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IMC based load frequency control of power system via reduced model order

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Abstract

This paper deals with non-integer internal model control (FIMC) based PID controller design for load frequency control (LFC) of single area non-reheated thermal power system. Firstly, a fractional second order plus dead time (SOPDT) reduced system model is obtained using genetic algorithm through step error minimization. Secondly, a FIMC based PID controller is designed for single area power system based on reduced system model. Proposed controller is equipped with single area non-reheated thermal power system. The resulting controller is tested using MATLAB under various conditions. The simulation results show that the controller can accommodate system parameter uncertainty as well as load perturbations.

AMS Subject Classification: 58E25, 91G80.

Key Words: model order reduction, genetic algorithm, non-iteger IMC filter, robust control, load frequency control(LFC).

1 Introduction

Generally, electric power system is studied in terms of generation, transmission and distribution systems in which all generators are operated synchronously at nominal frequency to meet the demand load. The frequency deviation in the power system is mainly due to mismatch between the generation and load plus losses at every second. There may be small or large frequency deviation based on the mismatch between generation and load demand. These mismatches due to random load fluctuations and due to large generator or power plant tripping out, faults etc. respectively. However, deviations could be positive or negative. The role of load frequency control(LFC) is to mitigate frequency perturbation. Thus the power system will operate normally [1]. This can be achieved by adopting a auxiliary controller in addition to the primary control(Governaor). From literature[1], conventional controller is used as auxiliary or secondary control. To get the parameters of this controller, the power system is modelled and simulated using MATLAB. This paper deals with the modelling of power system through fractional order differential equations and design of controller.

The fractional order dynamic system is characterised by differential equations in which the derivatives powers are any real or complex numbers. The approach of fractional order study is mainly used in the area of mathematics, control and physics [2]. The precision of modelling is accomplished using the theory of fractional calculus. In view of above fact, integer operators of traditional control methods have been replaced by concept of fractional calculus. Many modern controllers for LFC as secondary controllers are available like sliding mode control[3] and direct-indirect adaptive fuzzy controller technique [4]. It can be observed that power system parameters may alter due to ageing, replacement of system units and modelling errors, as a consequent problem to design a optimum secondary controller becomes a challenging work. From literature, it is noticed that robust controller is inert to system parameter alteration. Thus, a good robust controller design is needed to take care of parameter uncertainties as well as load disturbance in power system.

In literature, lot of robust control methods are presented for disturbance rejection and parameter alteration for LFC. Still a vast research is going on internal model control(IMC) by researchers due to its simplicity. With the two degree of freedom IMC(TDF IMC)[6], both set point tracking and load disturbance rejection can be achieved. As a consequent, IMC controller design is an ideal choice for secondary controller for LFC. Saxena[7] designed a TDF IMC for LFC using approximation techniques like Pade's and Routh's, which motivated to adopt the fractional IMC-PID controller as a secondary controller and is design based on a fractional reduced order model of a system.

2 Modelling of single area thermal non-reheated power system

This section deals with framing of fractional order model of a single area power system using a step error minimization technique through genetic algorithm. This is segregated into following subsections.

2.1 System modelling

The proposed work deals with modelling of the power system to design secondary controller. Due to this purpose, a single area non-reheated thermal power system has been considered[1]. The thermal power system equipped with different units like generator $G_P(s)$, turbine $G_t(s)$, governor $G_g(s)$. and their dynamics are given by (1)

$$G_g(s) = \frac{1}{T_G s + 1},\ G_t(s) = \frac{1}{T_T s + 1},\ G_p(s) = \frac{K_P}{T_P s + 1} \qquad (1)$$

The block diagram of a single area power system is shown in Fig. 1, where ΔP_d is Load disturbance(in p.u.MW), ΔX_G is Change in governor valve position, ΔP_G is Change in generator output(in p.u.MW), u is Control input, R is Speed regulation(in Hz/p.u.MW) and $\Delta f(s)$ is Frequency deviation(in Hz).
The overall transfer function is attained as
Case1: From Fig. 1 assume $\Delta f(s) = \Delta f_1(s)$ when $\Delta P_d(s) = 0$, the

