

Enhanced performance of PID load frequency controller for power systems

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Article Info

Article history:

Received Sep 8, 2018
Revised Mar 27, 2019
Accepted Apr 29, 2019

Keywords:

Complementary sensitivity
Kharitonov's theorem
Load frequency control (LFC)
PID

ABSTRACT

A novel control structure for designing a PID load frequency controller for power systems is presented. The controller with a single tuning parameter is designed based on a desired closed-loop complementary sensitivity function and Pade approximation. Comparative analysis demonstrates that proposed PID controllers improves the settling time and reduces overshoot effectively against small step load disturbances. Also, the performance and robustness of the controllers have been analyzed and compared. Simulation results show significantly improved performances when compared with recent results.

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1. INTRODUCTION

Frequency deviation in Power System due to variation between generation and load shall be rectified within a fraction of seconds resulting in stability and security. Load Frequency Control (LFC) of an extensive power framework can be alluded as the issue of controlling the recurrence by directing the created units with reaction to change in stack [1]. For framework soundness, LFC must furnish recurrence with zero enduring state mistakes and tie-line trade varieties, high damping of recurrence motions and diminishing overshoot of the unsettling influence. The objectives specified are conveyed effectively in past works by various creators utilizing Fuzzy rationale PI and PID controllers [2, 3], ideal control [4, 5]. Variable structure control [6, 7], versatile and self-tuning control [8, 9]. Down the line, different tuning rules have picked up the consideration for the previously mentioned goals in which Internal Model Control (IMC) [10] is one among them. The LFC PID controller configuration utilizing Laurent arrangement is clarified by Padhan and Majhi [11]. Double PI controller tuning utilizing swam enhancement calculation is introduced in [12]. The two-degree-of-freedom internal model control scheme suggested by Tan [10] consists of two controllers with two tuning parameters where simultaneous tuning of the two parameters is difficult. In practice, a simple control structure with a fewer number of tuning parameters is desirable. The proposed control structure (see Figure 1) for LFC design consists of only one controller (G_c). Kasireddy et.al designed a PID controller for LFC through reduced model order [13].

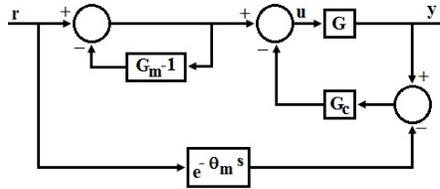


Figure 1. Proposed control structure

In Figure 1, G and $G_m e^{-\theta_m}$ represent the power system dynamics and its model, respectively. For LFC, controller design is inconvenient because G results in higher order plant models, which are approximated by lower order transfer functions with time delay using a relay-based identification method.

This paper has been alienated into 6 sections. Modeling of power system dynamics with necessary derivations discourse in section 2. In section 3, the PID controller design method is discussed followed by Section 4 in which the simulation results are presented. Section 5 deals with Robustness analysis and performance of a power system using Kharitonov’s rectangles followed by conclusions in section 6.

2. MODELING OF POWER SYSTEM DYNAMICS

Figure 2 shows single area power systems with a linear model. From Figure 2 it can be noticed that the power is supplied to the single area by a single generator. There are two types of turbine used for a generation: (a) non-reheated (NRT) and reheated (RT).

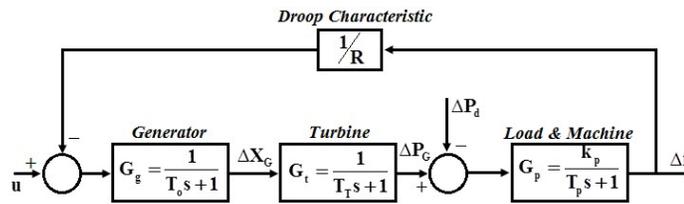


Figure 2. Single area power system

The plant model used for LFC without droop characteristics is

$$G = G_g G_t G_p \tag{1}$$

Where G_g , G_t , and G_p are the dynamics of the governor, turbine, and load & machine, respectively. For a reheated turbine,

