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Load frequency control in deregulated environments via active disturbance rejection

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ABSTRACT

Linear active disturbance rejection control (LADRC) method is investigated for the load frequency control (LFC) of power systems in deregulated environments. The connections between one area and the rest of the system and the effects of possible contracts are treated as a set of new disturbances besides the system load. LADRC uses an extended state observer (ESO) to estimate the disturbances and compensates them quickly. Thus it can achieve good disturbance rejection performance and is a good candidate for LFC design. The proposed method is tested on two power systems. Simulation results show that the LADRC is simple to tune for load frequency control systems, and good performance can be achieved.

Introduction

In the power system, frequency stability is an important index of power quality. However, the load of a power system is changing continuously and randomly. Any sudden load perturbation can cause the deviation of tie-line power exchanges and the frequency fluctuations. Therefore, to ensure the quality of the power supply, a load frequency control (LFC) system is needed. The goal of LFC is to reestablish primary frequency regulation capacity, return the frequency to its nominal value and minimize unscheduled tie-line power flows between neighboring control areas [1,2].

To increase competition in wholesale power market, large vertically integrated utilities providing power at regulated rates are being restructured to incorporate competitive companies selling unbundled power. Consumers are supposed to benefit from lower rates as a result of serious competitive bulk power markets. New players with different and sometimes opposing objectives have emerged. With increasing size and complexity of the restructured power systems, significant uncertainties and disturbances in power system control and operation are introduced. It is desirable that novel control strategies be developed to achieve LFC goals and maintain reliability of the electric power system in an adequate level.

Several methods have been proposed to design load frequency controllers in deregulated environments. Refs. [3–6] tried to modify the conventional LFC methods to take into account the effect of bilateral contracts on the dynamics; Ref. [7] proposed a market-based optimal LFC design method; Refs. [8,9] discussed decentralized LFC in deregulated environments based on optimal control theory and load disturbance accommodation theory; Refs. [10–13] discussed intelligence algorithms in designing load frequency controllers in deregulated environments; Ref. [14] uses GA to find the optimal integral gains and bias factors in the load frequency control of a three-area power system after deregulation.

While the proposed methods are shown to be able to improve the load frequency control performance in deregulated environments, some of the methods need to use full states of a control area as the feedback inputs; some lead to high-order controllers; and some are too complex to be understood by practical control engineers [15]. These factors make it difficult to apply the above mentioned advanced LFC techniques in practice, which motivates [16] to apply internal model control to design PID-type LFC controller in deregulated environment.

This paper applies active disturbance rejection control (ADRC) to solve the LFC problem in deregulated environments. ADRC was developed in [17,18]. The central idea is that both the internal dynamics and the external disturbances can be estimated and compensated in real time. ADRC was originally formulated using nonlinear control strategies, the nonlinear structure and a large number of tuning parameters make it hard to apply in practice. Refs. [19,20] considered the 'linear' version of ADRC, which greatly simplified the implementation of ADRC and made the tuning of ADRC easy for practicing engineers.

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Table 1
Nomenclature.

Δf_i	Frequency deviation of Area #*i* (Hz)
ACE_i	Control error of Area #*i* (puMW)
$\Delta P_{\mathrm{tie},i}$	Scheduled incremental change in tie-line power (puMW) between Area #*i* and other areas (puMW)
ΔP_c	Incremental change of governor setpoint (puMW)
ΔP_{Lk-i}	Deviation of contracted load demand of DISCO_k in Area #*i* (puMW)
$\Delta P_{\mathrm{Loc},i}$	Deviation of the total contracted load demands (puMW)
ΔP_{di}	Deviation of the un-contracted load disturbance in Area #*i* (puMW)
apf_{ki}	ACE participation factor of GENCO_k in AREA #*i*
$\Delta P_{m,k-i}$	Incremental change in generator output of GENCO_k in Area #*i* (puMW)
$\Delta X_{G,k-i}$	Incremental change in governor valve position of GENCO_k in Area #*i*
K_{Pi}	Subsystem equivalent gain of Area #*i* (Hz/puMW)
T_{Pi}	Subsystem equivalent time constant of Area #*i* (sec.)
T_{Tki}	Turbine time constant of GENCO_k in Area #*i* (sec.)
T_{Hki}	Governor time constant of GENCO_k in Area #*i* (sec.)
R_{ki}	Droop characteristic for GENCO_k in Area #*i* (Hz/puMW)
B_i	Frequency bias setting of Area #*i* (puMW/Hz)
T_{ij}	Tie-line synchronizing coefficient between Area #*i* and #*j* (puMW/Hz)
$G_{gki}(s)$	Transfer function for the governor of GENCO_k in Area #*i*
$G_{tki}(s)$	Transfer function for the turbine GENCO_k in Area #*i*
$G_{pi}(s)$	Transfer function of the generator in Area #*i*
ξ_i	Total contracted tie-line power flows from other areas to Area #*i* (puMW)
ρ_{ki}	Contracted load demand of GENCO_{k-i} from other areas (puMW)

In [21,22], linear active disturbance rejection control (LADRC) was applied to design LFC systems. It is shown that three-order LADRC is a good candidate for load frequency control and good damping performance can be achieved. In this paper, LFC in deregulated environments is investigated. The connections between one area and the rest of the system and the effects of possible contracts can be treated as disturbances for LADRC, and they can be estimated using the extended state observer and thus can be compensated quickly.

