Electrical Power and Energy Systems 33 (2011) 1542–1549

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Load–frequency control of interconnected power system with governor backlash nonlinearities

Tain-Sou Tsay *

Department of Aeronautical Engineering, National Formosa University, 64, Wen-Hua Road, Huwei, YunLin 63208, Taiwan

ARTICLE INFO

Article history:
Received 10 May 2010
Received in revised form 12 February 2011
Accepted 3 June 2011
Available online 4 August 2011

Keywords:
Interconnected power system
Nonlinear multivariable feedback system
Limit cycle

ABSTRACT

In this paper, the stability-equation method is applied to the analysis and design of an interconnected power system with governor backlash nonlinearities. The considered system is a nonlinear multivariable feedback control system. The governor nonlinearities tend to produce a sustaining oscillation in area frequency and tie-line power transient responses. Most conventional linear design techniques are usually unable to find the sustaining oscillation in design phase and need simulation verifications to check the validations after designs. However, the proposed method can consider effects of nonlinearities in the design phase. Some nonlinear design techniques need parameters optimization method by Lyapunov theorem or Integral of Square Errors (ISE) criteria. They are effective. However, they need large computation efforts. The proposed method can choice frequency bias parameters and integrator gains of supplementary controllers for avoiding the oscillation or reducing the amplitude of the oscillation to be acceptable. Simulation verifications show that the proposed method can provide a simple and effective way for the considered system.

1. Introduction

For reasons of economy and system reliability, neighboring power systems are interconnected, forming an augmented system referred to as "power pool". The various areas are interconnected through tie-lines. The net power flow on the tic-lines connecting a system to the external system is frequently scheduled by a priori contract basis. The tie-lines are used for contractual energy exchange between areas and provide inter-area support in case of abnormal conditions. Area load changes and abnormal conditions, such as outages of generation, lead to mismatches in frequency and scheduled power interchanges between areas. These mismatches have to be corrected through a Load–Frequency Control (LFC). The load–frequency control is based on an error signal called Area Control Error (ACE) which is a linear combination of net-interchange and frequency errors. The conventional control strategy used in industry is to take the integral of ACE as the control signal [1–14]. The control purpose is to reduce the frequency and tie-line power errors to zero in the steady state.

Many decentralized control strategies; e.g., variable structure controls [5–7], PI/PID and Fuzzy controls [9–14], have been employed in the design of LFC for interconnected power systems. Among the various types of decentralized LFC, the most widely employed is the simple conventional control. The conventional control for LFC is still popular with the power industries because of their simplicity, easy realization, low cost, robust and decentralized nature of the control strategy. It has also been shown that there is no significant advantage in using the more complex controllers over the conventional controllers [9–11]. The conventional proportional plus integral control strategy, which is widely used in power industry, is to take the integral of ACE as the control signal.

It is well known that many LFC scheme does not yield adequate control performance with consideration of the system nonlinearities such as governor deadband or generation rate constraint [1–4]. Governor deadband (GDB) nonlinearities tend to produce an unexpected sustaining oscillation in area frequency and tie-line power transient responses. Avoiding sustaining oscillation or reducing the amplitude of the sustaining oscillation is expected. Most conventional linear design techniques [5–14] need digital simulations to check effects of nonlinearities after controller designed. The nonlinearities considered in the design phase are expected. Some nonlinear design techniques need parameters optimization method by Lyapunov theorem [1–3] or Integral of Square Errors (ISE) criteria [4]. They are effective. However, they need large computation efforts. Simple and effective ways to evaluate effects of nonlinearities are expected. This is the motivation of this paper.

In this paper, the stability-equation method [15–17] is used to analyze and design the considered system. The considered system is a nonlinear multivariable feedback control system. Harmonic-balance equations and the characteristic equation [18–21] are

* Tel.: +886 5 631 5537; fax: +886 5 631 2415.
E-mail address: tstsay@nfu.edu.tw

0142-0615/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijepes.2011.06.005

Nomenclature

ACE_i	area control error of area i
A_i	amplitude of sinusoidal input of N_i
B_i	frequency bias parameter for area control error of area i
D	governor deadband
K_i	integrator gain of supplementary controller of area i
R_i	governor speed regulation of area i
T_{gi}	time constant of speed governor control system of area i
T_{ti}	time constant of steam turbine of area i
T_{ri}	reheat time constant of area i
K_{ri}	reheat coefficient of steam turbine of area i
T_{pi}	generator time constant of area i
K_{pi}	generator gain constant of area i
ΔF_i	frequency deviation of area i
Δp_{gi}	mechanical power deviation of area i
Δp_{ci}	change in speed changer position
Δp_{di}	real power increase in area i
Δp_{ri}	mechanical power deviation during steam reheat in area i
Δp_{tie}	tie-line power deviation out of area i
ΔX_{Ei}	governor valve displacement of area i
T_{12}	synchronizing power coefficient of tie-line connected between areas 1 and 2
a_{12}	$-P_{r1}/P_{r2}$
P_{ri}	MW capacity of area i
N_i	governor deadband nonlinearity of area i

evaluated for finding the unstable, limit-cycle and asymptotically stable regions in the parameter plane [16]. It will be see that there is no asymptotically stable region for some specified values of controlling and system parameters. This implied that sustain oscillation is always exist; i.e., the stable limit cycle is exist. In this condition, the acceptable amplitude of the sustaining oscillation is expected (e.g., tie-line power). The proposed method can provide information of amplitudes of sustain oscillations. In another way, the proposed method can be used to find the asymptotically stable region in the parameter-plane by selecting other specified values of controlling or system parameters. Furthermore, this paper can be applied the analyses and refining of the systems controlled by conventional linear control techniques; e.g., adjusting parameters of PI/PID controllers to refining the system performance.

