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Load frequency control strategy via fractional-order controller and reduced-order modeling

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ABSTRACT

This paper proposes a simple approach to design fractional-order (FO) controller via internal model control (IMC) technique for load frequency control (LFC) problem in power systems. The proposed scheme utilizes the concept of CRONE principle, model-order reduction and FO filter in IMC framework to derive a robust controller. Initially, the scheme is applied to single-area power system and then extended to two-area interconnected system. The turbines considered are non-reheated, reheated and hydro type; and physical constraints of turbine and governor are also taken into account to validate the applicability in more realistic environment. Simulation results show that it can bring improved disturbance rejection performance in nominal condition as well as in presence of uncertainties and constraints in plant parameters.

1. Introduction

Power system control is one of the most challenging task in control engineering because the total generated power should balance the total load in presence of numerous electrical machines such as generating units, protection devices, controller loops and power transmission lines that generally spread in large geographical areas. Essentially, there would be performance deterioration in the form of frequency fluctuations, voltage instability, constant but unexpected load change, operational limits, rotor angle instability, economy in operation, and physical and environmental disturbances. Therefore, these discrepancies must be eliminated for satisfactory operation of power system.

Among the various power system control strategies [1], LFC deals with the regulation of frequency fluctuations,*i.e.*, frequency should remain nearly constant in all control areas. In short, the LFC adjusts the load reference point against the variation of the load changes in order to keep the system frequency and tie-line power as closed to the prescribed values as possible. The main objectives of LFC are to: 1) maintain zero steady state error for frequency and tie-line power deviations, 2) reject sudden load disturbance, 3) attain optimal transient behavior under prescribed overshoot, settling time and error tolerance, 4) provide robust performance in presence of modeling uncertainties and nonlinearities, 5) establish better security margin of system in sense of stable frequency regulation, and less computing power [2–4]. Thus, LFC can be treated as an objective optimization and robust control problem. In view of this various LFC strategies have been developed using optimal, robust, adaptive and intelligent control perspectives [5–7].

These days FO control scheme has received great attention among the control practitioners due to improved control performance especially for the systems working in uncertain environment, and exact modeling of complex systems [8,9]. The FO system and control schemes are generally better than their integer-order (IO) counterparts. As a result, a few fractional-order PID (FO-PID) control methodologies have also been introduced for LFC problem. The first FO-PID scheme was presented by Alomoush [10] in which LFC has been considered as a constrained optimization problem for two-area power systems. The integral error criterion particularly *ITAE* was selected as an optimization function to evaluate PID parameters. In [11], the stability boundary locus method was employed to search the stabilizing FO-PID parameters of a hybrid single-area power systems. Later on, nature inspired evolutionary and soft computing schemes (like, the non-dominated sorting genetic algorithm-II, firefly algorithm, imperialist competitive algorithm) are introduced to design optimal FO-PID controllers for multi-area power systems [12–14]. In these intelligent optimization schemes, the multi-objective functions are framed using integral square indices such as *ITAE*, *ISE*, *ISDCO* (integral of the squared deviation in controller output) and other figure of merits to tune PID parameters. Although the aforementioned LFC schemes have shown their effectiveness and dominance over classical approach, there are deficiencies due to heavy computational burden, premature convergence during optimization process and sluggish disturbance

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attenuation.

IMC technique is a control strategy that has been successfully used for few decades [15–20]. It is observed that simplicity, robustness, sub-optimality and wide area applicability are some features that have popularized IMC among control scientists and practitioners. After the introduction of IMC scheme in FO systems and control for last 2–3 years, the FO-PID got a new way for its synthesis and tuning (See [21] and the references therein). Moreover, in literature on one hand, CRONE (abbreviation of “Commande Robuste d’Ordre Non Entier” which means “non integer order robust control”) principle is highly popular for designing FO controller [22] and on the other hand IMC is famous control scheme for designing IO controller. Fortunately, the pioneer work of Maâmar & Rachid [23] bridges both control schemes to build FO controller. Through this method, the controller acquires the FO-PID form via IMC methodology and tuning scheme is evolved using CRONE principle.

Motivated by the celebrated work of [23], the FO controller design scheme is proposed in this paper which make use of reduced-order modeling to acquire the dominant features of the higher-order plant. Also to the best of author’s knowledge, such LFC scheme is missing in power control research. Therefore in this paper, a FO-PID based on IMC and CRONE schemes is proposed for frequency regulation of single and multi-area power systems. The proposed design requires only frequency domain specifications particularly phase margin and gain crossover frequency as a prerequisite. The main advantages of this work is that: (i) the proposed scheme exhibits robustness as the controller parameters, tuned with the help of gain and phase margin specifications, works well when parametric uncertainties are present in power plant, (ii) the controller is optimal as it minimizes the integral error indices, and (iii) for executing LFC, substantial improvements are observed in the performance using the proposed method in comparison to the recently developed methods.