The main contributions of this paper are as follows:

(1) LFC design via active disturbance rejection control for multi-area power systems in deregulated environments is proposed.
(2) An anti-GRC scheme is proposed for active disturbance rejection control to compensate the generation rate constraints (GRC) in the turbine.

Compared with previous methods, the advantage of the proposed method is that the tuning of the controller parameters is easy. Moreover, simulation results show that the proposed method can achieve better performance.

All the symbols used in the paper are summarized in Table 1.

Multi-area LFC model in deregulated environments

In a traditional power system structure, the generation, transmission and distribution are owned by a single entity called a vertically integrated utility (VIU), which supplies power to the customers at regulated rates. In the restructured power systems, the VIU no longer exists. Deregulated system consists of generation companies (GENCOs), distribution companies (DISCOs), transmission companies (TRANSCOs) and independent system operator (ISO). The LFC problem for an *N*-area deregulated power system is shown in Fig. 1, and each area has the structure shown in Fig. 2, where K_i is the load frequency controller of Area #*i*.

In Fig. 2, ΔP_{di} denoted the total load demands of Area #*i*, apf_{ki} is the ACE participation factor of GENCO_{k-i} with

$$\sum_{k=1}^{n_i} \mathrm{apf}_{ki} = 1 \tag{1}$$

Signals which are different from the conventional environments are shown in the dashed lines in Fig. 2. $\Delta P_{\mathrm{Loc},i}$ denotes the total contracted load demands,

$$\Delta P_{\mathrm{Loc},i} = \sum_{j=1}^{m_j} \Delta P_{Lj-i} \tag{2}$$

where ΔP_{Lj-i} is the load demand of DISCO_{j-i}. Signals ξ_i is the total contracted tie-line power flows from other areas to Area #*i* [4],

$$\xi_i = \sum_{k=1,k\neq i}^{N} \left(\sum_{j=1}^{n_i}\sum_{t=1}^{m_k} \mathrm{gpf}_{(s_i+j)(z_k+t)} \Delta P_{Lt-k} - \sum_{t=1}^{n_k}\sum_{j=1}^{m_i} \mathrm{gpf}_{(s_k+t)(z_i+j)} \Delta P_{Lj-i} \right) \tag{3}$$

and ρ_{ki} is the contracted load demand of GENCO_{k-i} due to load demands from other areas [4],

$$\rho_{ki} = \sum_{j=1}^{N} \left(\sum_{t=1}^{m_j} \mathrm{gpf}_{(s_i+k)(z_j+t)} \Delta P_{Lt-j} \right) \tag{4}$$

In this new structure, GENCOs may or may not participate in the LFC task and DISCOs have the liberty to contract with any available GENCOs in their own or other areas. Thus, various combinations of possible contracted scenarios between DISCOs and GENCOs are possible. In another word, for restructured systems having several GENCOs and DISCOs, any DISCO may contract with any GENCO in another control area independently. This case is called as 'bilateral transactions'. All the transactions have to be cleared by the ISO. An 'Augmented Generation Participation Matrix' (AGPM) is adopted to express the possible contracts. The AGPM shows the participation factor of a GENCO in the load contract with a DISCO. The number of rows and columns of AGPM matrix is equal to the total number of GENCOs and DISCOs in the overall power system, respectively. The AGPM structure for a large-scale power system with *N*-control areas is given by

$$\mathrm{AGPM} = \begin{bmatrix} \mathrm{AGPM}_{11} & \cdots & \mathrm{AGPM}_{1N} \\ \vdots & \ddots & \vdots \\ \mathrm{AGPM}_{N1} & \cdots & \mathrm{AGPM}_{NN} \end{bmatrix}, \tag{5}$$

where

$$\mathrm{AGPM}_{ij} = \begin{bmatrix} \mathrm{gpf}_{(s_i+1)(z_j+1)} & \cdots & \mathrm{gpf}_{(s_i+1)(z_j+m_j)} \\ \vdots & \ddots & \vdots \\ \mathrm{gpf}_{(s_i+n_j)(z_j+1)} & \cdots & \mathrm{gpf}_{(s_i+n_j)(z_j+m_j)} \end{bmatrix} \tag{6}$$

where n_i and m_i are the number of GENCOs and DISCOs in Area #*i* and

$$s_i = \sum_{k=1}^{i-1} n_i, z_j = \sum_{k=1}^{i-1} m_j, s_1 = z_1 = 0, \text{ for } i,j = 1,\cdots,N \tag{7}$$

Each element of AGPM, gpf_{ij}, refers to 'generation participation factor' and shows the participation factor of $\mathrm{GENCO_i}$ in total load requirement of DISCO_j based on the contract. Sum of all entries in each column of AGPM is unity. The diagonal sub-matrices of AGPM, AGPM_{ii}, reflects the local demands of Area#*i* and off-diagonal sub-matrices, AGPM_{ij}, reflects the demands of DISCOs in Area #*j* on GENCOs in Area #*i*.

The load frequency control problem for multi-area power systems requires that not only the frequency deviation of each area must return to its nominal value but also the tie-line power flows must return to their scheduled values. So a composite variable, area control error (ACE), is used as the feedback variable to ensure the two objectives. For Area #*i*, the ACE is defined as

$$\mathrm{ACE}_i = \Delta P_{\mathrm{tie},i-\mathrm{error}} + B_i \Delta f_i \tag{8}$$