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Robust analysis and design of power system load frequency control using the Kharitonov's theorem

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A B S T R A C T

This paper presents a robust decentralized proportional-integral (PI) control design as a solution of the load frequency control (LFC) in a multi-area power system. In the proposed methodology, the system robustness margin and transient performance are optimized simultaneously to achieve the optimum PI controller parameters. The Kharitonov's theorem is used to determine the robustness margin, i.e., the maximal uncertainty bounds under which the stable performance of the power system is guaranteed. The integral time square error (ITSE) is applied to quantify the transient performance of the LFC system. In order to tune the PI gains, the control objective function is optimized using the genetic algorithm (GA). To validate the effectiveness of the proposed approach, some time based simulations are performed on a three-area power system and the results are then compared with an optimal PI controller. The comparisons show that the proposed control strategy provides the satisfactory robust performance for the wide range of system parameters and load changes in the presence of system nonlinearities and is superior to the other methods.

1. Introduction

Any power imbalance between generation and electrical load demand in the multi-area power systems leads to the system frequency deviations and scheduled tie-line power variations [1]. The problem of responding to the system real power imbalances in a power system is known as load frequency control (LFC) [2]. The main goals of the LFC system in an interconnected multi-area power system are minimizing the frequency and tie-line scheduled power deviations [3].

Because of the increased complexity of modern power systems, advanced control methods have been proposed in LFC, e.g., adaptive and self-tuning control [4,5]; predictive based control [6,7]; and intelligent control [8,9]. Improved performance can be achieved from the advanced control methods. However, these methods require either information on the system states or an efficient online identifier which can be difficult to apply in practice.

PI or PID controllers have been studied in many works and are popular in real world due to their simplicity in execution. Application of genetic algorithm and craziness particle swarm optimizations to find PI gain controller has been proposed in [10,11], respectively. An optimal PI design using Bacteria Foraging algorithm has been reported in [12]. However, these approaches are optimal and provide some shortcomings in the presence of system uncertainty. Generally, real power systems contain different kinds of uncertainties and disturbance due to changes in system parameters, load variations and error in modeling. In addition, the operating points of a power system change very much during a daily cycle. Therefore, an optimal LFC regulator design based on nominal system parameter values is certainly not suitable for the LFC problem, and therefore, implementation of these regulators on the system may be inadequate to provide the desired system performance.

To take the effect of system uncertainty into account, design and application of robust control methods for power system LFC has been considered in a number of papers. A robust LFC design using characteristic matrix eigenvalue has been reported in [13]. Two-degree-of-freedom Internal Model Control (IMC) method has been used in [14] for PID tuning of LFC system. In [15], design of load frequency controller using sequential quadratic programming has been performed. The application of Kharitonov's theorem for a single area power system has been presented in [16]. The LFC controller is obtained based on robust D-stability concept to assure good dynamic performance and the Kharitonov's theorem is employed to check the robust stability. In [17], the PID parameters are tuned based on the classical design approaches and the robust stability of the LFC is tested by the Kharitonov's theorem. However, the approach presented in [16] is developed and investigated only for a single area power system. In addition, [16,17] employed

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Kharitonov's theorem only to check the robust stability and furthermore, none of them considered the effect of generation rate constraint.

This paper presents a new robust PI design using the Kharitonov's theorem. In the proposed approach, the object is to maximize robustness margin and transient performance, simultaneously. The Kharitonov's based theorem such as zero exclusion condition and Tsypkin-Polyak function are employed to check the robust stability and to quantify the robustness margin. Time based simulations are performed to create the transient behavior of the LFC system and the ITSE is employed to quantify the transient performance. Generation rate constraints are further considered in the simulations due to their significant effect on the LFC dynamic. A control cost function containing robustness margin and transient performance is created and the genetic algorithm (GA) is used to optimize the PI gains. The proposed approach is tested on the three-area power system and the results are compared to the other PI controllers.

The proceeding sections of this paper are organized as follows. In Section 2, a brief description of the LFC dynamic with problem statement is presented. The Kharitonov's based theorems and concepts including Kharitonov rectangles, zero exclusion condition and Tsypkin-Polyak function are described in Section 3. In Section 4, the design procedure of robust PI controller is presented. Section 5 provides time-based simulations with detailed discussions and analysis. Finally, the conclusion is given in Section 6.

2. Power system LFC dynamic

The large power system consists of a number of control areas that are interconnected through some tie-lines. Due to large scale of most power systems, design and implementation of the decentralized controllers are preferable. Therefore, each control area has its own load frequency controller. The controller compensates every changes in the local loads or imbalances in the tie-line power interchanges and maintains the system frequency in its nominal value. The block diagram representation for ith control area with n generation units is depicted in Fig. 1.