$$G_t = \frac{c T_r s + 1}{(T_r s + 1)(T_T s + 1)}$$

Where T_r is a constant and c is the portion of the power generated by the reheat turbine in the total generated power. For non-reheated turbine $T_r = 0$. The plant model used for LFC with droop characteristic is

$$G = \frac{G_g G_t G_p}{1 + (G_g G_t G_p / R)} \tag{2}$$

From (1) and (2) can be represented by the second-order transfer function model

$$G = \frac{ke^{-\theta_m s}}{(T_1 s + 1)(T_2 s + 1)} \quad (3)$$

State space equations in the Jordan canonical form become

$$\dot{x}(t) = Ax(t) + bu(t - \theta_m) \quad (4)$$

$$y(t) = cx(t) \quad (5)$$

Where

$$A = \begin{bmatrix} -\frac{1}{T_1} & 0 \\ 0 & -\frac{1}{T_2} \end{bmatrix}; \quad b = \begin{bmatrix} 1 \\ 1 \end{bmatrix}; \quad c = \frac{k}{T_1 - T_2} [1 \quad -1]$$

When a relay test is performed with symmetrical relay of height $\pm h$, then the expression for the limit cycle output for $0 \leq t \leq \theta_m$ is

$$y(t) = ce^{At}x(0) + cA^{-1}(e^{At} - I)bh \quad (6)$$

Let the half period of the limit cycle output be τ . Then the expression for the limit cycle output for $\theta_m \leq t \leq \tau$ is

$$y(t) = ce^{A(t-\theta_m)}x(\theta_m) - cA^{-1}(e^{A(t-\theta_m)} - I)bh \quad (7)$$

The condition for a limit cycle output can be written as

$$y(0) = cx(0) = -y(\tau) = 0 \quad (8)$$

Substitution of $t = \tau$ in (7) and use of (6) gives the initial value of the cycling states

$$x(0) = (I + e^{A\tau})^{-1} A^{-1} (2e^{A(\tau-\theta_m)} - e^{A\tau} - I)bh \quad (9)$$

When t_p is the time instant at which the positive peak output occurs and $t_p \geq \theta_m$, then the expression of the peak output A_p becomes

$$A_p = c \left(e^{A(t_p-\theta_m)} x(\theta_m) - A^{-1} (e^{A(t_p-\theta_m)} - I)bh \right) \quad (10)$$

and the expression for the peak time becomes

$$t_p = \theta_m + \frac{T_1 T_2}{T_1 - T_2} \ln \left(\frac{1 + e^{-\tau/T_1}}{1 + e^{-\tau/T_2}} \right) \quad (11)$$

Substitution of A, b, and c in (9) and (10) give

$$T_1 (1 + e^{-\tau/T_2}) (2e^{-(\tau-\theta_m)/T_1} - e^{-\tau/T_1} - 1) - T_2 (1 + e^{-\tau/T_1}) (2e^{-(\tau-\theta_m)/T_2} - e^{-\tau/T_2} - 1) = 0 \quad (12)$$

$$A_p = kh \left(2 \left(1 + e^{-\tau/T_1} \right)^{\frac{-T_1}{T_1 - T_2}} \left(1 + e^{-\tau/T_2} \right)^{\frac{T_2}{T_1 - T_2}} - 1 \right) \quad (13)$$

The (11-13) are solved simultaneously to estimate θ_m , T_1 and T_2 from the measurements of τ , A_p and t_p . The relentless state gain k is thought to be known from the earlier or can be assessed from a stage flag test. Care has been taken to explain the arrangement of non-direct conditions, so intermingling may not occur to a false arrangement.

