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LMI based robust load frequency control for time delayed power system via delay margin estimation

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A R T I C L E I N F O

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A B S T R A C T

The employment of communication channels inevitably result in the advent of time delays in load frequency control (LFC) schemes. The existence of such time delays exerts potential threats on the stability of power systems. This paper aims to study a three-area time delayed power system and propose a linear matrix inequality (LMI) based robust LFC scheme with delay margin estimation. Analytic form of the delay margin is subsequently provided. Following that, LMI based robust controller design procedure is proposed based on delay margin estimation, wherein the robust performance index (RPI) is introduced. The robust controller gains are ultimately obtained with the estimated delay margin and a binary search technique which aims to find the minimum value of RPI. Simulations are conducted to evaluate performance of the proposed scheme: the effectiveness of the DME process is verified under an ideal power system condition; a second simulation incorporating the effects on GRC and GDB is conducted to further validate the rightness of DMC; parameter perturbations are considered in the next simulation; a comparative study which compares the proposed approach with other three existing methods is initialized in the fourth simulation test; at last, the impact of a micro grid comprises wind and solar energy generation units is incorporated to test the performance of the novel method. The simulation results indicate that the delay margin estimation procedure is effective and the proposed control scheme is robust and has superior performance over conventional LMI based robust control schemes.

1. Introduction

Load frequency control (LFC) has been extensively utilized in power grids to maintain system frequency and power exchange between multiple power areas within the allowable range near scheduled values [1,2]. Various LFC schemes have been proposed in the past 40 years, including the proportional-integral-derivative (PID) based LFC approach [3], fuzzy logic based robust LFC schemes [4], adoptive LFC technique in energy market [5], neural network based automatic LFC frames [6] as well as linear matrix inequality approach [7].

One of the major challenges for LFC schemes that may jeopardize system stability is existence of communication delays due to the employment of communication channels between control center and the terminal station, namely, the remote terminal units (RTUs) [8–10]. Small time delays in communication channels are generally ignored since their impacts on system stability are limited. However, the advent of much more dedicated networks, the employment of fiber-optic-cables, transmission protocols, power line carriers as well as phasor measurement units make the existence of large time delays possible in power system [11]. Several literatures have reported issues of large communication delays in the range of 0.5–15 s which may cause major consequences concerning system stability [12–14], [33–35,40]. Hence, it is of critical importance to estimate the maximum delay time with which power system stability will not be retained, namely, the delay margin.

Two kinds of delay margin estimation (DME) methods are being emplolyed in LFC scheme, which are the frequency-domain direct method (FDDM) and time-domain indirect method (TDIM). FDDM estimates delay margin by computing critical purely imaginary root of system characteristic equation and the examples of FDDM are critical eigenvalue tracing (CET) [15], cluster characteristic roots treatment (CCRT) [16,17], Schure-Cohn method (SCM) [18] and Rekesius substitution method (RSM) [19]. Those methods are capable of providing analytical results of system delay margin with the eigenvalue. Among them, CET method possesses the capability of tracing system eigenvalue when there are multiple constant time delays; CCRT method not only presents an explicit expression of stability region in terms of system parameters but also declares the number of characteristic roots that are unstable; SCM presented in [18] is implemented to calculate delay margin of automatic generation control (AGC); and RSM in [19] deals

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Nomenclature

Δf	system frequency deviation
ΔP_m	mechanical output deviation
ΔP_v	valve position deviation
D	damping coefficient
M	generator inertia moment
T_{ch}	turbine time constant
T_g	governor time constant
R	speed drop
β	frequency bias factor
K_P	proportional gain
K_I	integral gain
τ_k	the kth time delay
τ	the common time delay
γ	robust performance index
τ_{DME}	delay margin
$+$	general reverse of matrix
TDPS	time delayed power system
ACE	area control error
RT	root tendency
RPI	robust performance index
DME	delay margin estimation
GRC	generation rate constraints
GDB	governor dead band

with delay margin issue of a single area power system. While the only drawback of FDDM lies in that it can only deal with constant time delays. TDIM is based on Lyapunov stability theory as well as linear matrix inequalities (LMIs) [20–22]. Different from FDDM schemes, TDIM is capable of dealing with system DME issue with both constant and time varying delays. Some novel approaches are proposed to treat the nonlinearities of interconnected power systems. A Bacteria foraging optimization algorithm is proposed in [29,30], a Cukoo search algorithm is constructed in [31] and a BAT algorithm is established in [32] to deal with nonlinear interconnected power systems. However, the TDIM approaches are not so mathematically explicit as the FDDM approaches and it fails to provide an analytic expression of the delay margin of the time-delayed power systems.

