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A robust decentralized load frequency controller for interconnected power systems☆

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ABSTRACT

A novel design of a robust decentralized load frequency control (LFC) algorithm is proposed for an interconnected three-area power system, for the purpose of regulating area control error (ACE) in the presence of system uncertainties and external disturbances. The design is based on the concept of active disturbance rejection control (ADRC). Estimating and mitigating the total effect of various uncertainties in real time, ADRC is particularly effective against a wide range of parameter variations, model uncertainties, and large disturbances. Furthermore, with only two tuning parameters, the controller provides a simple and easy-to-use solution to complex engineering problems in practice. Here, an ADRC-based LFC solution is developed for systems with turbines of various types, such as non-reheat, reheat, and hydraulic. The simulation results verified the effectiveness of the ADRC, in comparison with an existing PI-type controller tuned via genetic algorithm linear matrix inequalities (GALMIs). The comparison results show the superiority of the proposed solution. Moreover, the stability and robustness of the closed-loop system is studied using frequency-domain analysis.

1. Introduction

A large-scale power system is composed of multiple control areas that are connected with each other through tie lines [1]. As active power load changes, the frequencies of the areas and tie-line power exchange will deviate from their scheduled values accordingly. As a result, the performance of the power system could be greatly degraded [2]. A local governor of the power system can partially compensate power load change through adjusting generator's output. However, with this type of governor, when the system load increases, the system frequency decreases and vice versa [3]. Therefore a supplementary controller is essential for the power system to maintain the system frequency at 60 Hz (a scheduled frequency in North America) no matter what the load is. This type of supplementary controller is called automatic generation control (AGC), or more specifically, load frequency control (LFC). For stable operation of power systems, both constant frequency and constant tile-line power exchange should be provided [4]. Therefore an Area Control Error (ACE), which is defined as a linear combination of power net-interchange and frequency deviations [1], is generally taken as the controlled output of LFC. As the ACE is driven to zero by the LFC, both frequency and tie-line power errors will be forced to zeros as well [1].

In the past six decades, there has been a significant amount of research conducted on LFCs. During the early stage of the research, LFC was based on centralized control strategy [5,6], which has "the need to exchange information from control areas spread over distantly connected geographical territories along with their increased computational and storage complexities" [3]. In order to overcome the computational limitation, decentralized LFC has recently been developed, through which each area executes its control based on locally available state variables [7]. Among various types of decentralized LFCs, the most widely employed in power industry is PID control [8–13]. The PI controller tuned through genetic algorithm linear matrix inequalities (GALMIs) [11] becomes increasingly popular in recent years. PID controller is simple to implement but usually gives long settling time (about 10 to 30 s) and produces large frequency deviation [14]. The PID controller introduced in [13] shows good performance in reducing frequency deviations. However, the robustness of the PID controller for multiple-area power system is not investigated in [13]. With the recent progress in control technologies, advanced controllers have come into adoption for load frequency controls. Due to the change of power flow conditions, parameters in a power system model fluctuate almost every minute [15]. To solve this problem, both H_∞ [16,17] and adaptive controllers [18,19] are applied to the power system. The controllers not only identify parameter uncertainties but regulate the ACE. In addition, a μ-synthesis controller was introduced in [20] to compensate modeling uncertainties. Fuzzy logic based LFC is presented in [21,22]. Such a controller is often combined with PI or PID controllers to optimally adjust PID gains. Most of the existing

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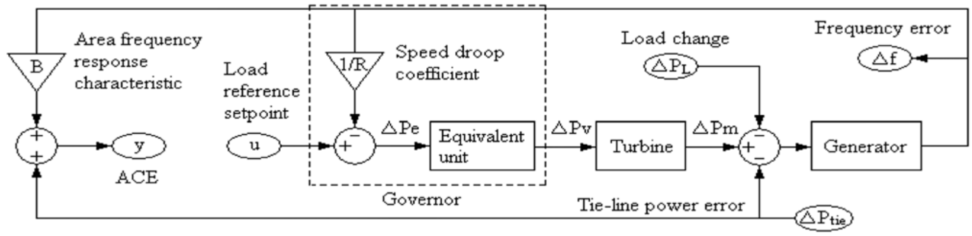

Fig. 1. Schematic of one-area power generating unit.

LFCs apply to the control areas comprising of thermal turbines, only a few of them [13,16] treat both thermal and hydraulic turbines.

This paper presents a novel solution in the form of a decentralized robust LFC for a three-area interconnected power system. Its performance is evaluated in the presence of parameter uncertainties and large power load changes. The power system studied here contains reheat, non-reheat, and hydraulic turbine units, which are distributed in the three areas respectively. This solution is based on active disturbance rejection control (ADRC), an emerging control technology that estimate and mitigate uncertainties, internal and external, in real time, resulting in a controller that does not require accurate model information and is inherently robust against structural uncertainties commonly seen in power systems. Particularly, compared to other complex advanced controllers [15–21], the ADRC only has two tuning parameters, making it simple to implement in practice. So far the ADRC has been successfully employed in MEMS, power converter, and web tension [22–26]. In this paper, it is the first time that the ADRC is modified and applied to the power system with three different turbine units. Some preliminary results of the research were published in [27], where the performance of the ADRC was compared with a LMI tuned PID controller [12] for the power system with only non-reheat turbine units.