2. Description of LFC model

Electric power systems are complex non-linear dynamical systems consisting of numerous generators and loads. However for modeling purpose, all the generators are lumped into single equivalent generator and likewise for loads. Since, power systems are exposed to small load changes, the system can be adequately represented by its linear model [2,33]. The basic power system notations are presented in Table 1.

2.1. Single-area power system

The block diagram of a single-area power system supplying power to single service area through single generator is shown in Fig. 1. The dynamics of this plant which consists of governor, non-reheated turbine, and load and machine can be written as

$$\frac{d}{dt}\Delta f(t) = -\frac{1}{T_P}\Delta f(t) + \frac{K_P}{T_P}(\Delta P_G(t) - \Delta P_d(t)) \tag{1}$$

Table 1
Nomenclature of Basic Power Systems Terms.

$\Delta f(t)$	Incremental change in frequency (Hz)
$\Delta P_d(t)$	Load disturbance (p.u. MW)
$\Delta P_G(t)$	Incremental change in generator output (p.u. MW)
$\Delta X_G(t)$	Incremental change in governor valve position (p.u. MW)
K_P	Electric system gain
T_P	Load and machine time constant (s)
T_T	Non-reheated turbine time constant (s)
T_r	Reheated turbine time constant (s)
T_w	Hydro turbine time constant (s)
T_G	Governor time constant (s)
c	Percentage of the power generated in the reheat portion
R	Speed regulation due to governor action (Hz/p.u. MW)
B_i	Frequency bias (p.u. MW/Hz)

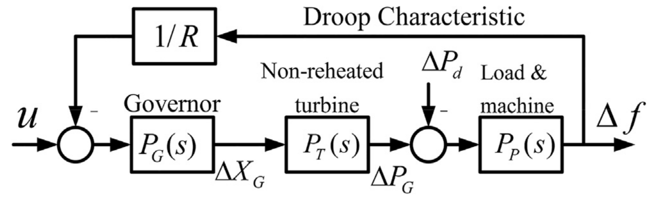

Fig. 1. Block diagram of single-area power system.

$$\frac{d}{dt}\Delta P_G(t) = -\frac{1}{T_T}\Delta P_G(t) + \frac{1}{T_T}\Delta X_G(t) \tag{2}$$

$$\frac{d}{dt}\Delta X_G(t) = -\frac{1}{RT_G}\Delta f(t) - \frac{1}{T_G}\Delta X_G(t) + \frac{1}{T_G}u(t) \tag{3}$$

In terms of transfer function model, the governor is

$$P_G(s) = \frac{1}{T_G s + 1}, \tag{4}$$

the non-reheated turbine is

$$P_T(s) = \frac{1}{T_T s + 1} \tag{5}$$

and the load and machine is

$$P_P(s) = \frac{K_P}{T_P s + 1} \tag{6}$$

Now using (4)–(6), the whole plant can be written as

$$\frac{\Delta f(s)}{u(s)} = P(s) = \frac{P_G(s)P_T(s)P_P(s)}{1 + P_G(s)P_T(s)P_P(s)/R} = \frac{K_P}{a_3 s^3 + a_2 s^2 + a_1 s + a_0} \tag{7}$$

where

$$a_3 = T_G T_T T_P,\ \ a_2 = T_G T_T + T_P T_T + T_P T_G,$$
$$a_1 = T_G + T_T + T_P,\ \ a_0 = 1 + \frac{K_P}{R} \tag{8}$$

As LFC is a disturbance rejection problem, so our aim is to find a control law: $u(s) = -C(s)\Delta f(s)$ such that $\lim_{t\to\infty}\Delta f(t) = 0$, for all ΔP_d.

Remark 1. Nonlinearities (backlash and wind-up problems) in the speed control are normally neglected except for rate limiter and the limits on valve position. All damping torque to prime-mover, generator and the HVDC system are also assumed to be negligible.

3. Design tools

In this section, we put forward few prerequisites to present our proposed work. Throughout the paper, the real and natural numbers are symbolized by $\mathbb{R}$ and $\mathbb{N}$, respectively. Further $\mathbb{R}^+$ denotes the real positive numbers. For any signal $x(t)$, its Laplace transform is denoted by $X(s)$. A stable continuous-time, linear time-invariant finite dimensional single-input single-output system described by a rational proper transfer function $G(s)$ is considered whose order is denoted with $\rho(G)$. A stable system $G(s)$ is a minimum-phase system if the zeros of the system are stable, *i.e.*, roots of the numerator polynomial are in left-half of complex s-plane.

3.1. Fractional-order system

Here, a brief exposition of FO operators and their properties are given. Fractional calculus is actually the generalization of IO integration and differentiation to any arbitrary real number. It is an old concept in mathematics however in control engineering it has witnessed a remarkable progress from last one decade after the introduction of FO controllers [8,9,24]. Now, we introduce the notion of generalized FO operators. The continuous integro-differential operator of order $\alpha \in \mathbb{R}$ (often denoted by ${}_xD_t^\alpha$, where x and t denote the limits of the operation)