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Robust analysis of decentralized load frequency control for multi-area power systems

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ABSTRACT

Robust analysis for decentralized load frequency control (LFC) for multi-area power systems is studied in this paper. It is observed that such an analysis can be decomposed into two steps considering the inherent structure of a multi-area power system: robustness analysis against the parametric variations in local-area power systems and robustness analysis against the structure and/or magnitude variations in the tie-line power flow network. A detailed structured singular value method is proposed for local-area robustness analysis, and an eigenvalue method is derived for tie-line robustness analysis. The proposed method is then applied to a four-area power system and the results show that the method is convenient and useful for decentralized load frequency control of multi-area power systems.

1. Introduction

In power systems, changes in the load affect the frequency and bus voltages in the systems. For small changes in the load the frequency deviation problem can be separated or decoupled from the voltage deviation. The problem of controlling the real power output of generating units in response to changes in system frequency and tie-line power interchange within specified limits, is known as load frequency control (LFC) [1]. It is generally regarded as a part of automatic generation control (AGC) and is very important in the operation of power systems.

Usually AGC is organized in three levels:

- Primary control is performed by the speed governors of the generating units, which provide immediate (automatic) action to sudden change of load (or change of frequency). With primary control, a variation in system frequency greater than the dead band of the speed governor will result in a change in unit power generation. Transients of primary control are in the time-scale of seconds.
- Secondary control restores frequency to its nominal value and maintains the power interchange among areas by adjusting the output of selected generators. Transients of secondary control are in the order of minutes.
- Tertiary control is an economic dispatch that is used to drive the system as economically as possible and restore security levels if necessary. Tertiary control is usually performed every 5 min.

The speed governor on each generating unit provides the primary speed control function, and all generating units contribute to the overall change in generation, irrespective of the location of the load change, using their speed governing. However, primary control action is usually not sufficient to restore the system frequency, especially in an interconnected power system so the secondary control loop is required to adjust the load reference set point through the speed-changer motor. Secondary control is commonly referred to as load–frequency control. See [2,3] for a complete review of recent advance in LFC.

LFC becomes more significant today with the increasing size and complexity of interconnected power systems. Multivariable control techniques can be used to design centralized load frequency controllers, however, due to the inherent structure of large-scale power systems, decentralized load frequency control is more appealing for its simplicity in design and implementation, see, for example, [4–10] for different control methods to design decentralized LFC.

Most of the methods uses decentralized controllers. Though simulation results show that the decentralized control may achieve good performance, no theoretical results have been found that can be used to analyze the robustness of the decentralized control for LFC. In this paper, robust analysis for decentralized load frequency control of multi-area power systems will be investigated. The

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Nomenclature

Δf_i	frequency deviation of Area #i (Hz)
B_i	frequency bias setting of Area #i (p.u. MW/Hz)
T_{ij}	synchronizing coefficients between Area #i and Area #j (p.u. MW/Hz)
ΔP_{di}	load disturbance in Area #i (p.u. MW)
$\Delta P_{\text{tie}-i}$	tie-line power between Area #i and other areas (p.u. MW)
ΔP_{ti}	generator output in Area #i (p.u. MW)
$G_{gi}(s)$	transfer function of the governor in Area #i
$G_{ti}(s)$	transfer function of the turbine in Area #i
$G_{pi}(s)$	transfer function of the rotor inertia and load in Area #i
R_i	speed regulation of Area #i (Hz/p.u. MW)

analysis is based on recent method ([11]) proposed to analyze the stability of a multi-area power system under a decentralized LFC. The method takes the inherent structure of the multi-area power system into consideration, and makes it possible to check the impacts of parametric variations in the local-area power systems and the structure and/or magnitude variations in the tie-line power flow network sequentially. Robustness analysis against the two groups of uncertainties will then be discussed. Finally, the proposed method will be applied to analyze the decentralized LFC for a four-area power system. It is shown that the method is convenient and useful for decentralized load frequency control of multi-area power systems.