3. PID CONTROLLER DESIGN

The nominal complementary sensitivity function for load disturbance rejection can be obtained as

$$T = \frac{GG_c}{1 + GG_c} \quad (14)$$

To reject a step change in the load of the power system, the asymptotic constraint should be satisfied so that the closed loop internal stability can be achieved [3].

$$\lim_{s \rightarrow \frac{1}{T_1}, \frac{1}{T_2}} (1 - T) = 0 \quad (15)$$

The desired closed-loop complementary sensitivity function is proposed as

$$T = \frac{(\alpha_2 s^2 + \alpha_1 s + 1)}{(\beta s + 1)^4} e^{-\theta_m s} \quad (16)$$

Where β is the only tuning parameter for obtaining the desired performance of the power system. As there always exists a trade-off between the nominal performance and robust performance, β must be tuned according to the desired choice. α_1 and α_2 can be obtained from (15) and the constraint as

$$\alpha_1 = \frac{T_1^2 \left(\left(1 - \frac{\beta}{T_1} \right)^4 e^{-\theta_m/T_1} - 1 \right) - T_2^2 \left(\left(1 - \frac{\beta}{T_2} \right)^4 e^{-\theta_m/T_2} - 1 \right)}{T_2 - T_1} \text{ and}$$

$$\alpha_2 = T_2^2 \left(\left(1 - \frac{\beta}{T_2} \right)^4 e^{-\theta_m/T_2} - 1 \right) + T_2 \alpha_1 \quad (17)$$

Using (14), (15) and second order Pade' approximation for the time delay term, we get

$$G_c = \frac{6(\alpha_2 s^2 + \alpha_1 s + 1)(l_2 s^2 + l_1 s + 1)}{km_0 s \left(\frac{m_2}{m_0} s^2 + \frac{m_1}{m_0} s + 1 \right)} \quad (18)$$

Where

$$l_1 = \frac{(6T_2 + 6T_1 + 4\theta_m)}{6} \quad l_2 = \frac{(6T_1 T_2 + 4T_1 \theta_m + 4T_2 \theta_m + \theta_m^2)}{6}$$

$$m_0 = 6\theta_m + 24\beta - 6\alpha_1$$

$$m_1 = 36\beta^2 + \theta_m^2 - 6\alpha_2 + 16\beta\theta_m + 2\alpha_1\theta_m$$

$$m_2 = 24\beta^2\theta_m + 2\alpha_2\theta_m + 4\beta\theta_m^2 + 24\beta^3$$

The (18) can be written in the form of a PID controller with lead/lag filter as

$$G_c = K_c \left(1 + \frac{1}{T_2 s} + T_d s \right) \left(\frac{a_2 s^2 + a_1 s + 1}{b_2 s^2 + b_1 s + 1} \right) \tag{19}$$

Where

$$K_c = \frac{6\alpha_1}{km_0} \qquad T_i = \alpha_1 \qquad T_d = \frac{\alpha_2}{\alpha_1}$$

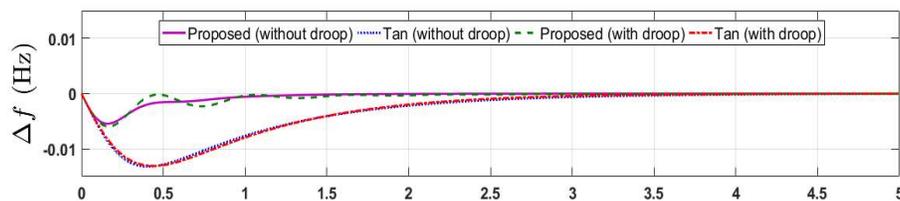
$$a_2 = l_2 \qquad a_1 = l_1 \qquad b_2 = \frac{m_2}{m_0} \qquad b_1 = \frac{m_1}{m_0}$$

