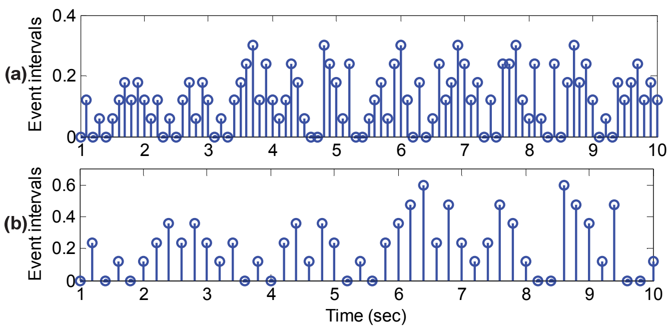

Fig.5 (a) Release instant and release interval with $\psi_i = .2$ and T=0.1 (b) Release instant and release interval with $\psi_i = .5$ and T=0.1

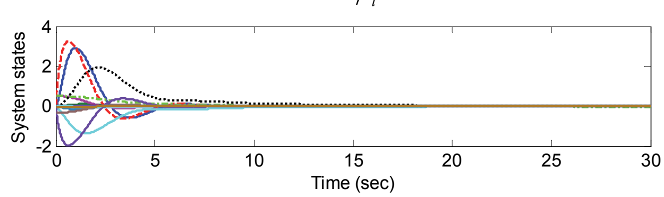

Fig. 6. System states response of perfect CT of LFC method with $\Psi_i = .2$

Table.1 Communication cost reduction, transmission rates, average release period and triggered time with different event triggered parameters

$\psi_i = 0$	$\psi_i = 0.1$	$\psi_i = 0.2$	$\psi_i = 0.3$	$\psi_i = 0.4$	$\psi_i = 0.5$
Communication cost reduction in (%)					
0	28.5	32.4	45.8	61.25	71.43
Transmission rates in (%)					
100	61.5	67.6	54.2	38.75	28.57
Average release period in(sec)					
0.01	0.01626	0.0147	0.0184	0.0258	0.0350
Trigger time in (sec)					
1000	615	676	542	387.5	285.7

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V. Simulation Results And Discussion

In this section, four area power system (Fig.1) coupled via communication network as smart grid is simulated with an intelligent controller. Due to packet loss, induced network delay, the CT of smart grid changes and hence the dynamic performance of power system degrades. With CT changes, the MSE of system states are computed to evaluate the dynamic performance of system. The system parameter of four area power system in this study is considered from [12].

A. Case-1: Mean square error of power system states

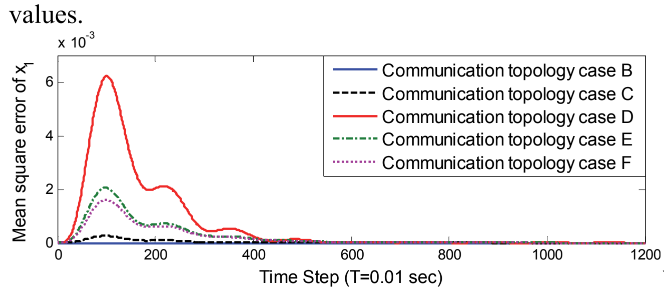
In this subsection, the MSE of power system states are computed. In order to validate the system dynamic performance and stability over the communication network, mean square error (MSE) of power system states can be computed.

$$x_i = [\Delta f_i \quad \Delta P_{t_i} \quad \Delta P_{g_i} \quad \Delta P_{tie}^{\ ij}]$$

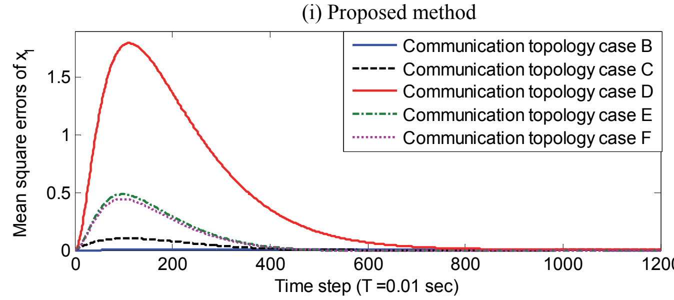
$$MSE(k) = \{(x(k) - x_0(k))^T (x(k) - x_0(k))\} \tag{28}$$

Where, $x_0(k)$ is the nominal state of power system at kth time, and $x(k)$ is the system state when a communication infrastructure is used. The sampling period is considered as 0.01 sec. The initial value of frequency deviation for studied system is considered as 0.5 Hz.

