Load Frequency Control in Power System using Feed-Forward Internal Model Control

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***Abstract* – In an interconnected power system, both tie-line power switching and area frequency fluctuation occurs frequently due to system parameter uncertainties modeling error and environmental disturbance. The load frequency control (LFC) is concentrated on to minimize the transient deviation in these variables (both tie-line power switching and area frequency) and when power demand transient, to bring the steady state frequency error to zero. This paper is worked on two degree of freedom (2DF) internal Model Control (IMC) with feed forward controller and IMC filter design, recently developed by Liu and Gao [3] to improve disturbance rejection and to minimize the effect of uncertainties . The feed-forward is added with Saxena and Hote [4] reported work on SOPDT model and results increasing in the robustness of the system.**

***Keywords* — Feed forward, Load frequency Control (LFC), Internal Model Control (IMC), Robustness.**

NOMENCLATURE OF PARAMETERS OF POWER SYSTEM [4]

K_P	Electric system gain
T_P	Electric system time constant (s)
T_T	Turbine time constant (s)
T_G	Governor time constant (s)
R	Speed regulation due to governor action (Hz/p.u. MW)
$\Delta f(t)$	Incremental frequency deviation (Hz)
ΔP_d	Load disturbance (p.u. MW)
$\Delta P_G(t)$	Incremental change in generation output (p.u. MW)
$\Delta X_G(t)$	Incremental change in governor valve position

1. INTRODUCTION

In this Generation, almost all equipment runs on electric energy. Electric energy is generated from natural energy is done by power system. For better performance, both frequency and voltage are to be stable at standard values in the electric system during operations. For India, the standard values for frequency and voltages are *50 Hertz and 240 Volts* respectively. The frequency deviates from its standard value due to change of load demands, system parameter uncertainties, modeling error and environmental disturbances. So, load frequency control (LFC) minimizing the frequency deviation errors, rejecting load disturbance and hence LFC maintains power system stability [1].

For LFC in single-area power systems, Tan [2] has worked on frequency controlling in third-order single area power plant by using a robust IMC based PID controller. In this paper LFC for single-area power plant is done by using both IMC and feed-forward control on Tan model theory. IMC filter design, recently developed by Liu and Gao [3] is used for better response and good disturbance rejection. This modified combination of feed forward and IMC with modified filter have capable of handling plant/model mismatches and uncertainties in parameters.

Saxena and Hote [4] proposed work is concentrated on model order reduction and disturbance rejection of single-area power plant by LFC via 2DF IMC. This paper is extended work on LFC and minimization of disturbance by controlling the feed forward filter constant.

2. IMC THEORY AND FEED-FORWARD IMC

A) Two-Degree-of-Freedom (2DF) IMC Controller

1DF-IMC (One Degree of Freedom IMC) designs to focus on achieving a better response to a step set point change and hence the resulting response is much more sluggish than is desirable and vice versa. To avoid this problem, two different controller Q_D (s) and Q_1 (s) with modified filter [3] are tuned independently, as shown in Fig. 1 [5].

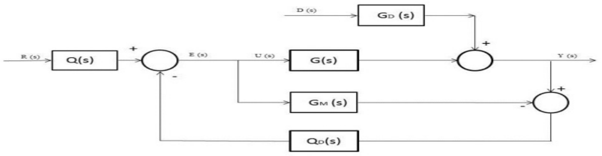

Fig. 1 Two Degree Freedom (2DF) IMC

In Fig. 1, we can define disturbance rejection filter (feedback Controller) as a Q_D (s) and Q_1 (s) as a set point filter.

