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Bat inspired algorithm based optimal design of model predictive load frequency control

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ABSTRACT

Bat inspired algorithm (BIA) has recently been explored to develop a novel algorithm for distributed optimization and control. In this paper, BIA-based design of model predictive controllers (MPCs) is proposed for load frequency control (LFC) to enhance the damping of oscillations in power systems. The proposed model predictive load frequency controllers are termed as MPLFCs. Two-area hydro-thermal system, equipped with MPLFCs, is considered to accomplish this study. The suggested power system model considers generation rate constraint (GRC) and governor dead band (GDB). Time delays imposed to the power system by governor-turbine, thermodynamic process, and communication channels are accounted for as well. BIA is utilized to search for optimal controller parameters by minimizing a candidate time-domain based objective function. The performance of the proposed controller has been compared to those of the conventional PI controller based on integral square error (ISE) technique and the PI controller optimized by genetic algorithms (GA), in order to demonstrate the superior efficiency of the BIA-based MPLFCs. Simulation results emphasis on the better performance of the proposed MPLFCs compared to conventional and GA-based PI controllers over a wide range of operating conditions and system parameters uncertainties.

Introduction

In large scale power systems, load frequency control (LFC) represents a very crucial issue during generation-load mismatches. Automatic generation control (AGC) system is responsible for maintaining the scheduled system frequency and the tie-line power during normal and abnormal operating conditions [1–3]. The function of an AGC system is usually termed as LFC [2]. In an interconnected power system, LFC is accomplished via two different control loops namely primary and supplementary speed control.

Over the past six decades, several approaches have been applied for LFC designs. Among various types of LFCs, proportional–integral (PI) controllers are commonly used thanks to its structure simplicity and its better dynamic response. On the contrary, performance of PI controllers is degraded significantly when the system complexity increases [4]. The preliminary results on optimal control designs of LFC were firstly presented in [5,6]. The challenge of optimal control, to achieve good performance, is the complex nonlinear mathematical equations in large-scale systems. A robust dynamic output feedback designs of H_∞ and H_2/H_∞ based LFCs via linear matrix inequalities (LMIs) have been addressed in [7]. However, such LMI-based design does not account for system nonlinearities and results in a controller with the same plant order, which in turn makes the design very complex especially for large scale power systems. Actually, different conventional control strategies are being used for LFCs. Methodologies for conventional design of PI and proportional–integral–derivative (PID) controllers are limited by slow, lack of efficiency and poor handling of system nonlinearities. Artificial Intelligence (AI) techniques like fuzzy logic control (FLC), artificial neural networks (ANNs), genetic algorithms (GAs), particle swarm optimization (PSO), ant colony optimization (ACO) and artificial bee colony (ABC) have been applied for LFC to overcome the limitations of conventional methods [8–20]. Genetic algorithms (GAs) have been extensively considered for the design of LFC. The parameters of optimal PID and fractional order PID controllers have been optimized via GAs for an interconnected two-area power system [8,9]. In [10], the parameters of PID sliding-mode based LFC of multi area power systems are optimized by GAs considering nonlinearities. Tuning of decentralized controllers for a realistic system comprising generation rate constraint (GRC),

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Nomenclature

B_i	frequency bias parameter	M_p	maximum overshooting
ACE_i	area *i* control error	N	number of control signals
U_i	controller output	Q, R	input output system weights in MPC
R_i	speed regulation (Hz/p.u.)	x_i, v_i	bat position and velocity respectively
T_{gi}, T_{ti}	governor and turbine time constants (s)	λ	wave length
T_{ij}	synchronizing torque coefficient between areas *i* and *j*	$f_{\min}$, $f_{\max}$	minimum and maximum frequencies of bat pulse
T_{ri}	time constant of re-heater (s)	L^T	mean loudness of all bats
k_{ri}	gain of re-heater	L_o, $L_{\min}$	maximum and minimum loudness levels
T_i	hydro governor time constant (s)	r_i	emission rate of ultrasonic pulses of bat *i*
T_w	water starting time (s)	x_i^t, v_i^t	position and velocity of bat *i* at time step *t*
ΔP_{Di}	load demand change	r^o	initial pulse emission rate
ΔP_{tie}	change in tie line power (p.u. MW)	ACE_{ref}	reference area control error
T_{pi}	power system time constant (s)	$n_{\max}$	maximum number of iterations
K_{pi}	power system gain		
Δf_i	system frequency deviation (Hz)		
T_s	settling time (s)		

