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Fractional order fuzzy-PID control of a combined cycle power plant using Particle Swarm Optimization algorithm with an improved dynamic parameters selection

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ABSTRACT

The effectiveness of the Particle Swarm Optimization (PSO) algorithm in solving any optimization problem is highly dependent on the right selection of tuning parameters. A better control parameter improves the flexibility and robustness of the algorithm. In this paper, a new PSO algorithm based on dynamic control parameters selection is presented in order to further enhance the algorithm's rate of convergence and the minimization of the fitness function. The powerful Dynamic PSO (DPSO) uses a new mechanism to dynamically select the best performing combinations of acceleration coefficients, inertia weight, and population size. A fractional order fuzzy-PID (fuzzy-FOPID) controller based on the DPSO algorithm is proposed to perform the optimization task of the controller gains and improve the performance of a single-shaft Combined Cycle Power Plant (CCPP). The proposed controller is used in speed control loop to improve the response during frequency drop or change in loading. The performance of the fuzzy-FOPID based DPSO is compared with those of the conventional PSO, Comprehensive Learning PSO (CLPSO), Heterogeneous CLPSO (HCLPSO), Genetic Algorithm (GA), Differential Evolution (DE), and Artificial Bee Colony (ABC) algorithm. The simulation results show the effectiveness and performance of the proposed method for frequency drop or change in loading.

1. Introduction

There has been a continuous development of the Combined Cycle Power Plants (CCPP), which combine a gas turbine and a steam turbine, because of their high energy efficiency and their low emission. In single-shaft combined cycle power plants the fuel supply system and the compressor are both attached to the turbine's shaft. Thus any frequency drop or change in loading have a direct effect on the air and fuel supply, which has a negative effect on the performance and stability of the system [1,2]. The need for accurate modeling of the gas turbine, parameters estimation, and stability frequency and electrical voltage in the presence of sudden changes or variations of the electrical load in the transmission and distribution systems has led to several publications in this area. In [1] the dynamic behavior and stability analysis of a CCPP for frequency drops are investigated. The performance and impact of the gas turbine dynamics and the model of the CCPP are discussed in [2,3]. Paper [2] combines some dynamic models of the CCPP and builds a new one. The work in [4] focuses on the frequency regulation performance to improve control strategies. The classical controllers of a combined cycle gas turbine (CCGT) plant using Firefly Algorithm (FA) are discussed in [5]. It develops a small signal model for CCGT and applies FA for optimization of classical controller gains. A sensitivity analysis is carried out to show the robustness of the proposed controller.

In recent years, there has been a growing interest in the application of fractional calculus in various fields of science and engineering. Fractional calculus is a generalization of the classical calculus integral and derivative operators with integer order to arbitrary order. It has applied in various fields such as mathematics, physics, engineering, chemistry, computer science and mechanics [6–8]. The use of fractional calculus in the area of control theory has become very popular since the last few years. This application extends the opportunity to enhance the system control performance of conventional controllers. In papers [9–13], several fractional order controllers problems and tuning methods are

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introduced and considered. Paper [14] deals with the tuning and auto-tuning of fractional order controllers for industry applications. This paper shows that the fractional order controllers are robust and can outperform standard PID controllers. In [15] a robust controller design based on fractional calculus for a wind turbine generator is presented. The fractional order PID (FOPID) filter controller tuning method based on Internal Model Control (IMC) is investigated in [16].

Evolutionary and Swarm Intelligence (SI) algorithms such as Genetic Algorithm (GA) [17], Particle Swarm Optimization (PSO) [18,19], and Artificial Bee Colony Algorithm (ABC) [20] techniques have a long history in solving optimization problems of control systems. In [21] the Imperialist Competitive Algorithm (ICA) is used for robust load-frequency control of power systems. The performance of the Fruit fly Optimization Algorithm (FOA) based fractional order fuzzy-PID controller for electronic throttle is investigated in [22]. The multi-area automatic generation control problem is discussed in [23]. The authors in [23] use FA for the optimization of FOPID controller gains. Paper [24] discusses an application of improved Differential Evolution (DE) to the design of FOPID controllers. It shows the superiority of the proposed approach compared to GA and PSO algorithms.