State-space model of the LFC system is a useful representation for the application of the robust control theory. The state-space model of ith control area (Fig. 1) is:

$$\dot{x}_i = A_i x_i + B_i u_i + F_i w_i \tag{1}$$

$$y_i = C_i x_i$$

where

$$x_i = [\Delta f_i, \Delta P_{tie,i}, \Delta P_{g1,i}, \ldots, \Delta P_{gn,i}, \Delta P_{t1,i}, \ldots, \Delta P_{tn,i}]^T$$
$$y_i = ACE_i$$
$$u_i = [\Delta P_{c,i1}, \ldots, \Delta P_{c,in}]^T$$
$$w_i = [\Delta P_{L,i}, w_{2i}]$$
$$A_i = \begin{pmatrix} A_{i11} & A_{i12} & A_{i13} \\ A_{i21} & A_{i22} & A_{i23} \\ A_{i31} & A_{i32} & A_{i33} \end{pmatrix}, \quad B_i = \begin{pmatrix} B_{i1} \\ B_{i2} \\ B_{i3} \end{pmatrix}, \quad F_i = \begin{pmatrix} F_{i1} \\ F_{i2} \\ F_{i3} \end{pmatrix}$$
$$A_{i11} = \begin{pmatrix} -D_i/2H_i & -1/2H_i \\ -2\pi \sum_{j=1, j\neq i}^{N} T_{ij} & 0 \end{pmatrix}$$
$$A_{i12} = \begin{pmatrix} 1/2H_i & \ldots & 1/2H_i \\ 0 & \ldots & 0 \end{pmatrix}$$
$$A_{i22} = diag[-1/T_{g1,i}, -1/T_{g2,i}, \ldots, -1/T_{gn,i}]$$
$$A_{i33} = -A_{i32} = diag[-1/T_{t1,i}, -1/T_{t2,i}, \ldots, -1/T_{tn,i}]$$
$$A_{i21} = \begin{pmatrix} -1/(T_{g1,i}R_{1i}) & 0 \\ \vdots & \vdots \\ -1/(T_{gn,i}R_{ni}) & 0 \end{pmatrix}, \quad A_{i12} = A_{i31}^T = 0_{2\times n}, \quad A_{i23} = 0_{n\times n}$$
$$B_{i1} = 0_{2\times n}, \quad B_{i2} = diag[\alpha_{1,i}/T_{g1,i}, \alpha_{2,i}/T_{g2,i}, \ldots, \alpha_{n,i}/T_{gn,i}], \quad B_{i3} = 0_{n\times n}$$
$$C_i = [\beta_i 1 0_{1\times n} 0_{1\times n}]$$
$$F_{i1} = [-1/2H_i 0], \quad F_{i2} = 0_{n\times 1}, \quad F_{i3} = 0_{n\times 1}$$

and

Δf_i	change in area frequency
$\Delta P_{c,i}$	change in governor load set point
$\Delta P_{g,i}$	change in governor valve position
$\Delta P_{t,i}$	change in turbine power
$\Delta P_{tie,i}$	tie-line power deviation
$\Delta P_{L,i}$	power demand deviation
T_{ij}	synchronizing coefficient with area j
$T_{g,i}$	governor time constant
$T_{t,i}$	turbine time constant
D_i	area load frequency characteristic
M_i	area equivalent inertia
R_i	droop characteristic
β_i	frequency bias
ACE_i	area control error
α	participation factor

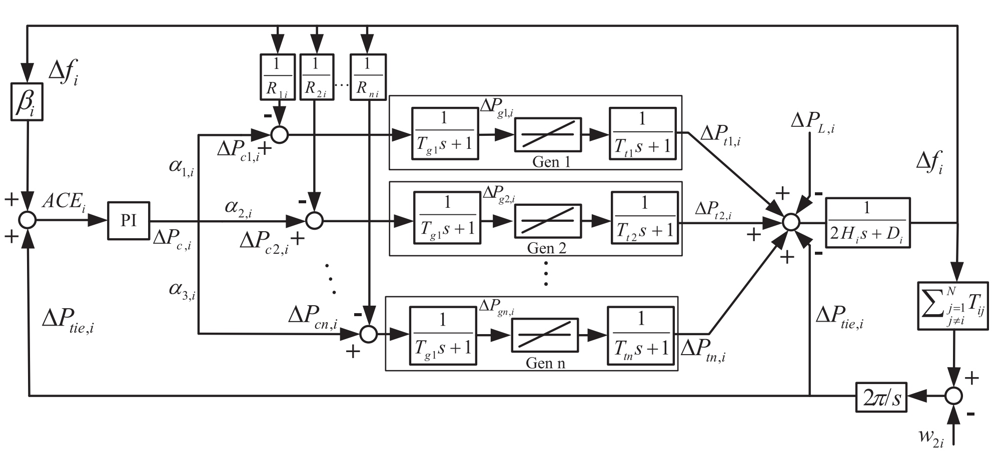

Fig. 1. Block diagram representation for the ith control area.