4. SIMULATION RESULTS

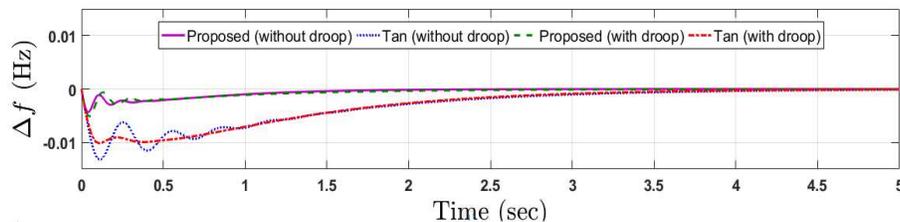
Consider a power system with a non-reheated and a reheated turbine whose model parameters are given by $K_P = 120$, $T_P = 20$, $T_T = 0.3$, $T_G = 0.08$, $R = 2.4$, $T_r = 4.2$ and $c = 0.35$ [11]. The identified models and controller settings (see Table 1) for the power system with non-reheated and reheated turbines are obtained using (11-13, 17). The Nyquist plots of the identified and actual models are shown in Figure 4 to illustrate the accuracy of the identification method. To get stable and robust response, β values in Table 1 are obtained from extensive simulation studies. Figure 3 and Figure 5 show the frequency change of the power system following a load demand $\Delta P_d = 0.01$. The stability robustness is tested by changing the parameters of the system by 50%. From the simulation results, it is evident that the proposed method gives significantly improved performances than the Tan’s method.

Table 1. Control parameters for identified model

Model Type	Identified Model	Control Parameters
NRT (WD)	$\frac{120e^{-0.4626s}}{(28.4952s + 1)(0.2202s + 1)}$	$K_c=2.0245, T_i=0.5005, T_d=0.1332, a_1=29.0238, a_2=15.1661, b_1=28.6982, b_2=5.77239, \beta=0.01$
NRT (D)	$\frac{250e^{-0.05s}}{2.028s^2 + 12.765s + 106.2}$	$K_c=0.7192, T_i=0.2075, T_d=0.1159, a_1=0.9212, a_2=0.1411, b_1=0.1515, b_2=0.0234, \beta=0.07$
RT (WD)	$\frac{120e^{-0.541s}}{(23.2137s + 1)(0.9057s + 1)}$	$K_c=3.6549, T_i=0.5797, T_d=0.2355, a_1=24.4801, a_2=29.7725, b_1=24.0884, b_2=20.2681, \beta=0.01$
RT (D)	$\frac{235.3e^{-0.035s}}{1.79s^2 + 16.9s + 100}$	$K_c=1.0619, T_i=0.2107, T_d=0.1828, a_1=1.154, a_2=0.1323, b_1=0.1973, b_2=0.0231, \beta=0.065$



(a) Nominal systems



(b) Parameters of the system change by 50%

Figure 3. Frequency deviation of the closed loop system with non-reheated turbine

