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Robust overlapping load frequency output feedback control of multi-area interconnected power systems

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ABSTRACT

This paper presents a new approach to the design of robust proportional-integral (PI) load frequency controller (LFC) with overlapping structure in the presence of generation rate constraint (GRC) and time-varying communication delays. The power system is decomposed into overlapping areas with tie-lines being the overlapping (shared) parts between the areas. The overlapping LFC design is based on the expansion-contraction principles, where the power system is first expanded in such a way as to decouple the areas from each other. Then, for obtaining an appropriate level of performance, robust local stabilising PI controllers are designed for each of the decoupled areas using an iterative linear matrix inequality (ILMI) algorithm such that asymptotic stability with a minimal H_∞ performance level is achieved. Finally, the designed robust local H_∞ controllers are contracted (transformed) to a robust overlapping LFC for implementation on the multi-area power system. Although the approach is applicable to multi-area power systems, a time-delay three-area interconnected power system experiencing communication delays is considered in this paper. Simulation results under different scenarios clearly illustrate an improved performance obtained with the overlapping structured LFC of this paper compared with existing decentralized LFCs.

1. Introduction

Load frequency controller (LFC) design is crucial in the operation of power systems to maintain the frequency and the power exchange between the areas as close as possible to the scheduled values when load demand exceeds generation. Due to the central roles LFC plays, it has been a subject of much research over many decades. In some research works, centralized LFC design based on state feedback theory has been addressed [1–3]. The centralized LFC refers to a central (global) controller which receives measurements from all states of a power system to generate control inputs for all areas. In other words, there exists a control station with one central controller receiving state measurements and sending control signals to all areas.

However, there are many practical drawbacks, such as low reliability, high computational and communication costs, with the centralized LFC scheme. To overcome these issues, decentralized LFC based on area control error (ACE) measurement has been proposed, as an alternative and has been studied widely [4–8]. The decentralized LFC scheme consists of local controllers where each controller receives locally measured ACE and generates local control signals. In other words, each area is controlled separately in the decentralized LFC scheme.

Local controllers in the decentralized LFC scheme, only use local ACE measurements while it has been found that tie-line powers between each pair of areas are the essential parts of the interconnections [9–11]. To deal with tie-lines (interconnections), overlapping structured LFC based on the physical overlapping structure of multi-area power system, has been proposed [11–13]. In this scheme, the overlapping decomposition technique, [14,15], is used to decompose the multi-area power system into overlapping areas. The overlapping part between every two neighboring areas corresponds to the tie-line power exchange between them. The overlapping structure of the power system is due to the fact that the tie-line power exchange between any two areas is the same in each of the areas. Once the overlapping decomposition is determined, the inclusion principle technique [14] is used to disjoint areas from each other. This is akin to breaking the ties among all areas. This process is called "expansion", and allows for the design of a local controller for each area separately. Once the local controllers are designed, they are put together in a structure compatible with the physical system. This process is called "contraction".

However, the above mentioned LFC design approaches ignore inherent delays in network communication channels. The network

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delays in communication channels are classified by [16,17] into: (i) constant delays which arise from a network congestion or a denial of service attack (cyber-attack), and (ii) time-varying or random delays which denote Byzantine failures (e.g. packets get delayed due to a router failure), malicious attacks, and data unavailability caused by a communication fault. More on time-delay LFC and causes for the delay can be found in [18–21].

As shown in [16], delays degrade the performance of LFC and may even cause instability. So, LFC design approaches with attention to communication delays have appeared in the open literature. These approaches may be categorized into two groups: delay-independent [18,19] and delay-dependent approaches [20,21,17,22]. Delay-independent techniques disregard information about the characteristics of the delays. On the other hand, delay-dependent approaches use available information about the characteristic of delays in the LFC design procedure. It is for the latter reason that delay-dependent approaches are more relaxed and preferred than delay-independent ones.

Robust delay-independent state feedback controllers have been designed in [18,19] by solving linear minimization problems (LMPs) with linear matrix inequalities (LMIs) as their constraints. However, state feedback based approaches require availability of all states, which makes them complex and costly to implement, especially for power systems.