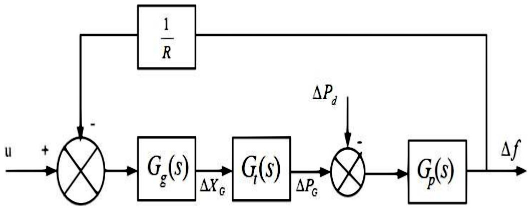

Figure 1: Single area power system linear model

corresponding transfer function is $G_1(s)$.
Case2: From Fig. 1 assume $\Delta f(s) = \Delta f_2(s)$ when $u(s) = 0$, the corresponding transfer function is $G_2(s)$.
Applying the theory of superposition principle to power system model, the overall transfer function is given by (2)

$$\Delta f(s) = \Delta f_1(s) + \Delta f_2(s) = G_1(s)u(s) + G_2(s)\Delta P_d(s) \tag{2}$$

The aim is to find control law $u(s) = -K(s)\Delta f(s)$ which mitigates the effect of load alteration on frequency deviation, where $K(s)$ is fractional IMC-PID controller.

2.2 Representation of Fractional system

This subsection deals with the fractional order systems through which it can develop a proposed model for power plant to design a secondary controller.
The representation for a linear time invariant fractional order dynamic system[8] is given as ,

$$H(D^{\alpha_0\alpha_1....\alpha_n})y(t) = F(D^{\beta_0\beta_1....\beta_m})u(t) \tag{3}$$

$$H(D^{\alpha_0\alpha_1....\alpha_n}) = \sum_{k=0}^{n} a_k D^{\alpha_k}, \ F(D^{\beta_0\beta_1....\beta_m}) = \sum_{k=0}^{m} b_k D^{\beta_k} \tag{4}$$

where $y(t)$ and $u(t)$ are output and input vectors respectively and D is differential operator. α_k, β_k are the order of derevatives. a_k and b_k are coefficients of derivatives, $a_k, b_k \epsilon \mathbb{R}$. Here H, F Fractional dynamic systems.
The transfer function of fractional order dynamic system is obtained

by applying Laplace transform to (3) and (4) (initial conditions are zero) and is given as (5)

$$G_3(s) = \frac{\sum_{k=0}^{m} b_k (s^\alpha)^k}{\sum_{k=0}^{n} a_k (s^\alpha)^k} \quad (5)$$

2.3 System identification

The proposed work utilizes the models that are fractional order in nature for design of controller. Model order reduction(MOR) technique deals with reduction of full order model without loosing their input-output behaviour [9].

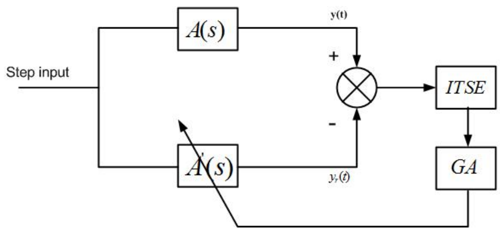

Figure 2: Step error minimization technique

The system $A(s)$ whose coefficients are known from the chosen system is reduced to $A'(s)$ which has unknown variables. The solution to these unknown variables is found through step error minimization technique which is shown in Fig. 2.

From Fig. 2, ITSE is the integral time multiplied squared error performance index and is denoted by J, which is defined as (6).

$$J = ITSE = \int_0^{t_{sim}} (y(t) - y_r(t))^2 .tdt = \int_0^{t_{sim}} (e(t))^2 .tdt \quad (6)$$

2.4 Genetic algorithm

John Holland and his co-workers developed the GA in the year 1960s & in 1970s and is a nature inspired optimization technique[10]. GA is superior over the other optimization algorithms in dealing with complex problems. GA can deal with the objective function which may be linear or non-linear, time varying or time invariant, continuous or discrete. Steps involved in GA to get parameters of $A'(s)$ as follows

1. Objective function encoding.
2. Specify the selection criterion or fitness function.
3. Generate random initial population of individuals.
4. Calculation of fitness value of all individual for every iteration and generate a new population using crossover and mutation. Iteration using new population again by replacing old population.
5. Obtain the best solution to the problem.

