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Load frequency control problem in interconnected power systems using robust fractional $PI^{\lambda}D$ controller

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Abstract In this paper, a robust Fractional Order $\mathbf{PI^{\lambda}D}$ controller that contains an integral fraction action and a simple filtered derivative action, is investigated on Automatic Generation Control (AGC) of a three areas reheat-thermal system. For more realistic study some nonlinear constraints have been introduced such as Governor Dead Band (GDB), Generation Rate Constraints (GRC) and boiler dynamics. The optimal controller parameters are tuned through new evolutionary algorithm known as Differential Evolution (DE) algorithm by minimizing the Integral of Squared Error (ISE) index. Obtained results reveal clearly the superiority of the investigated controller compared to the other controllers such as PID, PID^{μ} and $PI^{\lambda}D^{\mu}$ in terms of the performance index, peak overshoots, peak undershoots and settling time. Effectiveness and rapidity of the DE algorithm in the convergence have been shown and compared to Genetic Algorithm (GA). Finally, robustness analysis against higher degree of load disturbance and sever parametric variation demonstrates the effectiveness of the investigated controller.

1. Introduction

The main objective of an electrical power system is to ensure the balance between the total power generation with the total load demand and the associated system losses, then regulating the system frequency and tie-line power exchange [1,2]. To ensure the quality of power supply, it is obligatory to regulate the generator loads depending on the optimal frequency value through a secondary controller [3]. This scheme is known as the Load Frequency Control (LFC), named also AGC. It is one of the most important control problems in the design and operation of power systems, whose role is [4–7]: to keep

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Nomenclature

PID	Proportional Integral Derivative	ΔP_{m1}	mechanical power deviation for the area i (pu)
FO-PID	Fractional Order Proportional Integral Derivative	ΔP_{Ci}	power deviation of area i
LFC	Load Frequency Control	ΔP_{Li}	load variation of area i
AGC	Automatic Generation Control	T_{Gi}	steam turbine speed governor time constant (s)
ACE	Area Control Error	K_{Ri}	coefficient of reheater steam turbine
GRC	Generation Rate Constraint	T_{Ri}	reheater time constant (s)
GDB	Governor Dead Band	T_{Ti}	steam turbine time constant (s)
DE	Differential Evolution	K_{Pi}	power system gain constant
ISE	Integral of Squared Error	T_{Pi}	power system time constant (s)
Δf_i	frequency deviation of area i (Hz)	R_i	speed regulation value (Hz/p.u)

the frequency unchanged by the load, to keep the correct value of interchanged power between control areas, to maintain each unit's generation at the most economic value and the last objective is to ensure the non-violation of operating limits.

Different control strategies have been proposed in the literature for this secondary controller design. The most widely used are the classical PI and PID controllers [8–10] due to their implementation simplicity. The synthesis of these controllers is based on the power system model. Hence, a variation of the model parameters or the system operating points leads to the degradation of the controlled system performances. To rectify these problems, other emerging strategies have been proposed to enhance the performance of such classical controllers.

Some researchers proposed the use of two degrees of freedom PID controller in two and three areas considering some nonlinear constraints such as GDB and GRC [11,19]. Other propositions based on fuzzy logic controller have been proposed in two area reheat-thermal systems taken into account GDB and GRC constraints [12]. The use of fractional controller has been also implemented by several researchers [13,14,17,18]. In [17], the authors have proposed $I^{\lambda}D^{\mu}$ controller in three areas reheat-thermal AGC system with consideration of GRC. Authors in [18] proposed two-degrees of freedom PID (2-DOF-PID) controller in three areas reheat-thermal system with GRC constraints.

Owing to the complexity of the system, direct synthesis of the above proposed controllers is not straightforward. Therefore, an optimization of the controller parameters based on different techniques appears to be an attractive solution. The optimization techniques extensively used in the AGC problem are as follows: GA, Particle Swarm Optimization (PSO), Bacterial Foraging Optimization Algorithm (BFOA) and hybridization of PSO–BFOA [8–11,15].

In this paper, an attempt has been made for the optimal fractional $\mathbf{PI^{\lambda}D}$ controller design, made up with a fractional integral action and a simple filtered derivative action and applied to a three areas reheat-thermal AGC systems considering several nonlinearity constraints. The investigated controller will provide more effective compared to the simple PID controller and a fractional PID controllers such as PID^{μ} and $PI^{\lambda}D^{\mu}$ from different points of view. The design problem is formulated as an optimization problem in the basis of evaluating the ISE criterion. Then, the DE algorithm has been used to determine the optimal controller parameters. Simulation results show the effectiveness of the investigated controller in terms of performances index; and its robustness against a wide range of loading conditions, disturbance and parametric variation. Furthermore, the superiority of the investigated optimization algorithm is illustrated via a comparison with other evolutionary algorithm, which is the GA. In view of the above presentation, the main goals of this work are as follows:

- To design a robust fractional $\mathbf{PI^{\lambda}D}$ controller and compare its performance with others known controllers as well as; PID, PID^{μ} and $PI^{\lambda}D^{\mu}$ in a three areas reheat-thermal system with consideration of GDB, GRC and dynamic boiler.
- To optimize the above mentioned controllers using DE algorithm and compare its convergence characteristics with GA.
- To verify the robustness of obtained optimal value of the investigated ($\mathbf{PI^{\lambda}D}$) controller through different load disturbance and sensitivity analysis.

2. Power system modeling

The investigated $\mathbf{PI^{\lambda}D}$ controller is tested on three areas interconnected reheat-thermal AGC system as shown in Fig. 1 [16]. For more realistic analysis, some nonlinear constraints such as GDB, GRC and dynamic boiler are taken into account [11].

The transfer function model of the system under study is depicted in Fig. 2. The dynamic boiler scheme is presented in Appendix B. The nominal system parameters [17–19] are recapitulated in Appendix A. A dynamical frequency responses of the first area (Δf_1) with and without nonlinearities are presented in Fig. 3.

From Fig. 3, it has been noted that the system without any control is stable but it represents a steady state error. Hence, to reduce this error, we have implemented ($\mathbf{PI^{\lambda}D}$) controller.

3. Fractional calculus background

In mathematics, fractional calculus permits to convert the differential or integral operator with integer order to the fractional order [13]. The fractional operator noted ${}_aD_t^{\alpha}$, depending on the sign of α indicates differentiation or integration. This operator is presented in Eq. (1). There are some existing definitions for describing the fractional order functions. The most frequently used are, Riemann–Liouville

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