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H_∞ load frequency control of interconnected power systems with communication delays

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ABSTRACT

This paper considers the problem of power system load frequency control design incorporating the effect of using open communication network instead of a dedicated one for the area control error signals. To have this, we appropriately consider time-delays in the ACE signals. A delay-dependent two-term H_∞ controller design has then been proposed using linear matrix inequalities. Comparison of effectiveness of the proposed two-term controller with that of existing one-term and two-term controller designs establishes the superiority as well as applicability of the present design for the LFC problem.

1. Introduction

Load frequency control (LFC) is of importance in electric power system operation to damp frequency and voltage oscillations originated from load variations or sudden changes in load demands. This problem has been investigated by many researchers and various control strategies, e.g., Proportional–Integral (PI) control [6–8,20], H_∞ control using state feedback [4,5,11,13,21], variable structure control [19], adaptive control [3], have been employed in the design of LFC for interconnected power systems. Recently, several papers have been published to address the LFC schemes that yield adequate control performance in presence of nonlinearities in an interconnected power system [23–25]. In [23], the effects of governor dead-band nonlinearities have been considered in controller design phase to reduce the amplitude of sustain oscillation using parameter optimization technique. With the emerging intelligent techniques, newer control strategies have been adopted to consider the effect of uncertainty and disturbances in the power system model using fuzzy logic [24] and neural network [25] approaches with a view to improve the system performance. These control strategies have promising results, and notable features are mainly their applicability to a wide range of operating conditions and their model-free nature. Several design techniques for LFC based on centralized as well as decentralized one are available in literature. Decentralized controller designed using only local measurements has the capability of stabilizing systems in presence of nonlinear interaction terms in power system model and the corresponding more recent results can be seen in [26,27]. In recent years, several control strategies based on robust and optimal approaches have been considered for solution of LFC problems under deregulated environment. One of the recent developments after deregulation of the power industry is to introduce an open communication network/infrastructure to support an increasing variety of ancillary services for effective implementation of automatic generation control (AGC) scheme [8,9,18,28].

Most of the works on LFC reported in literature have not considered the problems associated with the communication network and this assumption, in true sense, is valid under the traditional dedicated communication links. In view of the structure of existing power system model used for LFC [3–5,8,11,13,19,21], the area control error (ACE) acts as a control input to regulate the frequency deviation automatically. In general, the ACE signals are sought through high speed communication channel and may involve negligible communication delay. In [7,13,14,18,22], the need for open communication network has been highlighted, which may cause a significant amount of communication delay present in the ACE signal. However, to the best of our knowledge, there are only few literatures

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that investigate the LFC design considering communication delay in the ACE signal, and subsequently a memory-less state-feedback control law ($u(t) = Kx(t)$) for such system has been considered in [22]. Further in [22], a delay-independent and memory-less decentralized control structure is considered for solution of LFC problem with communication delay. It is worth mentioning at this stage that, in [22] the possibility of designing a delay-independent with two-term controller in decentralized control framework has not been attempted for LFC problem. However, following the methods in [11,13], it has been emphasized in this paper that the possibility of designing of such controller is not feasible. Thus, a new delay-dependent two-term controller design is proposed and can even formulate a generalized framework for solution of decentralized control problem adopted in [22]. In [8], a robust PI based LFC with mixed H_2/H_∞ and H_∞ control designs technique have been derived using static output feedback (SOFB) control law in linear matrix inequality (LMI) framework to obtain the stabilizing controller gains. In this case, the delays are considered to be in the control input as well as in the states. In this paper, LFC is designed with state feedbacks considering the communication delays present in the ACEs (state delay) as well as in the feedback, and subsequently H_∞ based two-term delay-dependent controller is derived to investigate the effect of time-delay as well as the change in the load demand on the solution of LFC problem.

On the other hand, LFC design may be classified based on the state feedback controllers into two types (a) one-term controller (no delayed state) and (b) two-term controller (control law is generated using both delayed and present state information) [11,13]. Note that, the later one may yield better performance due to the additional control part that uses the past state information. However, existing designs of such two-term controllers [11,13] consider only delay-independent design criterion, i.e., the stability criterion does not include any information on the size of delayed state information while the controller is designed. Such designs consider the delay at infinity as a special case of it and yields conservative results. Clearly, the controller performance may be improved if one considers delayed states information to be limited and correspondingly delay-dependent design criterion is made. A comprehensive review on robust load frequency control for an interconnected time-delay power system and the effects of power system restructuring on the frequency regulation can be found in [9].