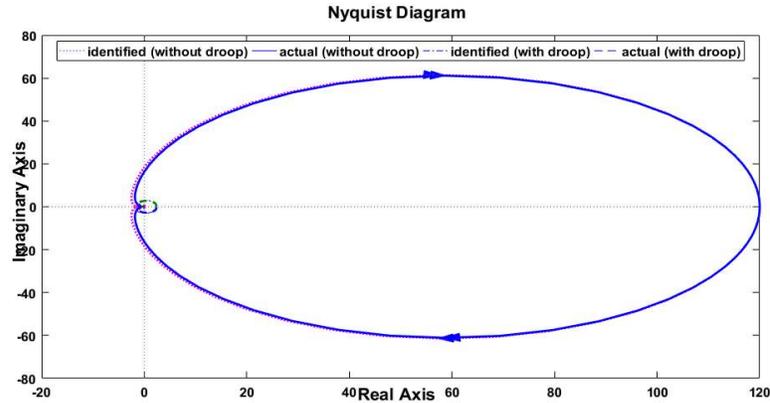


Figure 4. Nyquist plots for the power system with non-reheated turbine

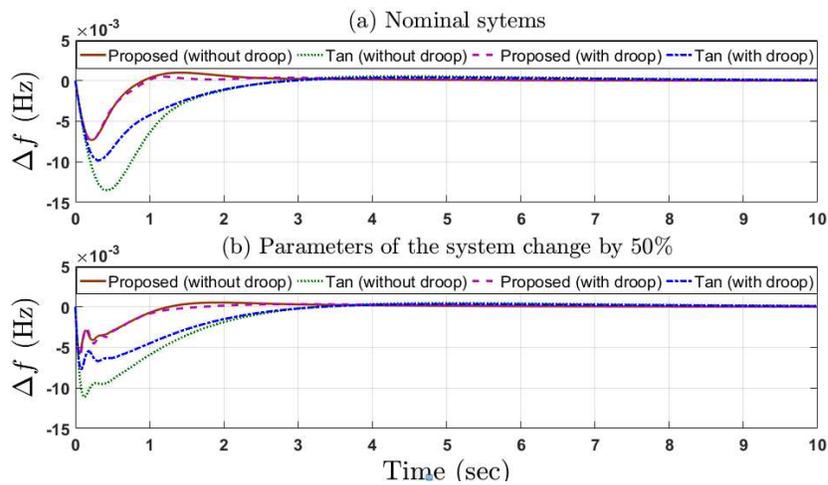


Figure 5. Frequency deviation of the closed loop system with reheated turbine

5. ROBUSTNESS ANALYSIS AND PERFORMANCE

In this section, Robustness of the system has been analyzed using Kharitonov’s Theorem. Closed-loop characteristic equation $\Delta_{CL}(s)$ and denominator of the closed-loop transfer function $T(s)$ are the polynomials that make the control system stable. Considering the forward-path and feedback-path transfer functions $G(s)$ and $H(s)$, characteristic equation is

$$\begin{aligned} \Delta_{CL}(s) &= 1+G(s)H(s) = 0 \\ \Delta_{CL}(s) &= a_n s^n + a_{n-1} s^{n-1} + \dots + a_1 s + a_0 \end{aligned} \tag{20}$$

For simplicity, assume that the leading coefficient a_n is constant and the coefficients have been normalized so that $a_n = 1$. The polynomial coefficients can then be expressed as

$$a_i \in [a_i^{\min}, a_i^{\max}], \quad i=0,1,\dots,n-1 \tag{21}$$

so, the characteristic equation becomes

$$\Delta_{CL}(s) = s^n + a_{n-1} s^{n-1} + \dots + a_1 s + a_0 \tag{22}$$

According to Kharitonov’s Theorem, an n th-degree interval polynomial family described by (1a) and (1b) is robustly stable if and only if each of the four Kharitonov polynomials is stable, that is, all the roots of those polynomials have strictly negative real parts.

For the system

$$G(s) = \frac{120}{(0.08s + 1)(0.3s + 1)(20s + 1)}$$

The characteristic equation is

$$\Delta_{CL}(s) = 0.48s^3 + 7.624s^2 + 20.38s + 121 = 0 \tag{23}$$

For $\pm 10\%$ variations in the coefficients of the polynomial, The intervals of the polynomial will become

$$a_3 \in [0.528, 0.432] \quad a_2 \in [8.3864, 6.8616] \quad a_1 \in [22.418, 18.342] \quad a_0 \in [133.1, 108.9]$$

Figure 6 shows Kharitonov’s rectangles rotate around the origin in a counter-clockwise direction to satisfy the monotonic phase increase property of Hurwitz polynomials. For clarity, the graph is zoomed in Figure 7 to show the zero-exclusion point. As the Kharitonov’s rectangles do not pass through the origin, it is concluded that the closed loop system guarantees the robust stability.

