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Non-integer IMC Based PID Design for Load Frequency Control of Power System through Reduced Model Order

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ABSTRACT

This paper deals with non-integer internal model control (FIMC) based proportional-integral-derivative(PID) design for load frequency control (LFC) of single area non-reheated thermal power system under parameter divergence and random load disturbance. 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/SIMULINK under various conditions. The simulation results show that the controller can accommodate system parameter uncertainty and load disturbance. Further, simulation shows that it maintains robust performance as well as minimizes the effect of load fluctuations on frequency deviation. Finally, the proposed method applied to two area power system to show the effectiveness.

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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, 2]. This can be achieved by adopting a auxiliary controller in addition to the primary control(Governor). From literature[1, 2], conventional controller is used as auxiliary or secondary control. To get the parameters of this controller, the power system is modeled and simulated using MATLAB. This paper deals with the modeling of power system through fractional order differential equations and design of controller.

The fractional order dynamic system is characterized 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 [3]. The precision of modeling is accomplished using the theory of fractional calculus[4]. In view of above fact, integer operators of traditional control methods have been replaced by concept of fractional calculus[5, 6]. Many modern controllers for LFC as secondary controllers are available like sliding mode control[7], two degree of freedom PID controller[8], fuzzy controller[9], microprocessor based adaptive control strategy[10] and direct-indirect adaptive fuzzy controller technique[11, 12, 13]. It can be observed that power system parameters may alter due to aging, replacement of system units and modeling 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)[14], 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[15] 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. REDUCTION METHOD FOR SINGLE AREA THERMAL 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 investigated

The proposed work deals with modeling 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 $G_g(s)$, boiler etc. and their dynamics are given by (1)

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

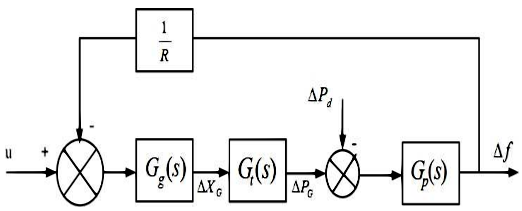


Figure 1. Single area power system linear model

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 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. Fractional system representation

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[16] is given as ,

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

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

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 derivatives. 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)

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

2.3. Design of proposed system

The full order transfer function of single area power system is obtained from (1) and (2), which is given by (6)

$$G_1(s) = \frac{K_P}{T_P T_T T_G s^3 + (T_P T_T + T_T T_G + T_G T_P)s^2 + (T_P + T_T + T_G)s + (1 + K_P/R)} \tag{6}$$

substitute the values of T_P = 20 sec, T_T = 0.3 sec, T_G = 0.08 sec, R = 2.4, K_P = 120 from [14] in (6), we get $G_1(s)$ as (7)

$$A(s) = G_1(s) = \frac{250}{s^3 + 15.88s^2 + 42.46s + 106.2} \tag{7}$$

The equation (7) 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 (8)

$$A'(s) = \frac{K_1 e^{-Ls}}{s^b + ps^c + q} \tag{8}$$

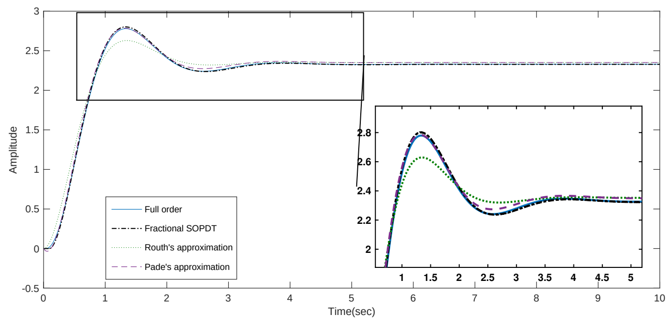
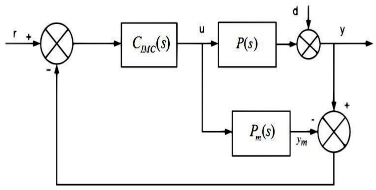


Figure 2. Comparison of step responses of full order model with fractional SOPDT, Routh and Pade approximation

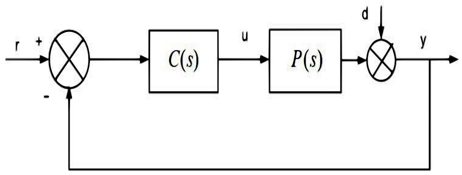
Here the order of $A'(s)$ is less than the $A(s)$ and is in fractional form. The step error minimization technique[17, 18] through Genetic Algorithm(GA)[19, 20] is utilized to obtain parameters of $A'(s)$ are given as $K_1 = 16.385, L = 0.095, b = 1.897, c = 0.962, p = 1.954, q = 7.031$. This is done through MATLAB & simulation.
Thus the attained reduced fractional model $A'(s)$ is

$$A'(s) = \frac{16.385e^{-0.095s}}{s^{1.897} + 1.954s^{0.962} + 7.031} \tag{9}$$

The step responses of original model, proposed, Pade's approximation and Routh's approximation are compared and shown in Fig. 2. The performance index ITSE of proposed Pade's and Routh,s methods are 0.0015, 0.027 and 0.06 respectively. From Fig. 2 and above ITSE values, it is observed that the response of proposed method is very closer to full order model(original).