Design of a two-term H_∞ state feedback LFC for a two-area interconnected power system is considered in this paper. The power system model under consideration takes into account of time-delays in the ACE signals as state delays. Lyapunov–Krasovskii (LK) functional approach discussed in [10–12,16,17] is considered to establish delay-independently as well as delay-dependently stability criterion in LMI framework and solving this LMI criterion, one can obtain the desired controller gains. Finally, through a numerical example it is seen that existing delay-independent design of two-term controllers lead only to the one-term controller since the control gain matrix corresponding to the delayed state obtained either zero or very small than that of the gain matrix corresponding to non-delayed states. Further, it is shown by comparing simulation results, the proposed two-term controller yields more damped response of the system compared to one-term controllers.

The paper is organized as follows. The power system time-delay model is discussed in Section 2. Section 3 presents different state feedback stabilizing criterion for H_∞ controller design using LK functional approach in an LMI framework. First, a one-term controller design criterion is presented based on [11,22] and then the proposed two-term controller design criterion is presented. Simulation results are presented in Section 4. Finally, Section 5 concludes the paper.

2. LFC Model with multiple state delays

The different types of possible LFC structures under regulated and deregulated power markets are (i) free LFC-it does not support deregulation of power market and here LFC commands are sent out traditionally through point to point communication (ii) charged LFC and bilateral LFC-it supports deregulated power market scenario and requires open communication network for passing the LFC command and various other ancillary services, details can be found in [28]. It may be noted that the power market scenario in most of the countries is "free LFC" type, but gradually across the globe the power generations are getting less importance which ultimately means an end to existing "free LFC" structure. Thus, in turn, power markets are expected to follow "charged LFC" type with or without bilateral contracts (or bilateral LFC). The initiative in this regard can be found in [14] and references there in.

Here, we provide a brief discussion on "charged LFC" structure without bilateral contract [28] as shown in Fig. 1, as the present work is motivated towards developing control methods supporting LFC problem for such power market scenario. In this case, transmission companies (TRANSCOs) has an obligation to provide LFC to the generation companies (GENCOs) but does not own it, in such a power market scenario TRANSCOS purchases power from GENCOs and sale it to distribution companies (DISCOs). In such situation TRANSCOs have to execute central control algorithm, measuring frequency deviation and net tie-line deviation, and in consequence issues control commands to GENCOS to adjust their real power output. Whereas in case of "bilateral LFC" type structure, there is no central control algorithm, as TRANSCO do not provide LFC, DISCOS must enter into load matching (LM) contracts with GENCOs, thus leading to highly decentralized type of control strategies i.e communications among control areas are frequent. The time delays in a LFC problem are invariably considered on the communication channels between the control centre and operating stations; notably on the measured frequency and measured tie-line power flow and have impacts on the performance of LFC and even cause system instability. Following literature [8,13,20–22] addresses decentralized control strategies for LFC problem with communication delays as in all those cases controller design is attempted to take into account "bilateral LFC" type structure. To simplify the LFC model we consider one GENCO each in two control areas, but multiple GENCOs can exist when "charged LFC co-exists with "bilateral LFC", also the model can be directly extended for more number of control areas.

In view of the above discussion, a two-area interconnected power system model with communication delay is shown in Fig. 2 in the next page. The notations used for the ith area, $i = 1,2$, are given in the following.

ΔP_{vi}	governor valve position
ΔP_{mi}	mechanical power output of the alternator
Δf_i	frequency deviations
ΔE_i	ACE signals
ΔP_{12}	tie-line power flow from area 1 to area 2
B_i	Proportional gains of local PI controllers
K_i	Integral gains of local PI controllers
T_{pi}	Power system time constants
D_i	Generator damping coefficients
T_{gi}	Governoror time constants
T_{chi}	Turbine time constants
R_i	Speed droops
T_i	Stiffness coefficients
ΔP_{di}	load disturbances
M_i	Moment of inertia of the generators