Modified filter F'(s) replaces F(s) in ODF-IMC for designing of effective IMC controller and for better disturbance rejection.

$$F(s) = \frac{\gamma s^2 + \mu s + 1}{(\lambda s + 1)^x} \tag{1}$$

where x = 3 or 4 , depending upon the requirement to make controller proper and γ, μ and λ are defined in [3], [4]. TDF-IMC controller can be derived as

$$Q_D(s) = G_{M^{-1}} \frac{\gamma s^2 + \mu s + 1}{(\lambda s + 1)^x} \tag{2}$$

B) Feed-Forward Controller

The combination of feed forward plus feedback control give better performance over normal feedback control. If modelling errors present, feed forward control can frequently minimize the measured disturbance effects on the process output. Feed forward control can be implemented with either the classical feedback or IMC structure. In Fig.2 [5], feed forward controller Q_{ff} (s) in IMC structure

$$Q_{ff} = -\frac{G_D(s)}{G_P(s)} \tag{3}$$

And if Q_{ff} (s) is not in proper, then add filter F_f (s) = $1/(\varepsilon s + 1)^b$ with this controller, where b is an integer, to make Q_{ff}(s) proper/semi-proper for physical realization. And 2DF IMC is simplified into one controller C(s) [5], giving better disturbance rejection for (a) SOPDT process model and (b) Tan's [2],[6] proposed model.

For (a) $$C^{SOPDT}(s) = \frac{QQ_D(s,\lambda)}{\{1 - p'(s)QQ_D(s,\lambda)\}} \tag{4}$$

For (b) $$C^{Tan}(s) = K_p + \frac{K_i}{s} + K_d s = K_{PID} \tag{5}$$

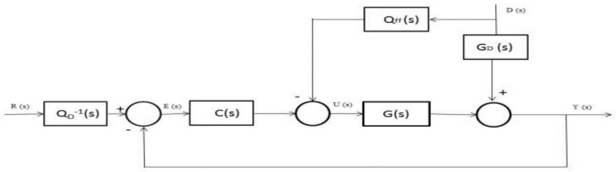

Fig. 2. Feed forward Controller with IMC

3. SINGLE-AREA POWER PLANT FOR LFC DESIGN

The single area power plant for LFC design made of four dynamics subsystems is shown in Fig.3 [4] i.e.

1. Governor G_g (s)

$$G_g(s) = \frac{1}{(T_G s + 1)} \tag{6}$$

2. Non-reheated turbine G_t (s)

$$G_t(s) = \frac{1}{(T_T s + 1)} \tag{7}$$

3. Load and Machine Gp (s)

$$G_p(s) = \frac{K_P}{(T_P s + 1)} \tag{8}$$

4. 1/R is the droop characteristics, a part of feedback gain to get better damping properties of the power system.

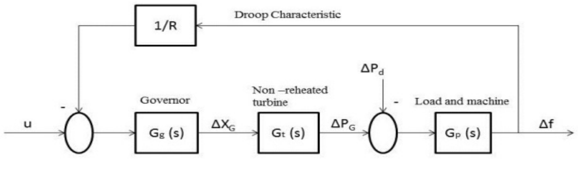

Fig. 3. Linear Model of a single-area power system

The whole system model can be illustrated by

$$\Delta f(s) = G(s) + G_d(s)\Delta P_d(s) \tag{9}$$

Where

$$G(s) = \frac{G_g(s)G_t(s)G_p(s)}{(1 + G_g(s)G_t(s)G_p(s)/R)} \quad (10)$$

$$G(s) = \frac{K_p}{\{T_G T_T T_P s^3 + (T_P T_T + T_T T_G + T_G T_P)s^2 + (T_G + T_T + T_P)s + (1 + K_P/R)\}} \quad (11)$$

$$G_d(s) = \frac{G_p(s)}{(1 + G_g(s)G_t(s)G_p(s)/R)} \quad (12)$$

The objective of LFC is to minimize the effect on $\Delta f(s)$ due to load disturbance $\Delta P_d(s)$ [**7**] and other parameter changes by evaluating the control law: $u(s) = -K(s)\ \Delta f(s)$, where K(s) is IMC based compensator to control the power plant G(s).

