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Fractional-order load-frequency control of interconnected power systems using chaotic multi-objective optimization

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ABSTRACT

Fractional-order proportional-integral-derivative (FOPID) controllers are designed for load-frequency control (LFC) of two interconnected power systems. Conflicting time-domain design objectives are considered in a multi-objective optimization (MOO)-based design framework to design the gains and the fractional differ-integral orders of the FOPID controllers in the two areas. Here, we explore the effect of augmenting two different chaotic maps along with the uniform random number generator (RNG) in the popular MOO algorithm—the Non-dominated Sorting Genetic Algorithm-II (NSGA-II). Different measures of quality for MOO, e.g. hypervolume indicator, moment of inertia-based diversity metric, total Pareto spread, spacing metric, are adopted to select the best set of controller parameters from multiple runs of all the NSGA-II variants (i.e. nominal and chaotic versions). The chaotic versions of the NSGA-II algorithm are compared with the standard NSGA-II in terms of solution quality and computational time. In addition, the Pareto optimal fronts showing the trade-off between the two conflicting time domain design objectives are compared to show the advantage of using the FOPID controller over that with simple PID controller. The nature of fast/slow and high/low noise amplification effects of the FOPID structure or the four quadrant operation in the two inter-connected areas of the power system is also explored. A fuzzy logic-based method has been adopted next to select the best compromise solution from the best Pareto fronts corresponding to each MOO comparison criteria. The time-domain system responses are shown for the fuzzy best compromise solutions under nominal operating conditions. Comparative analysis on the merits and de-merits of each controller structure is reported then. A robustness analysis is also done for the PID and the FOPID controllers.

1. Introduction

Large-scale power system networks comprise of several interconnected subsystems representing particular geographical areas. Each of these subsystems has their own generation capability and has variable load demand. These sub-systems are connected by tie lines which control the flow of power between the different areas [1]. A sudden load demand in a certain area results in a drop in system frequency which is detrimental for connected electrical loads. To ensure proper power quality, the load-frequency controllers in the interconnected power system regulate the flow of power among the different areas through the tie lines and balance the load and the drop in frequency. The LFCs balance the mismatch between the frequencies of the interconnected areas and schedule the flow of power through the tie lies, helping the interconnected power system to overcome the aberrations introduced due to varying load demand, generation outage, etc. Recently, the LFCs are gaining more importance due to the integration of renewables in the grid which have an inherent stochastic characteristic due to the vagaries of nature unlike those of the base load thermal power plants [2,3]. Thus, proper design and operation of the LFCs are very important for the stable and reliable operation of large-scale power systems. Control of interconnected power system considering various aspects has been a topic of intense research in the recent past. Different type of generating units and their effects have been studied, e.g. thermal with reheat [4], generation rate constraint (GRC) [5], reheat and battery energy storage both the areas [6], hydro turbine and hydro-governor in both the areas [7], thermal with reheat turbine along with hydro and gas turbine plants in both the areas [8], etc.

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Traditionally a proportional-integral (PI) or a proportional-integral-derivative (PID) controller is used for the LFCs [9] and a variety of different methods exist for proper tuning of the controller parameters. Many robust control design techniques have been applied to the LFC problem so that the designed controller is able to handle uncertainties of the system. Some variants of robust designs include an adaptive output feedback-based robust control [10], adaptive robust control [11], decentralized robust control using iterative linear matrix inequalities (LMIs) [12], decentralized control [13], etc. Optimal control designs using linear quadratic regulator (LQR) technique has been reported in [14]. Several other popular control philosophies like the model predictive control (MPC) [15], sliding mode control [16], singular value decomposition (SVD) [17], etc. have also been applied in decentralized LFC of multi-area power systems.

Many computational intelligence-based techniques have been employed in the design of LFCs as well. Global optimization techniques using evolutionary and swarm intelligence has been used to tune the PID controller parameters in various literatures. Genetic algorithm (GA) has been used in the design of LFCs in [7]. A variable structure controller has been designed for LFCs using GA in [18]. Fuzzy logic-based gain scheduling has been done in [19] to obtain improved control strategy for LFC. The application of neural networks in the problem of load-frequency control has been investigated in [20,21]. There are other literatures which employ robust control techniques like H_∞ loop shaping [22], μ-synthesis [23] and LMI approaches [12,22] with intelligent genetic algorithms to obtain robust controllers. A detailed review of the existing design methodologies in LFC has been documented in [24–26]. Other intelligent algorithms like Bacterial foraging algorithm [27], fuzzy logic [28], and recurrent fuzzy neural network [29] have also been applied in LFC of multi-area inter-connected power systems.