This paper is organized as follows. First, the considered interconnected power system is described. Then, the proposed method is presented. Finally the proposed method is applied to analyze and design the considered system. Simulation verification results show that the proposed method can provide a simple way for choosing proper values of parameters to avoid sustaining oscillation or reducing amplitudes of sustaining oscillations.

2. The two-area interconnected power system

The two-area interconnected power system consists of two single areas connected through a power line called the tie line. Each area feeds its user pool, and the tie line allows electric power to flow between areas. Since two areas are tied together, a load perturbation in one area affects the output frequencies of both areas as well as the power flow on the tie line. The control system of each area needs information about the transient situation of both areas to bring the local frequency back to its steady state value. Information about the other area is found in the output frequency fluctuation of that area and in the tie line power fluctuation. Thus, the tie line power is sensed, and the resulting tie line power signal is fed back into both areas.

A block diagram of the two area interconnected power system is given in Fig. 1 in which governors, reheat turbines and generators are considered. Transfer functions of reheat turbines are given by

$$\frac{\Delta P_{gi}(s)}{\Delta X_{Ei}(s)} = \frac{1 + K_{ri}T_{ri}s}{(1+sT_{ri})(1+sT_{ti})}, \quad i = 1,2 \tag{1}$$

and differential equations of the overall system [1–4] are given as:

$$\Delta\dot{F}_1 = -T_{p1}^{-1}\Delta F_1 + K_{p1}T_{p1}^{-1}(\Delta P_{g1} - \Delta P_{tie} - \Delta P_{d1}) \tag{2}$$

$$\Delta\dot{P}_{g1} = -T_{r1}^{-1}\Delta P_{g1} + \Delta P_{r1}\left[T_{r1}^{-1} - K_{r1}T_{r1}^{-1}\right] + K_{r1}T_{t1}^{-1}\Delta X_{E1} \tag{3}$$

$$\Delta\dot{P}_{r1} = T_{t1}^{-1}\Delta X_{E1} - T_{t1}^{-1}\Delta P_{r1} \tag{4}$$

$$\Delta\dot{X}_{E1} = -R_1^{-1}N_1(A_1)T_{g1}^{-1}\Delta F_1 - T_{g1}^{-1}\Delta X_{E1} + T_{g1}^{-1}N_1(A_1)\Delta P_{c1} \tag{5}$$

$$ACE_1 = B_1\Delta F_1 + \Delta P_{tie} \tag{6}$$

$$\Delta P_{c1} = -K_1\int ACE_1 dt \tag{7}$$

$$\Delta\dot{F}_2 = -T_{p2}^{-1}\Delta F_1 + K_{p2}T_{p2}^{-1}(\Delta P_{g2} - a_{12}\Delta P_{tie} - \Delta P_{d2}) \tag{8}$$

$$\Delta\dot{P}_{g2} = -T_{r2}^{-1}\Delta P_{g2} + \Delta P_{r2}\left[T_{r2}^{-1} - K_{r2}T_{r2}^{-1}\right] + K_{r2}T_{t2}^{-1}\Delta X_{E2} \tag{9}$$

$$\Delta\dot{P}_{r2} = T_{t2}^{-1}\Delta X_{E2} - T_{t2}^{-1}\Delta P_{r2} \tag{10}$$

$$\Delta\dot{X}_{E2} = -R_2^{-1}N_2(A_2)T_{g2}^{-1}\Delta F_2 - T_{g2}^{-1}\Delta X_{E2} + T_{g2}^{-1}N_2(A_2)\Delta P_{c2} \tag{11}$$

$$\Delta\dot{P}_{tie} = 2\pi T_{12}(\Delta F_1 - \Delta F_2) \tag{12}$$

$$ACE_2 = B_2\Delta F_2 + a_{12}\Delta P_{tie} \tag{13}$$

$$\Delta P_{c2} = -K_2\int ACE_2 dt \tag{14}$$

where $N_1(A_1)$ and $N_2(A_2)$ represent quasi-linear gains or describing functions [15–18] of governor deadband (backlash) nonlinearities [1–4]; A_1 and A_2 represent amplitudes of sinusoidal inputs of nonlinearities N_1 and N_2, respectively. The corresponding transfer functions of governors and generators are shown in Fig. 1.

In conventional systems, an integral controller sets the turbine reference power of each area. Since a perturbation in either area affects the frequency in both areas and a perturbation in one area is perceived by the other through a change in tie line power, the controller of each area should not only; take the frequency variation as input but also the tie line power variations. Since an integral controller has just one input, these two contributions, namely local frequency variation and tie line power variation, must be combined into a single signal so that it can be used as an input of the controller. The easiest way of doing this is to combine them linearly, i.e. the input of the integrator in area 1 is $\Delta P_{tie} + B_1\Delta F_1$, and the input of the integrator in area 2 is $a_{12}\Delta P_{tie} + B_2\Delta F_2$. The input of each controller is called the Area Control Error (ACE).

The nonlinearities destabilize the system and tend to produce a sustaining oscillation in area and tie-line power transient responses [1–4]. There are frequency bias parameters $B_i (i = 1, 2)$ and integrator gains $K_i (i = 1, 2)$ of the supplementary controllers