dead band, and time delays, is addressed in [11]. The application of PSO for optimizing an integral controller and a PI controller, is reported in [12]. The authors of [13] tuned the PI controllers via PSO using a new cost function and compared their results with [12]. The design of a fuzzy logic PI controller based LFCs via multiple tabu search (MTS) algorithm, is presented in [14]. In [15], a robust PID design based on the imperialist competitive algorithm (ICA) has been considered for LFC application. Bacterial foraging optimization algorithm (BFOA) has been suggested by Ali et al. for optimizing PI and PID-based LFCs for a two-area power system with and without GRC [16,17]. Maiden application of BFOA to optimize integral controller gains, governor speed droop and the frequency bias parameters has been investigated for a three-area unequal thermal systems [18]. Optimizing the gains of PID controllers in a nonlinear hydro-thermal system via ACO has been addressed in [19]. In [20], Elsisi et al. considered the application of ABC optimization for optimal tuning of PID controllers in a two-area power system.

Over the last few decades, the interest in model predictive control (MPC) has progressed significantly. Progressive interest in MPC results from its fast response and stability against nonlinearities, constraints and parameters uncertainties [21]. These powerful features of MPC will enhance the performance of proposed MPLFCs. The authors of [22–25], presented some primary results on MPC applications in LFC. In [22], MPC has been applied in a multi-area power system for economic dispatch. In [23], a new state contractive constraint-based predictive control scheme was used for LFC of a two-area interconnected power system. This MPC algorithm consists of a basic finite horizon and an additional state contractive constraint. In [24], feasible cooperation-based MPC method was used in distributed LFC instead of centralized MPC while parameter uncertainties and GRC were not considered. In [25], Mohamed et al. presented the decentralized MPC-based LFC of multi-area interconnected power system where the controller of each area was designed separately. However, the design did not account for the GRC that was only considered while model simulation. Remarkably, such design may lead to a degraded system performance once the interactions between different areas become significant.

This paper proposes the application of BIA for optimal tuning of MPC-based LFCs in two area interconnected power system to damp out low-frequency oscillations. The MPC control design is formulated as an optimization problem where BIA is devoted to search for optimal controller parameters by minimizing a candidate time-domain based objective function. Realistic constraints imposed by GRC, GDB and time delays, are considered in the suggested design algorithm. The performance of the proposed BIA-based MPC is evaluated by comparison with conventional and GA-based PI controllers. Simulations results on a two-area test system are presented to confirm the superiority of the proposed method compared with other design methods. Furthermore, robustness of the proposed BIA-based MPLFCs is tested against system parameters uncertainties.

BIA optimization

Bat inspired algorithm

This search algorithm has been developed based on the echolocation behavior of bats in locating their victims. The prime foundations of BIA optimization were firstly introduced by Yang [26]. These bats emit a series of ultrasound pulses and listen for the echoes that bounce back from the surrounding objects. The bandwidth of released ultrasound waves varies depending on the species and increases using harmonics. These waves are reflected with time delays and different sound levels which enable each bat to catch a specific prey. Optimization via BIA has been considered for optimal tuning of decentralized power system stabilizers (PSSs) in a multimachine power system [27]. Recently, BIA has been utilized to search for optimal parameter setting of dual mode PI controllers [28]. A summary of the basic steps, involved in BIA optimization, is given below.

Step 1. All bats utilize echolocation to sense distance and classify between prey and barrier.
Step 2. Each bat flies with a velocity (v_i) at position (x_i), having fixed frequency ($f_{\min}$) varying wavelength (λ), and loudness (L_o) to seek a prey. The bat tunes the frequency of its emitted pulse in the range ($f_{\min}$, $f_{\max}$) and adjusts the rate of pulse emission (r) in the range of $[0, 1]$ according to target closeness.
Step 3. Frequency, loudness and pulse emission rate of each bat are varied.
Step 4. Their loudness changes from a large value L_o to a minimum constant value $L_{\min}$.

The position x_i and velocity v_i of each bat are updated during the optimization process where the positions x_i^t and velocities v_i^t at a time step t, are computed as follows:

$$f_i = f_{\min} + (f_{\max} - f_{\min})\alpha, \quad \alpha \in [0\ 1] \tag{1}$$