(a)



(b)

Figure 3. Block diagram of a) IMC configuration b) equivalent conventional feedback control

3. FRACTIONAL IMC CONTROLLER DESIGN

3.1. Internal Model Control

In this section, model based IMC method for load frequency controller design is considered, which is developed by M. Morari and coworkers[21, 22]. The block diagram of IMC structure is shown in Fig. 3a, where $C_{IMC}(s)$ is the controller, $P(s)$ is the power plant and $P_m(s)$ is the predictive plant. Fig. 3b shows block diagram of conventional closed loop control. From Fig. 3a and Fig. 3b, we can relate $C(s)$ and $C_{IMC}(s)$ as

$$C(s) = \frac{C_{IMC}(s)}{1 - C_{IMC}(s)P_m(s)} \tag{10}$$

Steps for IMC controller design[23] are as follows.
Step1: The plant model can be represented as

$$P_m = P_m^+ P_m^- \tag{11}$$

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

$$C_{IMC}(s) = \frac{1}{P_m^-} f(s),\ f(s) = \frac{1}{(1 + \tau_c s^{\lambda+1})^r} \tag{12}$$

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 ≥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 (9) via method discussed below.
Consider the system [23], is given by (13)

$$P_m(s) = \frac{ke^{-\theta s}}{a_2 s^{\beta} + a_1 s^{\alpha} + 1}, \beta > \alpha \tag{13}$$

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 (11), the invertible part of $P_m(s)$ is

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

Using (12), the Fractional IMC controller is

$$C_{IMC}(s) = \frac{a_2 s^{\beta} + a_1 s^{\alpha} + 1}{k} \frac{1}{(1 + \tau_c s^{\lambda+1})} \tag{15}$$

substitute (15) in (10), then the conventional controller $C(s)$ is evaluated and simplified as

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

where $e^{-\theta s}$ is approximated as $(1 - \theta s)$ using first order Taylor expansion[23].
Again $C(s)$ is decomposed into FIMC PID filter via technique discussed below.
Multiplying and dividing RHS of (16) by $s^{-\alpha}$

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

substitute $a_2 = \tau^2$ and $a_1 = 2\zeta\tau$ in (17) and rearranged as,

$$C(s) = [\frac{s^{1-\alpha}}{1+(\tau_c/\theta)s^{\lambda}}][\frac{2\zeta\tau}{k\theta}(1+\frac{1}{2\zeta\tau s^{\alpha}}+\frac{\tau}{2\zeta}s^{\beta-\alpha})] \quad (18)$$

where first part is fractional filter and second part is fractional PID controller.

3.2. FIMC to single area non-reheated power system

To design FIMC, the (9) can be re-framed in the form of (13) is

$$A'(s) = \frac{2.3303e^{-0.095s}}{0.142s^{1.897}+0.2676s^{0.962}+1} \quad (19)$$

From (13),(18) and (19), we get $\tau = 0.3768$, $\theta = 0.095$, k=2.3303, $\beta = 1.897$, $\alpha = 0.962$, $\zeta = 0.3551$ substituting above values in (18), the fractional IMC-PID filter for single area power system is

$$C(s) = \frac{s^{0.038}}{1+10.526\tau_c s^{\lambda}}1.21(1+3.736s^{-0.962}+0.5305s^{0.935}) \quad (20)$$

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 DISCUSSIONS

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

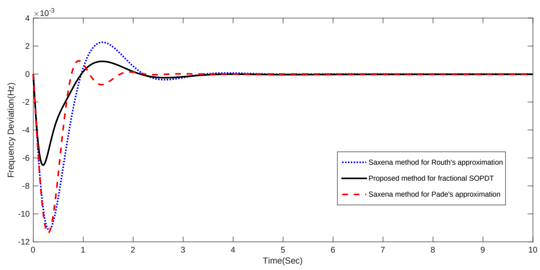


Figure 4. Comparison of response of power system using proposed with other methods

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. 4. It is clear from Fig. 4 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.

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	$1.4 * 10^{-5}$	$8.44 * 10^{-6}$	$6.8 * 10^{-6}$

4.1. Robustness

Examining robustness of controller is vital because modeling of system dynamics is not perfect. So we have chosen fifty percentage uncertainty in system parameters to check robustness of controller. The uncertain parameter δ_i, for all $i = 1, 2, .., 5$ are taken as[14]. 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. 5a and Fig. 5b respectively.