The PSO algorithm is inspired by natural concepts such as bird flocking and fish schooling, and shows significant success in solving different optimization problems. Several variants of this algorithm are available in different references and can be classified according to fuzziness, accordance, attraction, activity, grouping, mobility, divisibility, interaction, uncertainty, continuity, topology, hierarchy, restriction, cooperation, objective, recursion, etc. [25]. A variant of PSO algorithm which is named Comprehensive Learning PSO (CLPSO) is introduced in [26]. This algorithm tries to benefit from all particles' best experiences to update a particle's velocity, and hence prevent from a premature convergence. In [27], authors develop the CLPSO algorithm to the Heterogeneous CLPSO (HCLPSO), in which the swarm population is divided into two heterogeneous subpopulations to enhance exploration and exploitation performances, and therefore maintain the diversity of the algorithm. The PSO algorithm has been used in different areas of science and engineering, including classification, sensor networks, swarm robotic, and optimization problems [28]. In [29] the application of a fractional order PID controller to an Automatic Voltage Regulator (AVR) is discussed. This paper employs a PSO algorithm to tune the gains of the FOPID controller. The Automatic Generation Control (AGC) of the two areas thermal power system with craziness based PSO is presented and studied in [30]. A hybrid PSO fuzzy-PID controller is proposed and implemented for speed control of a gas turbine in [31]. This paper evaluates the performance of the proposed algorithm and compares the main characteristics of the step response, such as rise time, settling time, and overshoot during startup and operating condition of the gas turbine, with other controllers. In [32] a new algorithm based on hybridizing between DE and PSO algorithms is presented to find the optimal parameters of a PID controller. A detailed review of the PSO concepts and its application can be found in [28,33,34].

In this paper, a new PSO algorithm based on dynamic control parameters selection is proposed. The DPSO algorithm uses a new mechanism and selects the best performing combinations of acceleration coefficients, inertia weight, and population size. A fractional order fuzzy-PID controller based on the DPSO algorithm is proposed to improve the performance of a single-shaft combined cycle power plant. The proposed controller is used as a speed (frequency) controller of the CCPP. The simulation results show the dynamic performance of the fuzzy-FOPID with optimum gains during frequency drop or change in loading based on two cost functions: Integral Time Absolute Error (ITAE) and Integral Time Squared Error (ITSE). These results are compared with those obtained using conventional PSO, CLPSO, HCLPSO, GA, DE, and ABC algorithms.

This paper is organized as follows: in Section 2, the combined cycle plant model is presented. The basic concept of fuzzy-FOPID controller is described in Section 3. Section 4 provides a brief overview of the PSO algorithm. In this section the main idea of the DPSO algorithm is discussed. Simulation results are presented and discussed in Section 5 and finally, the paper is concluded in Section 6.

2. Combined cycle power plant model

A CCPP is the combination of a gas turbine generator (Brayton cycle) and a steam turbine generator (Rankine cycle) for the production of electric power. The plant consists of several components, such as a gas turbine, a combustor, a compressor, a waste heat recovery boiler, a steam turbine and a generator. The compressed air is sent to the combustor by the compressor. The air burns with fuel, and makes a high temperature and high pressure combustor gas. The gas turbine is driven by this combustor high pressure gas. The energy of the exhaust high temperature gas is collected by the waste heat recovery boiler. This collected energy is used to drive the steam turbine. The plant power output is the sum of the gas turbine generator and the steam turbine generator power outputs [2]. Since the air is adiabatically compressed, the compressor discharge temperature T_d and the ratio of input–output temperature x for isentropic compression are given as follows:

$$T_d = T_i\left(1+\frac{x-1}{\eta_c}\right), \tag{1}$$

$$x = (P_{r0}W_a)^{\frac{\gamma-1}{\gamma}}, \tag{2}$$

where T_i and η_c are the ambient temperature and the compressor efficiency, respectively, P_{r0} is the nominal compressor pressure ratio, W_a is the airflow, and γ is the ratio of specific heat. From the energy balance equation in the combustion chamber, the relationship between T_d and the gas turbine inlet temperature T_f is described as follows:

$$T_f = T_d + (T_{f0}-T_{d0})\frac{W_f}{W_a}, \tag{3}$$

where W_f is the fuel flow, T_{f0} is the gas turbine inlet temperature, and T_{d0} is the compressors discharge temperature. The relationship between T_f and the gas turbine exhaust temperature T_e can be obtained by the following equation:

$$T_e = T_f\left[1-\left(1-\frac{1}{x}\right)\eta_t\right], \tag{4}$$

where η_t is the turbine efficiency. The energy supplied to the gas turbine and the steam turbine are defined as:

$$E_g = K_0\{(T_f-T_e)-(T_d-T_i)\}W_a, \tag{5}$$

$$E_s = K_1 T_e W_a, \tag{6}$$

where K_0 is the gas turbine output coefficient, and K_1 is the steam turbine output coefficient. The dynamic model and main signals of the CCPP are shown in Fig. 1 and Table 1. The parameters used for the CCPP are the same as those used in [1,2]. The plant model consists of two control loops. The first one is the frequency (speed) control loop, which changes the fuel flow to balance the difference between generation and load in frequency (speed) deviation (annotated in red). Our approach will be applied to this particular loop. The second one is the temperature control loop and consists of two branches (annotated in green). The normal temperature control branch (air flow controller in Fig. 1) acts on the air valves when the exhaust gas temperature exceeds the reference value. The overheat control branch acts through the fuel supply on sever overheat.