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Constrained population extremal optimization-based robust load frequency control of multi-area interconnected power system

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ABSTRACT

This paper proposes a robust proportional-integral (PI) controller with its parameters designed by constrained population extremal optimization for load frequency control problem of multi-area interconnected. During the process of optimization, the robust performance index is used as fitness function, where linear matrix inequalities technique is employed to describe the H_∞ constraint, and the taking error performance requirement such as integral time absolute error is incorporated as another constraint. Three different two-area interconnected power systems are used as test systems to demonstrate the effectiveness of the proposed controller by comparing with other PI control methods and one optimized model predictive control. In addition, in order to investigate the performance of proposed controller for the LFC problem of large scale system, a three-area interconnected power system is used as another test system. The comprehensive experimental results fully demonstrate that the proposed control scheme in this paper performs better than other control strategies on the most considered scenarios under the conditions of load disturbance and parameters uncertainties in terms of system response and control performance indices.

1. Introduction

Load frequency control (LFC) is of great importance for power systems or microgrids to maintain the scheduled system frequency and power exchange between areas during normal and abnormal conditions [1]. The control objective of LFC is to minimize the frequency deviation and net tie-line flow error between control areas. More specifically, the LFC should be ensured stabilization considering system nonlinearities, model parameters uncertainties, and load disturbance or resonance attack [1–4], which may take place in realistic power engineering. Over the past decades, considerable efforts have been devoted to developing control strategies for LFC problem, which can be roughly separated into two categories. The first category employs various advanced techniques [4–14] to design advanced controllers for LFC of interconnected power system or microgrids. For example, model predictive control [6–9], H_∞ and μ-synthesis [10], fuzzy logic [12,13] and sliding model technique [14] have been utilized for LFC issue. The second category is known as proportional-integral-derivative (PID) [15,16] or proportional-integral (PI) controller [17–28], which keeps preferred choice of an engineer because of the simple but reliable control structure. Also, the PI/PID controller needs lower user-skill requirements and offers simplified dynamic model, so it is favorable in engineering practice. Thanks to these attractive properties, the control strategies of LFC system equipped with PI controller have witnessed a boom of development since last two decades [17–28] Ali et al. [17] applied the bacteria foraging optimization to deal with LFC problem of two-area interconnected power system. Mohanty et al. [18] used differential evolution (DE) algorithm to design PI controller for LFC considering multi-source in power system. In [20,21], the authors used cuckoo search (CS) algorithm and bat algorithm to solve the LFC problem considering some nonlinear terms e.g., generation rate constraint (GRC) and governor dead band (GDB). Adb-Elazim et al. [22] designed the load frequency controller of two-area system via firefly algorithm. In [23,24], authors suggested PI controllers equipped with fuzzy systems for LFC problems. Rerkpreedapong et al. [26] suggested genetic algorithm (GA) to tune the PI control parameters subjecting to the H_∞ constraints in terms of LMI. In addition, Pandey et al. [28] combined the particle swarm optimization (PSO) and linear matrix inequalities (LMI) to design robust PI controller for LFC in hybrid power systems. As mentioned above, the control methods in [26,28] based on LMI technique, but these methods do not take into account some nonlinear features simultaneously. From a comprehensive literature survey on the LFC

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Nomenclature

i	the subscript referring to i-th area
Δ	deviation
f	the system frequency
$\mathrm{ACE_i}$	area control error
N	the number of areas
λ_i	frequency bias parameter
D_i	generator damping coefficient
R_i	speed regulation
T_{gi}	the speed governor time constant
T_{ti}	the turbine time constant
T_{ri}	the reheat time constant
K_{ri}	The p.u megawatt rating of high pressure stage
J	objective function
u_i	controller output signal
T_w	The hydro turbine time constant
K_{pi}, T_{pi}	The time constant and gain of power system
ΔP_{tiei}	tie-line flow error
K_{PP}, K_{II}	the parameters of PI controller
t	time in second
T_{ij}	tie-line synchronizing coefficient between area i and j
ΔP_{Li}	load disturbance
t_{sim}	time range of simulation

List of abbreviations

LFC	load frequency control
(C)PEO	(constrained) population extremal optimization
LMI	linear matrix inequalities
PI	proportional-integral
PID	proportional-integral-derivative
GA	genetic algorithm
(C)PSO	(constrained) particle swarm optimization
BFOA	bacterial foraging optimization algorithm
MPC	model predictive control
ACO	ant colony optimization
ABC	artificial bee colony
GRC	generation rate constraint
GDB	governor dead band
IAE	Integral of absolute error
ISE	Integral of square error
ITAE	Integral of time multiplied absolute error
ITSE	Integral of time multiplied square error

issues of power systems presented in [1], few works focus on LMI technique subject to the H_∞ constraint for the LFC issue by considering these characteristics of realistic power system simultaneously.

