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# Decentralized load frequency control in deregulated environments

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ABSTRACT

Decentralized load frequency control (LFC) problem for multi-area power systems in deregulated environments is studied in this paper. A decentralized PID tuning method is proposed by assuming that the tie-line power flows are disconnected. The general transfer function model of LFC for decentralized control design of deregulated power systems is derived first, and then an IMC-PID method is used to design the local load frequency controllers. A method to analyze the stability of the decentralized LFC for conventional environments is also extended to the deregulated case. The proposed method is tested on a four-area power system under various operating conditions. Simulation results show that the proposed design method is simple to follow, can achieve good performance, and results in implementable PID controllers.



## 1. Introduction

Frequency control is one of the most profitable auxiliary services for power systems through maintaining short-term balance of energy and frequency of the power systems. Frequency control is usually accomplished through generator governor response (primary frequency regulation) and load frequency control (LFC). 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].

In 1996 the US Federal Energy Regulatory Commission (FERC) issued Order 888, a ruling on open access transmission, now known as electricity deregulation, or restructuring. The ruling intended to increase competition in wholesale power markets. Large vertically integrated utilities providing power at regulated rates are being restructured to incorporate competitive companies selling unbundled power. Consumers were 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. The already complex engineering system has to include economics, business, social and environmental aspects. Deregulation is affecting all business aspects of the power industry from generation to transmission.

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 the 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; Ref. [10] used a FACTS device controlled by a decentralized control law to damp the transient frequency deviation; Refs. [11–14] discussed intelligence algorithms in designing load frequency controllers in deregulated environments; Ref. [15] uses GA to find the optimal integral gains and bias factors in the load frequency control of a three-area power system after deregulation. To account modeling uncertainties, robust control methods were also developed for LFC in deregulated environments. Ref. [16] proposed a robust decentralized load–frequency controller based on the Riccati-equation approach for power systems with parametric uncertainties; Ref. [17] presented an approach based on structured singular value ($\mu$-synthesis). In this method, the connections between one area and the rest of the system and the effects of possible contracts are treated as a set of new disturbance signals to achieve decentralization. Refs. [18–21] formulated the LFC in a deregulated electricity environment as a multi-objective problem and solved by the mixed $H_2/H_\infty$ control approach. 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 complex to be understood by practical control engineers [22]. These factors make it difficult to apply the above mentioned advanced LFC techniques in practice.

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**Table 1**
Nomenclature.

| $\Delta f_i$ | Frequency deviation of Area #$i$ (Hz) |
|---|---|
| $\mathrm{ACE}_i$ | Control error of Area #$i$ |
| $\Delta P_{\mathrm{tie},i}$ | Scheduled incremental change in tie-line power Between Area #$i$ and other areas (MW) |
| $\Delta P_c$ | Incremental change of governor setpoint |
| $\Delta P_{Lk-i}$ | Deviation of contracted load demand of $\mathrm{DISCO}_K$ in Area #$i$ |
| $\Delta P_{\mathrm{Loc},i}$ | Deviation of the total contracted load demands |
| $\Delta P_{di}$ | Deviation of the un-contracted load disturbance in Area #$i$ (puMW) |
| $\mathrm{apf}_{ki}$ | ACE participation factor of $\mathrm{GENCO}_k$ in AREA #$i$ |
| $\Delta P_{mk-i}$ | Incremental change in generator output of $\mathrm{GENCO}_k$ in Area #$i$ (puMW) |
| $\Delta X_{Gk-i}$ | Incremental change in governor valve position of $\mathrm{GENCO}_k$ in Area #$i$ |
| $K_{Pi}$ | Subsystem equivalent gain of Area #$i$ |
| $T_{Pi}$ | Subsystem equivalent time constant of Area #$i$ |
| $T_{Tki}$ | Turbine time constant of $\mathrm{GENCO}_k$ in Area #$i$ |
| $T_{Hki}$ | Governor time constant of $\mathrm{GENCO}_k$ in Area #$i$ |
| $R_{ki}$ | Droop characteristic for $\mathrm{GENCO}_k$ in Area #$i$ (Hz/puMW) |
| $B_i$ | Frequency bias setting of Area #$i$ |
| $T_{ij}$ | tie-line synchronizing coefficient between Area #$i$ and #$j$ |
| $G_{gki}(s)$ | Transfer function for the governor of $\mathrm{GENCO}_k$ in Area #$i$ |
| $G_{tki}(s)$ | Transfer function for the turbine $\mathrm{GENCO}_k$ in Area #$i$ |
| $G_{pi}(s)$ | Transfer function of the generator in Area #$i$ |
| $\xi_i$ | Total contracted tie-line power flows from other areas to Area #$i$ (puMW) |
| $\rho_{ki}$ | Contracted load demand of $\mathrm{GENCO}_{k-i}$ from other areas (puMW) |

In this paper, we will adopt the two-degree-of-freedom (TDF) internal model control (IMC) method to tune decentralized PID-type load frequency controllers in deregulated environments. The TDF–IMC-PID method has been studied in [23,24] for LFC in conventional situation and the performance of the control system is only related to two tuning parameters. To extend the method to deregulated environments, we first derive a transfer function model for multi-area power systems in deregulated environments, and the TDF–IMC-PID method is applied to design decentralized load frequency controllers. Then stability of the decentralized control system is analyzed. The proposed method is tested on a four-area power system with different contracted scenarios. Simulation results show that the proposed design method is simple to follow, can achieve good performance, and results in implementable PID controllers. These properties make it applicable in practice.