A viable alternative to state feedback is output feedback. A delay-dependent LMI-based approach is proposed in [20] to design a robust, decentralized, output feedback, proportional-integral (PI)-type LFC for a multi-area power system, in the presence of constant communication delays. A robust, decentralized, delay-dependent, proportional-integral-derivative (PID)-type LFC design is reported in [21] to achieve stability and an appropriate performance in the presence of constant and time-varying network delays. The robust decentralized PID-type LFC is obtained in [21] by solving a non-linear minimization problem (NLMP). Also, findings of [17] can be used to guide the tuning of PI controllers for different delay margins. In [22], a robust overlapping output feedback LFC in the presence of constant communication delays is designed. Finally, the load frequency control problem with integration of electric vehicles in the presence of constant delays is studied in [23,24]. For detailed survey on LFC design approaches, see [25].

Based on the above discussions, this paper investigates designing a robust overlapping delay-dependent output feedback LFC in the presence of constant and time-varying communication delays. Indeed, this paper is continuation of authors' research given in [22], and the main advances compared with [22] are as follows.

- Firstly, [22] studies the LFC design problem for a state-delayed power system proposed by [18,19]. Possibility of tuning local PI controllers in the presence of time-delays is ruled out in [18,19,22] due to its difficulty. So, additional control inputs (u_i in Fig. 1 of [22]) are introduced in each area to stabilize the system. In other words, local PI controllers are pre-defined, and additional control inputs are designed to obtain stability. However, additional control inputs used in [18,19,22], require extra communication channels to be installed for information transfer, and thus adds more cost, complexity, computational requirements and probability of occurring faults in the communication channels.
In order to avoid all these substantial issues arise from extra control inputs, this paper deals with stability and control of an input-delayed power system [20,21]. Based on the input-delayed model, this paper designs local PI controllers instead of using extra control inputs, to achieve stability as well as acceptable H_∞ performance in the presence of network delays. As a consequence of introducing time-varying communication delays in input signals, derived LMIs used for LFC design procedure, are substantially different from [22] (See Remark 4).
- Secondly, results of this paper can be used to design robust overlapping LFC in the presence of constant and time-varying delays which usually occur in communication networks, while [22] just focuses on the LFC design with constant communication delays. Thus, techniques of [22] cannot be used to deal with time-varying delays. So, this paper extends stability criterion of [22] to time-varying delay systems.
- Finally, there are constraints for the generation rate due to physical limitations, and these constraints affect the performance of the load frequency control system. This paper takes the nonlinearity, called the generation rate constraint (GRC), into account during LFC design. However, [22] does not consider any nonlinearity in the LFC design.

A brief comparison of the main differences between this paper and existing time-delay LFC approaches is given in Table 1.

The overlapping LFC design in this paper is based on the expansion-contraction process [14], explained briefly in Section 3, and can be summarized as follows:

1. A state space model of the power system is first developed and then expanded to generate a higher-dimensional system (expanded system) comprised of completely disjoint areas. The existence of disjoint areas in the expanded system allows for the design of a local robust PI-controller for each of the areas.
2. A delay-dependent iterative algorithm including LMPs with LMI constraints is proposed to design local controllers for disjoint areas of the expanded system such that stability with a minimal disturbance rejection level is achieved.
3. The local controllers are aggregated to form a decentralized LFC of a block-diagonal structure, which is then contracted (transformed) to an overlapping structured LFC for implementation on the power system.

To show the effectiveness of new LFC design approach, a time-delay three-area interconnected power system reported in [20,21] is used as the case study. For this system, a PI-type LFC with overlapping structure is designed, and the results are compared with decentralized LFCs of [20,21]. Simulation results show that the overlapping LFC scheme leads to improved responses in respect of settling time and oscillation compared with decentralized LFC schemes of [20,21].

Table 1
Comparison of this paper with existing time-delay load frequency control design approaches.

Paper	Structure of LFC	Type of robust LFC	Type of communication delay	The optimization problem
[18]	Decentralized	State feedback	Constant	LMP
[19]	Centralized	Two-terms state feedback	Constant	LMP
[20]	Decentralized	PI-type output feedback	Constant	LMP
[21]	Decentralized	PID-type output feedback	Both constant and time-varying	NLMP
[22]	Overlapping	PI-type output feedback	Constant	LMP
This paper	Overlapping	PI-type output feedback	Both constant and time-varying	LMP