As reported in [29–31], in presence of time delays or nonlinearities such as GRC and GDB, most existing LFC methodologies exhibit relative poor control performance. To the best of our knowledge, only few research works consider a multi-area interconnected power system with these severe and realistic factors. Elsisi et al. [30] proposed a novel model predictive control method optimized by bat inspired algorithm (BIA-MPC) for LFC of a two-area hydro-thermal power including GRC, GDB, time delays and thermodynamic process, and its effectiveness is illustrated by comparing with GA-based PI controller and conventional PI control method. However, as advanced controller, BIA-MPC is more complex than PI-type controller, from an implementation point of view. By considering these nonlinear features, it is still a tremendously challenge to improve LFC performance by PI-type controller especially suffering from load fluctuations and parameters uncertainty. As discussed in [20,21], the evolutionary algorithm techniques-based PI controllers have potential ability to handle nonlinear terms by minimizing the integral time absolute error (*ITAE*) performance index. In addition, as discussed in [32], a tracking error performance requirement constraint i.e., *ITAE*, which is used to obtain the desired performance, contributes to improving the control performance for various systems (e.g., pneumatic servo system, separating tower process and F18 fighter aircraft system). On the other hand, for improving the control system performance, using H_∞ performance or taking error performance as fitness function is often not enough [33]. Thus, combining the performance requirement constraint i.e., *ITAE* with H_∞ performance described by LMI technique may improve LFC performance to some extent.

Recently, in evolutionary computing literature, extremal optimization (EO) [34,35], provides a novel insight due to its heuristic mechanism from self-organized criticality [36]. EO abandons elite selection mechanism while focuses on changing the bad elements or individuals by mutation. As a result, EO and its variations such as population extremal optimization (PEO) [37] and multi-objective population-based extremal optimization (MOPEO) [38,39], have been widely applied by many researchers in combinatorial and continuous optimization domain [40–45] Also, EO and its variations have been demonstrated more efficient because of their advantages in computational complexity, memory requirements and adjustable parameters compared to other popular nature-inspired algorithms including GA and PSO. Unfortunately, there are only few reported works concerning constrained population extremal optimization (CPEO), let alone concerning CPEO-based LMI technique subjecting to the H_∞ constraint and performance requirement constraint in optimal design of PI controller for multi-area power system. This is one of primary motivations to extend PEO algorithm to the constrained version by embedded into tournament-constraint-handling method [46] for designing robust PI controller for LFC of power system.

Motivated by the analysis above, this paper proposes a robust PI control scheme called CPEO-LMI-PI with its control parameters designed by CPEO wherein the LMI technique is employed to describe the H_∞ constraint, and the *ITAE* performance is incorporated as another constraint. Compared with existing controllers by minimizing the robust performance index, the proposed control scheme in this paper has following advantages:

(1) The H_∞-LMI control strategy has disadvantage in structure controller which is high order and inapplicable to implement, while the proposed CPEO-LMI-PI is a PI-type which is more appealing from an implementation point of view.
(2) The control methods reported in [26,28] ignore some nonlinear terms e.g., GRC and GDB, while the proposed controller considers these nonlinear terms by solving a constraint i.e., *ITAE* performance index during the simulation.
(3) Although there are many popular evolutionary algorithm techniques such as GA and PSO, these algorithms may pain from slow convergence and may get local minimum solutions. As for PEO algorithm with less adjustable parameters, the optimization ability has been demonstrated by various problems. Thus, to solve the

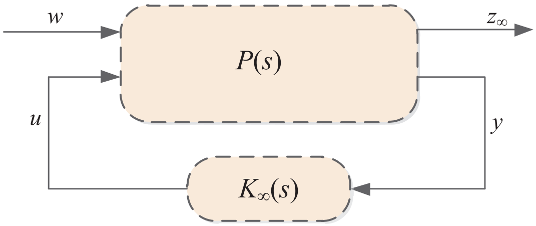

Fig. 1. The block diagram of closed-loop system via robust H_∞ control.