The main contributions of this paper are as follows.

(1) A general LFC design method for multi-area power systems in deregulated environments is proposed;
(2) A method to analyze the stability of the decentralized LFC systems in deregulated environments is proposed.

Compared with previous methods, the advantages of the proposed method are that the model is easy to handle, the design method is easy to apply, and the resulting controllers are easy to implement. Moreover, simulation results show that our method can achieve better performance.

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

## 2. Multi-area LFC model in deregulated environments

In the competitive environment of power systems, the vertically integrated utility (VIU) no longer exists. A deregulated system will consist of generation companies (GENCOs), distribution companies (DISCOs), transmission companies (TRANSCOs) and independent system operator (ISO). In the system, any GENCO in any area may supply DISCOs in its user pool and DISCOs in other areas through tie-lines between areas. 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’. The transactions have to be implemented through an independent system operator. The impartial entity, ISO, has to control many ancillary services, one of which is automatic generation control (AGC), and LFC is regarded as the secondary level of AGC [25].

In deregulated environments, any DISCO has the liberty to buy power at competitive prices from different GENCOs, which may or may not have contract in the same area as the DISCO. Thus there can be various combinations of possible contract scenarios between DISCOs and GENCOs. The concept of an ‘Augmented Generation Participation Matrix’ (AGPM) is used to express the possible contracts. The AGPM shows the participation factor of a GENCO in the load following contract with a DISCO. An AGPM for a large-scale power system with $N$ control areas has the following structure

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

where

$$\mathrm{AGPM}_{ij} = \begin{bmatrix} \mathrm{gpf}_{(s_i+1)(z_j+1)} & \cdots & \mathrm{gpf}_{(s_i+1)(z_j+m_j)} \\ \vdots & \ddots & \vdots \\ \mathrm{gpf}_{(s_i+n_i)(z_j+1)} & \cdots & \mathrm{gpf}_{(s_i+n_j)(z_j+m_j)} \end{bmatrix} \tag{2}$$

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

$$s_i = \sum_{k=1}^{i-1} n_i, \quad z_j = \sum_{k=1}^{i-1} m_j, \quad s_1 = z_1 = 0, \quad \text{for} \quad i,j = 1,\cdots,N \tag{3}$$

Let $n = \sum_{i=1}^{N} n_i$ and $m = \sum_{j=1}^{N} m_j$, then $n$ denotes the total number of GENCOs in the $N$-area system, and $m$, the total number of DISCOs. So AGPM is, in fact, a matrix with $n$ rows and $m$ columns. Each element of AGPM, $\mathrm{gpf}_{ij}$, refers to ‘generation participation factor’ and shows the participation factor of $\mathrm{GENCO}_i$ in the total load following requirement of $\mathrm{DISCO}_j$ based on the possible contract. The sum of all entries in each column of an AGPM is unity. The diagonal sub-matrix of AGPM, $\mathrm{AGPM}_{ii}$, reflects the local demands of Area #$i$ and off-diagonal sub-matrix, $\mathrm{AGPM}_{ij}$, reflects the demands of DISCOs in Area #$j$ on GENCOs in Area #$i$.

The block diagram 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, $\Delta P_{di}$ denoted the total load demands of Area #$i$, $\mathrm{apf}_{ki}$ is the ACE participation factor of $\mathrm{GENCO}_{k-i}$ with

$$\sum_{k=1}^{n_i} \mathrm{apf}_{ki} = 1 \tag{4}$$

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,

$$\Delta P_{\mathrm{Loc},i} = \sum_{j=1}^{m_j} \Delta P_{Lj-i} \tag{5}$$

where $\Delta P_{Lj-i}$ is the load demand of $\mathrm{DISCO}_{j-i}$. Signals $\xi_i$ is the total contracted tie-line power flows from other areas to Area #$i$,

$$\xi_i = \sum_{k=1,k\neq i}^{N} \left( \sum_{j=1}^{n_i} \sum_{t=1}^{m_k} \mathrm{gpf}_{(s_i+j)(z_k+t)} \Delta P_{Lt-k} - \sum_{t=1}^{n_k} \sum_{j=1}^{m_i} \mathrm{gpf}_{(s_k+t)(z_i+j)} \Delta P_{Lj-i} \right) \tag{6}$$

and $\rho_{ki}$ is the contracted load demand of $\mathrm{GENCO}_{k-i}$ due to load demands from other areas,