2. Stability analysis of decentralized LFC

Consider the load frequency control problem for a multi-area power system shown in Fig. 1. Each control area has the structure shown in Fig. 2. The control area is a simplified power system consisting of many generating units. According to [1], the collective performance of all generators in the system is the interesting part in the analysis of LFC. The intermachine oscillations and transmission system are not considered. It is assumed that the response of all generators to changes in system load are coherent and can be represented by an equivalent generator, which has an inertia constant and a damping constant equal to the sum of the inertia constants and damping constants of all the generating units. The model is simple but captures the essential dynamics of a power system and has been widely used for LFC design purpose.

The load frequency control problem for a multi-area power system 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, the area control error (ACE), is used as the feedback variable to ensure the two objectives. For Area #i, the area control error is defined as

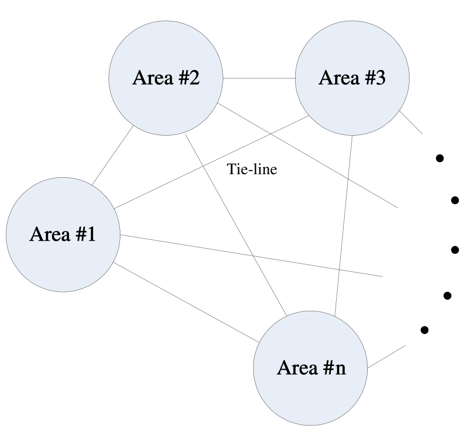

Fig. 1. Simplified diagram of a multi-area interconnected power system.

$$\text{ACE}_i = \Delta P_{\text{tie}-i} + B_i \Delta f_i \quad (1)$$

and the feedback control for Area #i takes the form

$$u_i = -K_i(s)\text{ACE}_i \quad (2)$$

where $K_i(s)$ is the local LFC controller.

According to [12,13], a decentralized controller can be designed assuming that there are no tie-line power flows, i.e., $\Delta P_{\text{tie}-i} = 0 (i = 1, \ldots, n)$. In this case the local feedback control will be

$$u_i = -K_i(s) B_i \Delta f_i \quad (3)$$

Denote the transfer functions of the governor, the turbine, and the rotor inertia and load for Area #i by $G_{gi}(s)$, $G_{ti}(s)$, and $G_{pi}(s)$, respectively, then the transfer function from u_i to Δf_i can be easily found as

$$G_i(s) = \frac{G_{pi} G_{ti} G_{gi}}{1 + G_{pi} G_{ti} G_{gi} / R_i} \quad (4)$$

So it is clear that to design a decentralized load frequency controller, one just needs to design controllers for the following transfer function for Area #i.

$$P_i(s) = G_i(s) B_i \quad (5)$$

It is shown that the decentralized load frequency control of multi-area power systems requires designing local controllers for the model (5). Each local controller can be designed independently. However, since tie-line power flows among areas are ignored in the local load frequency control design, we need to check the stability of the whole system to ensure the designed decentralized controller works after the local controllers have been tuned. Many multivariable stability theories can be applied to check the stability of a multi-area power system under a decentralized LFC controller. However, the multi-area power system has its specific structure, so a simple method can be derived for the stability analysis. The following result is from [11].

Theorem 1. *Given an n-area power system shown in Fig. 1 and assume that each area has the structure as shown in Fig. 2. Then the whole power system is stable if and only if the following transfer function is stable.*

$$h(s) := \det(I + N(s)T/s) \quad (6)$$

where the 'tie-line network matrix' T is a constant matrix defined by

$$T := \begin{bmatrix} \sum_{j\neq 1}^{n} T_{1j} & -T_{12} & \cdots & -T_{1n} \\ -T_{21} & \sum_{j\neq 2}^{n} T_{1j} & \cdots & -T_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ -T_{n1} & -T_{n2} & \cdots & \sum_{j\neq n}^{n} T_{1j} \end{bmatrix} \quad (7)$$