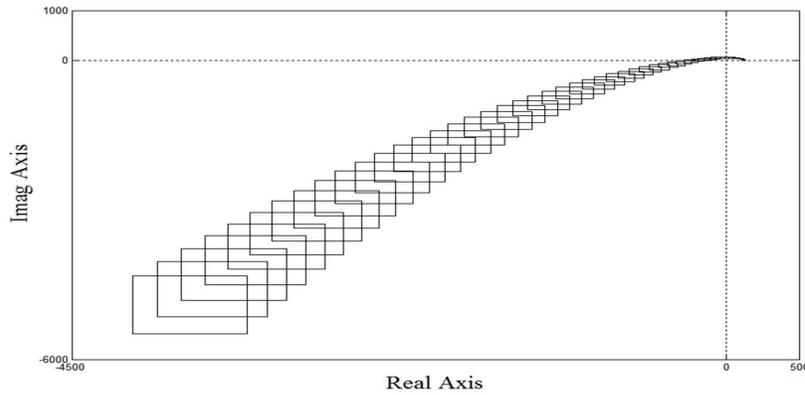


Figure 6. Response of the system with $\pm 10\%$ variations in the coefficients of polynomial on the complex plane

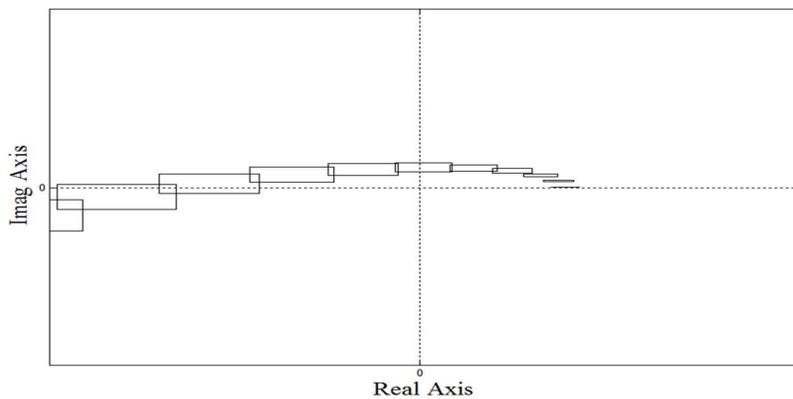


Figure 7. Response of the system showing zero exclusion point

Table 2 shows it is observed that the proposed method gives less Integral Absolute Error (IAE), Integral Squared Error (ISE) and Integral Time Absolute Error (ITAE) as compared to Tan's method, so closed loop performance is improved. If we compare the total variations of the control signals, the results of both methods are almost same. Thus, with same control signals, the proposed method gives comparatively fewer errors.

Table 2. Various errors and total variations

Type of Model	Integral Time Absolute Error	Integral Absolute Error	Integral Squared Error	Total variations
NRT (WD)-Tan	0.5164	0.1061	0.001494	0.0199
NRT (WD)-Proposed	0.5147	0.1008	0.001184	0.0127
NRT (D)-Tan	0.5303	0.106	0.001363	0.0214
NRT (D)-Proposed	0.521	0.1007	0.001175	0.0189
RT (WD)-Tan	2.002	0.2007	0.002254	0.0735
RT (WD)-Proposed	2.058	0.2061	0.002273	0.07906
RT (D)-Tan	2.006	0.2007	0.01223	0.0729
RT (D)-Proposed	1.966	0.2006	0.002264	0.0797

6. CONCLUSION

The Load Frequency Characteristics of a single-area power system with non-reheated and reheated turbines have been deliberated. The proposed method is flexible and gives satisfactory performance in nominal as well as the perturbed case. The proposed PID controller with a new control structure and a single tuning parameter (β) gave better performance than Tan's controller. By showing the zero exclusion point by Kharitonov's rectangles, it guarantees the robust stability for closed loop power systems. The proposed scheme can easily be extended to multi-area power systems.

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