Although these aforementioned DME schemes are mostly proposed a few years ago, they generally aim to treat ordinary time delayed LMI systems and are rarely applied in LFC scheme of a time delayed multi-area power systems [27,30,31]. A FDDM based DME approach was proposed to conduct stability analysis of a generator excitation with constant time delays [23], and delay margin of a single-area power system with constant communication delays was computed with the same algorithm [24]. The stability of a two-area time delayed power system was analyzed with FDDM based on the work of paper [17–19] and proposed the corresponding LFC scheme based on the analysis [11].

This paper aims to propose a robust LFC scheme for time delayed multi-area power system based on LMI theories via DME. FDDM is employed and DME proposed in [17] is applied to a three-area power system with uniformed time delay. Hence, the introduction of the DME procedure can largely enhance the performance of the LFC scheme as compared to approaches reported in other literatures. Meanwhile, since most of the DME approaches and LFC schemes are based on one or two-area power systems [11,21], it is of critical importance to apply the DME approach into three-area power systems. Moreover, a three-area power system can better reflect the practical situation of a multi-area power system with communication delays [12,25,27]. A recursive procedure is utilized twice to eliminate transcendental terms of characteristic equation and an analytical formula is obtained to describe the system delay margin. Furthermore, external disturbance is considered in system modeling and the robust performance index (RPI) is introduced to define the impact of external disturbance on system output [25]. With the delay margin calculated previously, a LMI based stability criteria for TDPS is introduced to guarantee system stability with the delay time smaller than the delay margin. Afterwards, a binary search technique (BST) is utilized to find the optimum value of RPI and a robust load frequency controller is proposed.

The main contributions of this paper are as follows: it proposes a novel robust LFC scheme incorporating the DME procedure, which largely promotes the performances of existing LFC approaches as reported in literatures; the effects of GRC and GDB are considered in the LMI based LFC scheme, which is merely mentioned in existing literatures; parametric perturbations are considered for robustness test; a comparative study incorporating three existing approaches is conducted to fully reveal the performance of the novel approach; the impact of distributed power generation units is also considered to fully simulate the practical operation of a multi-area power system. The remaining parts of this paper will be organized as follows. In Section 2, model of a multi-area LFC scheme will be introduced. In Section 3, a robust LFC scheme with DME scheme will be proposed and the algorithm to find the optimum RPI will be provided. In Section 4, simulations of a three-area TDPS including five case studies will be conducted. In Section 5, a conclusion will be drawn to summarize this paper.

2. LFC scheme for multi-area TDPS

This section presents dynamic model of LFC scheme for TDPS. The dynamical behavior of a complex power system is generally described by a group of differential algebraic equations, wherein system parameter deviations, external disturbances as well as time delays can be taken into consideration. During an external disturbance, dynamic nonlinear equations can be linearized near an operation equilibrium point and small signal stability analysis can be conducted. As [12]

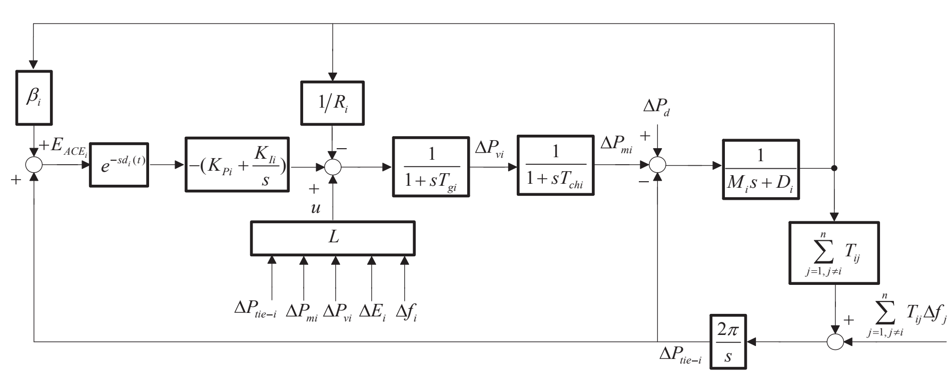

Fig. 1. Control diagram of one area in a multi-area TDPS.