2.5 Design of proposed system

From above subsections, the technique to reduce the higher order integer model to fractional order model is discussed. This technique is applied to a system presented in subsection 2.1 and proposed model derived. The full order transfer function of single area power system is obtained from (1) and (2), which is given by (7)

$$G_1(s) = \frac{K_P}{T_P T_T T_G s^3 + (T_P T_T + T_T T_G + T_G T_P)s^2 + (T_P + T_T + T_G)s + (1 + K_P/R)} \tag{7}$$

substitute the values of $T_P = 20$ sec, $T_T = 0.3$ sec, $T_G = 0.08$ sec, $R = 2.4$, $K_P = 120$[6] in (7), we get $G_1(s)$ as (8)

$$A(s) = G_1(s) = \frac{250}{s^3 + 15.88s^2 + 42.46s + 106.2} \tag{8}$$

The equation (8) represents integer higher order model which is converted to fractional order model assumed to be $A'(s)$
Consider fractional SOPDT reduced model $A'(s)$ given by (9)

$$A'(s) = \frac{K_1 e^{-Ls}}{s^b + ps^c + q} \tag{9}$$

Here the order of $A'(s)$ is less than the $A(s)$ and is in fractional form. The techniques shown in subsections 2.2, 2.2 and 2,3 are

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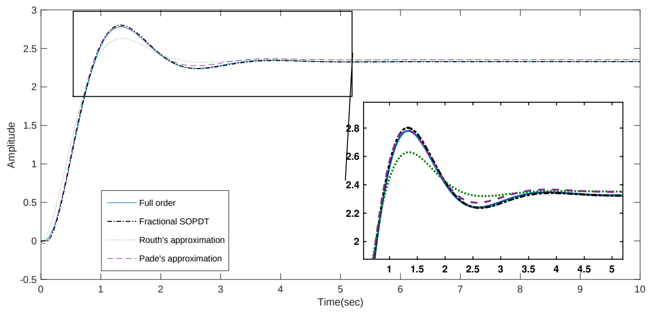


Figure 3: Comparison of step responses of full order model with fractional SOPDT, Routh and Pade approximation

utilized to obtain parameters of $A'(s)$ are given as $K_1 = 16.385, L = 0.095, b = 1.897,\ c = 0.962, p = 1.954, q = 7.031$. This is done through Matlab & simulation.
Thus the attained reduced fractional model $A'(s)$ is

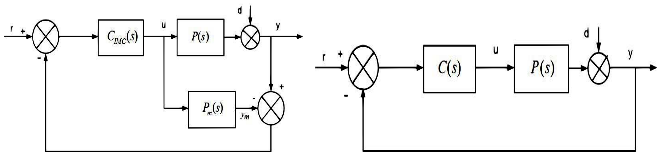
$$A'(s) = \frac{16.385e^{-0.095s}}{s^{1.897} + 1.954s^{0.962} + 7.031} \tag{10}$$

The step responses of original model, proposed, Pade's approximation and Routh's approximation are compared and shown in Fig. 3. The ITSE of proposed Pade's and Routh,s methods are 0.0015, 0.027 and 0.06 respectively. From Fig. 3 and above ITSE values, it is observed that the response of proposed method is very closer to full order model(original).

3 IMC based LFC design

In this section, model based IMC method for load frequency controller design is considered, which is developed by M. Morari and coworkers[11]. The block diagram of IMC structure is shown in Fig. 4a, where $C_{IMC}(s)$ is the controller, $P(s)$ is the power plant and $P_m(s)$ is the predictive plant. Fig. 4b shows block diagram of conventional closed loop control. From Fig. 4a and Fig. 4b, we can relate $C(s)$ and $C_{IMC}(s)$ as

$$C(s) = \frac{C_{IMC}(s)}{1 - C_{IMC}(s)P_m(s)} \tag{11}$$



(a) (b)

Figure 4: Block diagram of a) IMC configuration b) equivalent conventional feedback control

Steps for IMC controller design[12] are as follows.
Step1: The plant model can be represented as

$$P_m = P_m^+ P_m^- \tag{12}$$

where P_m^-= minimum phase system and P_m^+= non-minimum phase system, like zeros in right side of S-plane etc.
Step2: The IMC controller is

$$C_{IMC}(s) = \frac{1}{P_m^-} f(s),\ f(s) = \frac{1}{(1+\tau_c s^{\lambda+1})^r} \tag{13}$$

where $f(s)$ is low pass filter with steady state gain of one
where τ_c is the desired closed loop time constant and r is the positive integer, $r \geq 1$, which are chosen such that $C_{IMC}(s)$ is physically realizable. Here r is taken as 1 for proper transfer function.
The FIMC controller is designed for fractional SOPDT is given by (10) via method discussed below.
Consider the system [12], is given by (14)

$$P_m(s) = \frac{ke^{-\theta s}}{a_2 s^\beta + a_1 s^\alpha + 1}, \beta > \alpha \tag{14}$$