This paper is organized as follows. The dynamic modeling of the power system is given in Section 2. The ADRC design is introduced in Section 3. Simulation results are shown in Section 4. Stability analyses are presented in Section 5. The concluding remarks are made in Section 6.

2. Dynamic model

In this section, the dynamic model of a three-area interconnected power system is developed. As shown in Fig. 1, each area of the power system consists of one generator, one governor, and one turbine unit. The generator, governor, and turbine constitute a power generating unit. In addition, each area includes three inputs, which are the controller input $U(s)$ (also denoted as u), load disturbance $\Delta P_L(s)$, and tie-line power error $\Delta P_{tie}(s)$, one ACE output $Y(s)$, and one generator output Δf. In Fig. 1, ΔP_v denotes valve position change, ΔP_e electrical power, and ΔP_m mechanical power. The ACE alone is a measurable output. For each area, it is defined by (1), where B is area frequency bias setting [1].

$$ACE = \Delta P_{tie} + B\Delta f. \tag{1}$$

We use transfer function (TF) to model the one-area generator unit for the sake of convenience in frequency-domain analyses. Let the transfer function from $\Delta P_e(s)$ to $\Delta P_m(s)$ be $G_{ET}(s) = Num_{ET}(s)/Den_{ET}(s)$, where $Num_{ET}(s)$ and $Den_{ET}(s)$ are the numerator and denominator polynomials, respectively, and they vary in different generating units. From [1], the TF of non-reheat turbine unit ($G_{ET}(s)$) is given by

$$G_{ET}(s) = \frac{Num_{ET}(s)}{Den_{ET}(s)} = \frac{1}{(T_g s + 1)(T_{ch} s + 1)}. \tag{2}$$

From [1], the TF of reheat turbine unit is represented by

$$G_{ET}(s) = \frac{Num_{ET}(s)}{Den_{ET}(s)} = \frac{F_{hp} T_{rh} s + 1}{(T_g s + 1)(T_{ch} s + 1)(T_{rh} s + 1)}. \tag{3}$$

From [1], the TF of hydraulic turbine unit is

$$G_{ET}(s) = \frac{Num_{ET}(s)}{Den_{ET}(s)} = \frac{(T_R s + 1)(-T_w s + 1)}{(T_g s + 1)[T_R(R_T/R)s + 1][(T_w/2) + 1]}. \tag{4}$$

According to [1], the TF of the generator is

$$G_{Gen}(s) = \frac{1}{Den_M(s)} = \frac{1}{Ms + D}. \tag{5}$$

The parameters in (2)–(5) are defined in Table 6 of Appendix. From Fig. 1, the output $Y(s)$ for each area can be represented by

$$Y(s) = G_P(s)U(s) + G_D(s)\Delta P_L(s) + G_{tie}(s)\Delta P_{tie}(s), \tag{6}$$

where $G_p(s)$, $G_D(s)$, and $G_{tie}(s)$ are the TFs between the three inputs ($U(s)$, $\Delta P_L(s)$, and $\Delta P_{tie}(s)$) and ACE output ($Y(s)$). The three transfer functions in (6) are expressed as

$$G_P(s) = \frac{RBNum_{ET}(s)}{Num_{ET}(s) + RDen_{ET}(s)Den_M(s)} \tag{7}$$

$$G_D(s) = \frac{-RBDen_{ET}(s)}{Num_{ET}(s) + RDen_{ET}(s)Den_M(s)} \tag{8}$$

$$G_{tie}(s) = \frac{Num_{ET}(s) + RDen_{ET}(s)Den_M(s) - RBDen_{ET}(s)}{Num_{ET}(s) + RDen_{ET}(s)Den_M(s)}, \tag{9}$$

where $Num_{ET}(s)$ and $Den_{ET}(s)$ have different expressions (as shown in (2)–(4)) corresponding to different turbine units.

The proposed ADRC-based control system is shown in Fig. 2. Under a decentralized control strategy, the ADRC controller is placed in each area acting as local LFC. Three decentralized areas are connected to each other through tie lines. Non-reheat, reheat and hydraulic turbine units are distributed in the three areas orderly. The parameter values of the system are obtained from [1,15] and are listed in Table 7 in Appendix. Substituting the parameter values into the $G_p(s)$ between the controller input $U(s)$ and ACE output, we will have

$$G_{PN}(s) = \frac{1.05}{0.015\ s^3 + 0.2015\ s^2 + 0.52\ s + 1.05} \tag{10}$$

$$G_{PR}(s) = \frac{2.205\ s + 1.05}{0.21\ s^4 + 1.801\ s^3 + 3.928\ s^2 + 2.975\ s + 1.05} \tag{11}$$

$$G_{PH}(s) = \frac{-5.25\ s^2 + 4.2\ s + 1.05}{1.14\ s^4 + 8.2\ s^3 + 7.945\ s^2 + 6.235\ s + 1.05}, \tag{12}$$

where $G_{PN}(s)$ denotes the TF for area 1, $G_{PR}(s)$ the TF for area 2, and $G_{PH}(s)$ the TF for area 3. From (12), we can see that the transfer function of hydraulic unit has a positive zero, which can bring instability to the system. This problem can be solved by fine tuning the controller parameters. The system with hydraulic turbine unit will be stabilized by the controller as well. The controller design and parameter tuning are introduced in the following section.