Fractional-order controllers have been gaining popularity in recent years due to added capability to handle control design specifications [30,31]. Fractional-order PID controllers have been applied in a wide variety of control systems and have generally proved to be better than their integer order (IO) counterparts [32]. Recently, fractional-order controllers have been applied to power systems and favourable results have been obtained. In [33], a fractional order controller has been designed for an automatic voltage regulator (AVR) with particle swarm optimization (PSO) algorithm to show that the FO controllers have more robustness to tackle uncertainties than the conventional IO-PID controller. Alomoush [34] has applied fractional-order controllers for LFC of a two-area interconnected power system and an automatic generation control for an isolated single-area power system. It has been shown in [34] that the fractional-order PID controller has more flexibility in design and can adjust the system dynamics better than the IO-PID controller. FOPID controllers are also shown to be robust and competitive to IO-PID controllers [35–38]. In these previous literatures, only a single objective intelligent optimization has been employed to design the control system. However, it is well known that there exists multiple trade-offs among different design specifications in control [39] and similar system design [40]. It is not possible to simultaneously minimize all design objectives using a particular control structure and different controller structure may yield different trade-offs depending on the choice of the conflicting control objectives [41,42]. Thus, there is a requirement of multi-objective approach for addressing different conflicting objectives in the control system design [42]. In [42–44], time and frequency domain multi-objective formulation have been used to study the design trade-offs among various conflicting FOPID design objectives in an automatic voltage regulator (AVR) system. It has been shown in [42–44] that sometimes the FOPID and at other times the PID controller performs better depending on the choice of the conflicting objective functions. This concept of MOO for FO controllers has been extended in this paper for two-area LFC problem. In this paper, FOPID controllers in the two-area LFC are designed using chaotic multi-objective NSGA-II algorithm. Set point tracking and low control signal are chosen as the two conflicting objectives for the MOO-based tuning of FOPID/PID controllers and the performance improvement due to the FOPID compared to the PID is illustrated by numerical simulations.

The main highlights of the paper include:

- Augmenting the NSGA-II algorithm with different chaotic maps (like Logistic and Henon maps) to obtain better Pareto optimal solutions.
- Using Pareto metrics like hyper-volume indicator, spacing metric, Pareto spread and diversity metric [45–47], to assess the performance of the chaotic MOO algorithms.
- Use of FOPID controller to obtain better system performance for the two-area LFC.
- Demonstration of conflicting time-domain trade-offs in the controller performances for the FOPID and the PID controller and use of a fuzzy-based mechanism for selecting the best compromise solution.
- Robustness study of FOPID as LFC over that with PID, under system parametric uncertainty and random change in load patterns.

The rest of the paper is organized as follows. Section 2 gives a brief description of the two-area LFC problem in the interconnected power system. Section 3 introduces the basics of fractional calculus, FOPID controller and its flexibility over PID. Section 4 outlines the conflicting time-domain criteria-based MOO for the design of the LFC system. Section 5 introduces the chaotic versions of the multi-objective NSGA-II algorithm. Different MOO measure-based selection of the best optimizer and the controller are enunciated in Section 6, along with the respective time-domain responses. In Section 7, the effect of uncertainty in the synchronizing coefficient and the effect of randomly changing load patterns in both areas are explored. The paper ends with the conclusions in Section 8 followed by the references.

2. Load-frequency control of interconnected two-area power system

The main functionalities of the LFC are

a) To keep the operating power system frequency within specified tolerance limits to ensure power quality
b) To ensure proper load sharing between the generators of the interconnected system
c) To honour the pre-specified load exchange constraints by controlling the power flow between the interconnected areas.

A schematic diagram for the two-area LFC is depicted in Fig. 1. The parameters of the various units of the system are shown in Table 1 [23]. The area control error (ACE) in each area is a function of the frequency deviation (Δf) and the inter area tie-line power flow (ΔP_{tie}). The ACE is fed as an input to the FOPID controller where it calculates the appropriate control signal to be applied. This control signal is fed into the amplifier and then the actuator to produce an appropriate change in the mechanical torque of the turbine (prime mover). This produces a change in the active power output of the generator to compensate the power flow in the system and thus Δf and ΔP_{tie} are kept within desired limits. The tasks of the PID/FOPID controller in each area are to ensure faster damping of individual ACEs and also damping the inter-area power oscillation ΔP_{tie}.

Each area includes steam turbine, governor, reheater stages along with GRC nonlinearity in the turbine and dead-band in the