The perfect CT (Case A) (Fig.2 (a)) is selected in analysis as a reference while computing the MSE of state vector for other areas. Further the impact of CT changes on the dynamic performance of four area power system using MAS technique is analyzed and compared with suboptimal control design by [12]. It is clear that CT mode is highly random as time progresses. The MSE of state variables for five imperfect CT with respect to perfect CT for area-1 is illustrated in Fig. 7(a). It is clear that dynamic response of area-1 remains sensitive to CT changes compared to [12]. Further the MSE of state variables of other area with respect to perfect CT for area-2 to area-4 is illustrated in Fig.7 (b) to Fig. 7 (d). The accuracy of these states seeks importance in providing information to AGC control center, on how the others areas communicate to its neighbouring areas using MAS technique. The comparative variation of MSE for state x_i all the four areas are shown in Fig.7 (b). It may be ascertained that system parameters and bias coefficient have influence on the computation of MSE values.



(i) Proposed method



(ii) Sub optimal control design by [12]

(a) Dynamic performance of Area-1

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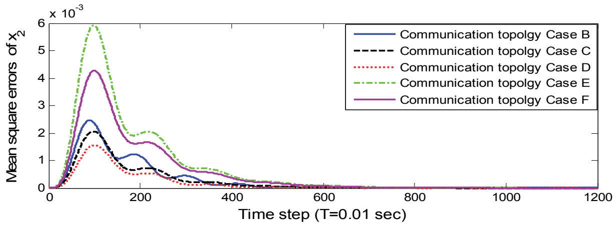
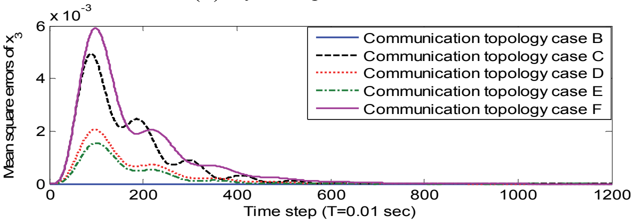
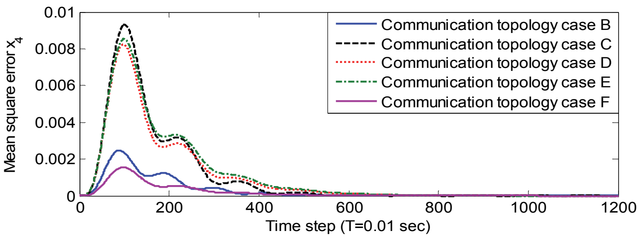


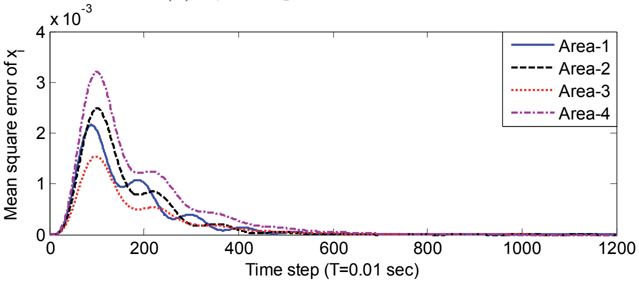
(b) Dynamic performance of Area-2



(c) Dynamic performance of Area-3



(d) Dynamic performance of Area-4

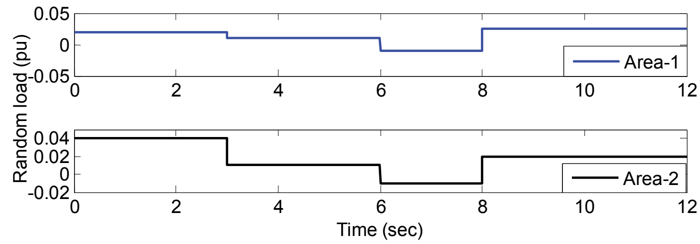


(e) Dynamic performance of all area

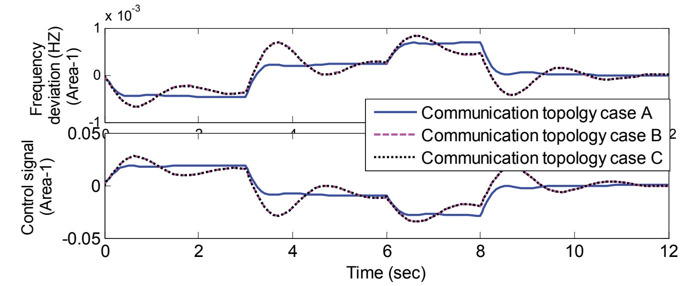
Fig.7 Dynamic response of states and all areas mean square error with MAS technique