where $\alpha : 0.5 \leq \alpha \leq 1.5$, $\beta : 1.5 \leq \beta \leq 2.5$, θ= time delay. Here $a_2 = \tau^2$ and $a_1 = 2\zeta\tau$.
Using (12), the invertible part of $P_m(s)$ is

$$P_m^-(s) = \frac{k}{a_2 s^\beta + a_1 s^\alpha + 1} \tag{15}$$

Using (13), the Fractional IMC controller is

$$C_{IMC}(s) = \frac{a_2 s^\beta + a_1 s^\alpha + 1}{k} \frac{1}{(1+\tau_c s^{\lambda+1})} \tag{16}$$

substitute (16) in (11), then the conventional controller $C(s)$ is evaluated and simplified as

$$C(s) = \frac{a_2 s^{\beta} + a_1 s^{\alpha} + 1}{k(\tau_c s^{\lambda+1} + \theta s)} \quad (17)$$

where $e^{-\theta s}$ is approximated as $(1 - \theta s)$ using first order Taylor expansion[12].
Again $C(s)$ is decomposed into FIMC PID filter via technique discussed below.
Multiplying and dividing RHS of (17) by $s^{-\alpha}$

$$C(s) = \frac{(a_2 s^{\beta} + a_1 s^{\alpha} + 1)}{k(\tau_c s^{\lambda+1} + \theta s)} \frac{s^{-\alpha}}{s^{-\alpha}} \quad (18)$$

substitute $a_2 = \tau^2$ and $a_1 = 2\zeta\tau$ in (18) and rearranged as,

$$C(s) = [\frac{s^{1-\alpha}}{1 + (\tau_c/\theta)s^{\lambda}}][\frac{2\zeta\tau}{k\theta}(1 + \frac{1}{2\zeta\tau s^{\alpha}} + \frac{\tau}{2\zeta}s^{\beta-\alpha})] \quad (19)$$

where first part is fractional filter and second part is fractional PID controller.
To design FIMC to power system, the (10) can be re-framed in the form of (14) is

$$A'(s) = \frac{2.3303e^{-0.095s}}{0.142s^{1.897} + 0.2676s^{0.962} + 1} \quad (20)$$

From (14),(19) and (20), we get $\tau = 0.3768$, $\theta = 0.095$, k=2.3303, $\beta = 1.897$, $\alpha = 0.962$, $\zeta = 0.3551$
substituting above values in (19), the fractional IMC-PID filter for single area power system is

$$C(s) = \frac{s^{0.038}}{1 + 10.526\tau_c s^{\lambda}} 1.21(1 + 3.736s^{-0.962} + 0.5305s^{0.935}) \quad (21)$$

The value of τ_c and λ are selected in such a way, that it minimizes tracking error and achieves robust performance.

4 Results and Analysis

In this section, a model with proposed system and its controller is designed in simulation and an extensive simulation is carried out.

In this model an performance index ISE is accompanied to determine the error of frequency deviation. Based on ISE, Overshoot, undershoot and settling time, we choose best λ and τ_c. The obtained parameters λ and τ_c are λ=0.22 and τ_c=0.02

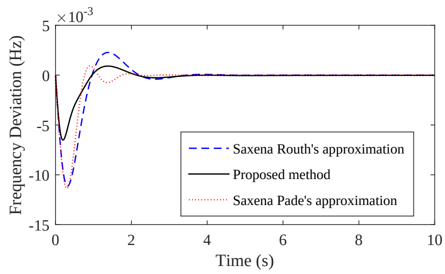


Figure 5: Comparison of response of power system using proposed with other methods

To evaluate performance a step load disturbance $\Delta\ P_d(s)$=0.01 is applied to a single area power system as shown in Fig. 1. The frequency deviation $\Delta\ f(s)$ of proposed method in comparison with Pade's and Routh's method under nominal case is shown in Fig. 5. It is clear from Fig. 5 that the frequency deviation of the system for proposed controller due to load disturbance is diminished compared to Pade's and Routh's approximation methods. The performance index of proposed and other two methods are compared and shown in Table 1 under nominal case. From Table 1 it is observed that the performance index ISE is significantly low as compared with other methods.