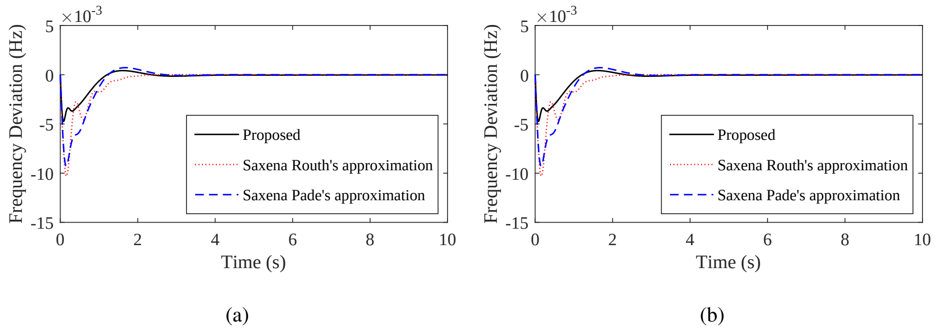


Figure 5. Comparison of response of power system using proposed method with other method for a) lower and b) upper bound uncertainties

From Fig. 5a and Fig. 5b , 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 compared to other two controllers.

4.2. Proposed method extended to two area power system

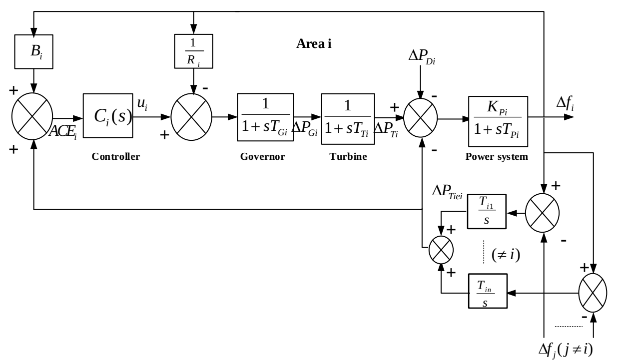


Figure 6. Block diagram of multi area power system

The block diagram of multi area power system linear model is shown in Fig. 6. The parameter values of model are given below[24].
T_{P1} =T_{P2} =20 secs, T_{T1} =T_{T2}= 0.3 secs, T_{G1} = T_{G2}= 0.08 secs, R_1 = R_2= 2.4, K_{P1} = K_{P2}=120
Here i=1,2 and two area power system is assumed to be identical for simplicity.
As followed above subsections, the controller is designed for two area power system with an assumption that there is no tie line exchange power($T_{12} = 0$).
The resulting FIMC-PID controller for area1 and area2 of two area power system are given as (21)

$$C_1(s) = C_2(s) = \frac{s^{0.038}}{1 + 0.01s^{0.64}} 1.21(1 + 3.736s^{-0.962} + 0.5305s^{0.935}) \quad (21)$$

To evaluate the performance of controller, a step load disturbance $\Delta\ P_d(s)$=0.01 is applied to a two area non reheated power system. The frequency deviations in area1 & area2 and deviation in tie line of proposed method

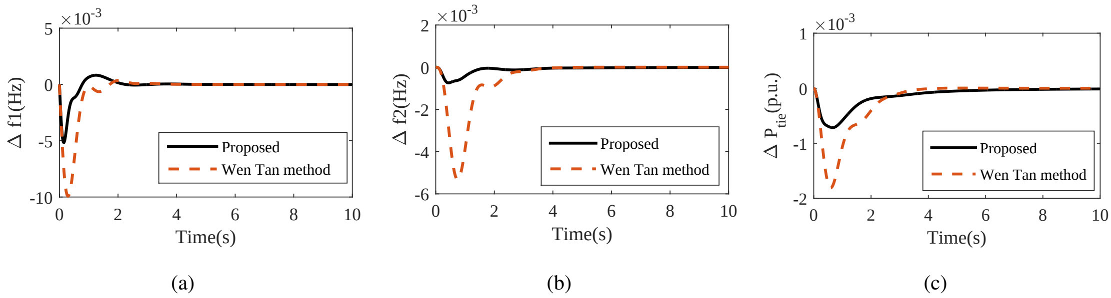


Figure 7. Responses of two area power system

are compared with Wen Tan method[24], which is shown in Fig. 7. It is clear from figures that the deviations of the power system for proposed controller due to load disturbance is diminished compared to Wen Tan method.

5. CONCLUSION

A good robust LFC technique is required to act against load perturbation, system parameter uncertainties and modeling 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. The performance of proposed method is good when applied to two area power system.

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