B. Case-2: System response with random load using MAS technique as CT changes in SG

In this subsection the performance of system with multi step random load is evaluated. A multi-step change in load is applied for area-1 and area-2 is given in Fig.8 (a) and corresponding frequency deviation and control signal of area-1 with different CT is presented in Fig.8 (b). It is clear that proposed coupled power system with CT using MAS technique performed satisfactorily. Further the impact of time delay (0.5 sec) on system performance with CT changes using MAS techniques for random load is presented and corresponding frequency deviation and control signal of area-1 is given in Fig.9. From Fig.9, it is clear that, the frequency deviation in area-1 becomes oscillatory, as CT changes. For perfect CT (case A), the frequency deviation on random load with delay introduced is less oscillatory than other CTs, i.e. case B & case D. In order to show the behavior of power system dynamics during changes of CT from one type (Case A) of CT to other type (Case B) of CT, a simulation is performed for 12 sec, in which at 5 sec, the CT changes from case A to case B with random load applied in area-1. The impact of CT changes during controller action is illustrated in Fig.10. It is worth to remark that proposed controller design implemented with MAS performs well even if CT is changed during simulation time. The system performance is also validated with time varying delay $\tau = [0, 0.5]$ sec with CT changes for random load. The frequency deviation of area-1 with time varying delay is shown in Fig.11. It is clear that frequency deviation response settles down quickly for case A. On the other hand for case B, oscillations can be seen following the load disturbance, but remains within the limits and settles down. This suggests the suppression of instability. The study suggests using controller design as MAS, it is possible to have a large degree of intelligence and flexibility to face variable and uncertain environment.

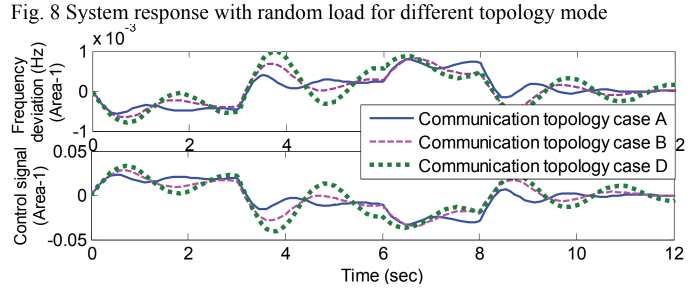


(a) Random load



(b) Area-1 system performance with CT

Fig. 8 System response with random load for different topology mode



(a) Area-1

Fig.9 System response with random load and 0.5 sec delay for different topology mode

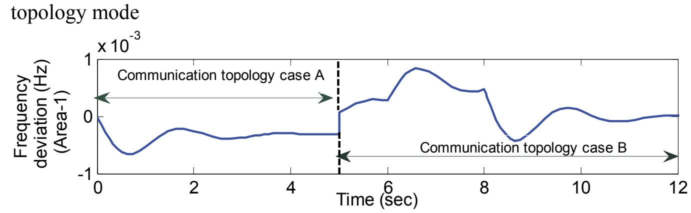


Fig. 10 Frequency deviation with change in CT for random load

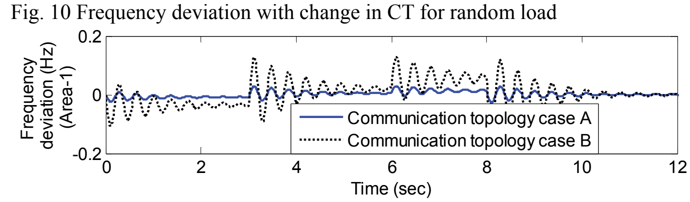


Fig.11 Frequency deviation with change in CT for random load with time varying delay

VI. CONCLUSION

This paper presented an intelligent controller for LFC in SG environment having changes in CT using MAS technique. The MAS based on PSO technique was applied to tune the controller parameters. An event triggered approach has been presented to improve the dynamic performance of power system in SG environment under the LFC scheme. The dynamic variation of MSE confirmed the reliable and accurate representation of states vector. The variation of maximal and sub-maximal peaks of frequency deviation satisfied the LFC and networked structure framework as smart grid. To demonstrate the effectiveness of proposed approach, some case studies were performed on multi-area LFC problem as CT changes in SG. The outcome of studies suggested satisfactory performance for all cases and improved the dynamic performance of system. Thus this paper highlights the MAS technique for communication infrastructure and its application for LFC in SG. Thus, MAS based scheme seems to be a feasible solution in the multi-area power system for implementation of power flow balance in order to regulate the frequency deviation. Our future work may be directed towards the design of robust control, considering cost of communication signal in event-triggered control of the LFC method.

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