The system dynamics changes due to unknown random load disturbance. To test the performance of proposed method, step load perturbation is applied to single area power system and corresponding responses are shown in Fig. 6. From Fig. 6 it is clear that, the frequency deviation response of proposed technique is significantly better than the other methods. Further from Fig. 6, it is observed that the overshoot and under shoot values of frequency deviation for proposed method are better compared to others. Hence proposed controller is better than other controller against disturbance rejection.

Examining robustness of controller is vital because modeling of system dynamics is not perfect. So we have chosen fifty percentage

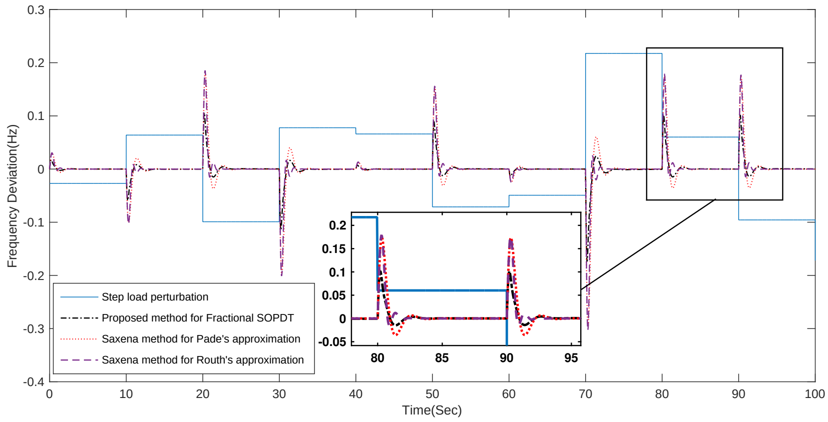


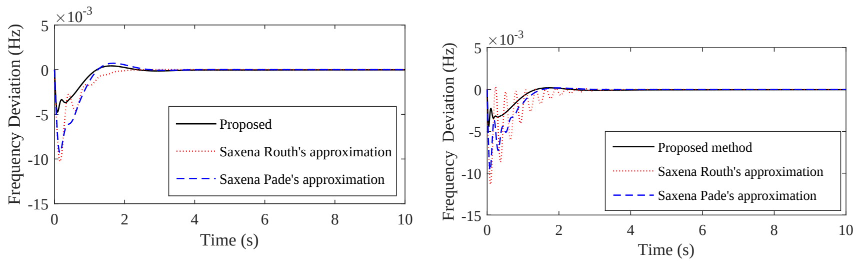
Figure 6: Comparison of system responses when step load perturbation applied

Table 1: Comparison of performance index for proposed and other reduced models under nominal and 50% Uncertainty cases

Methods	Nominal case	50% Uncertainty case	
		Lower bound	Upper bound
	ISE	ISE	ISE
Pade's approximation(Saxena)	$8.4 * 10^{-4}$	$9.1 * 10^{-3}$	$8.4 * 10^{-3}$
Routh's approximation(Saxena)	$8.7 * 10^{-4}$	$9.2 * 10^{-3}$	$8.9 * 10^{-3}$
Proposed method	$1.4 * 10^{-5}$	$8.44 * 10^{-6}$	$6.8 * 10^{-6}$

uncertainty in system parameters to check robustness of controller. The uncertain parameter δ_i, for all $i = 1, 2, .., 5$ are taken as[6]. Here δ is parameter uncertainty. The lower bounds and upper bounds of system uncertainty responses for proposed, Pade's and Routh's method are shown in Fig. 7a and Fig. 7b respectively.

From Fig. 7a and Fig. 7b , it is noticed that the proposed controller is robust when there is plant mismatch and system parameter uncertainty. The performance index ISE of proposed and other methods under 50 % uncertainty case are compared and given in Table 1. It is observed that, there is significant difference in ISE between the proposed and Pade's, Routh's. Thus proposed controller is more robust campared to other two controllers.



(a) (b)

Figure 7: Comparison of response of power system using proposed method with other method for a) lower and b) upper bound uncertainties

5 Conclusion

A good robust LFC technique is required to act against load perturbation, system parameter uncertainties and modelling error. In this paper a good approximation model reduction technique i.e step error minimization method is adopted to design a robust fractional IMC based PID controller for non-reheated thermal power system. It consists of fractional filter and fractional order PID. The tuning parameters, time constant τ_c and non integer λ are evaluated to get fast settling time and better overshoot/undershoot respectively. The simulation results showed that the proposed controller is more robust and good at set point tracking and for disturbance rejection.

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