4. PERFORMANCE ANALYSIS AND SIMULATION

Consider numerical value of a power system [4] are given by

$K_P = 120$, $T_G = 0.08$, $T_P = 20$, $T_T = 0.3$, $R = 2.4$ (13)

Using (13), the plant model G(s), a third-order under-damped system is represented as

$$G(s) = \frac{250}{(s^3 + 15.88s^2 + 42.46s + 106.2)} \quad (14)$$

In [4] Saxena and Hote reported work, equation (14), a third-order system is approximated into a second-order plus dead-time (SOPDT) model using same parameters value given in (13). The SOPDT model G_{MR}^{SOPDT} is represented by

$$G_{MR}^{SOPDT}(s) = \frac{18.8268e^{-0.0757s}}{(s^2 + 2.6403s + 8.0015)} \quad (15)$$

Hence Q_D in (2),

$$Q_D(s) = \frac{(s^2 + 2.6403s + 8.0015)(0.1649s^2 + 0.5567s + 1)}{18.8267(0.2s + 1)^4} \quad (16)$$

Where $\gamma = 0.1649$, $\delta = 0.5567$, $\lambda = 0.2$, and $x = 4$.

For given data, feed forward controller $Q_{ff}(s)$ in (3) for filter constant 'ε'=0.02 is

$$Q_{ff}(s) = \frac{2.88s^4 + 53.20s^3 + 263.44s^2 + 681.704s + 961.18}{0.181s^4 + 11.93s^3 + 151.27s^2 + 403.07s + 960.17} \quad (17)$$

We define simplified controller $C^{SOPDT}(s)$ [5] in (4) and $C^{Tan}(s)$ [2] in (5) for SOPDT model are expressed as

$$C^{SOPDT}(s) = \frac{0.1649s^4 + 0.992s^3 + 3.789s^2 + 7.0947s + 8.0015}{s(0.03s^3 + 0.837s^2 + 2.206s + 6.005)} \quad (18)$$

$$C^{Tan}(s) = 0.4036 + \frac{0.6356}{s} + 0.1832s \quad (19)$$

The response of disturbance rejection of power system is shown in fig. 4 for normal SOPDT model and in fig. 5 for Tan's [2] proposed model on SOPDT, with and without feed forward controller.

Integral Absolute Error (IAE)	SOPDT	SOPDT with Feed-Forward
Nominal Case	7.5216	2.4146

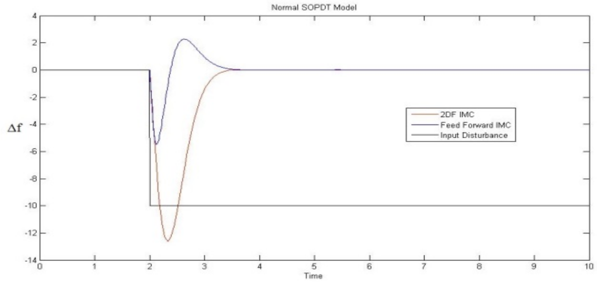

Fig. 4 disturbance rejection response of SOPDT model with and w/o feed forward controller.

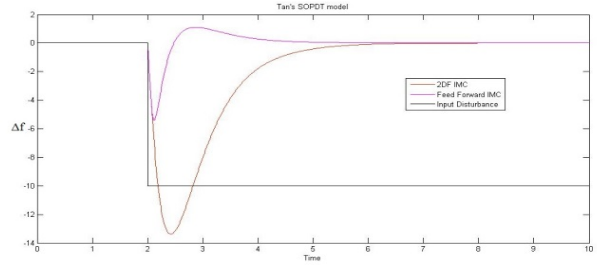

Fig. 5. Disturbance rejection response of Tan's SOPDT model in 2DF IMC and feed forward IMC.

Integral Absolute Error (IAE)	Tan's SOPDT model	Tan's SOPDT model with Feed-Forward
Nominal Case	32.297	2.5665

To verify the robustness and performance of a power system model, suppose the deviation of parameters of this system by 50%, as expressed in [4], i.e.

$\Delta_1 = 1/T_P \in [0.0331, 0.1]$ $\Delta_2 = K_P/T_P \in [4, 12]$
$\Delta_3 = 1/T_T \in [2.564, 4.762]$
$\Delta_4 = 1/RT_G \in [3.0821, 10.639]$
$\Delta_5 = 1/T_G \in [9.615, 17.857]$

The disturbance rejection response graph of the tuned Feed-forward IMC for upper and lower bounds uncertain system are shown in Fig. 6 and Fig. 7.

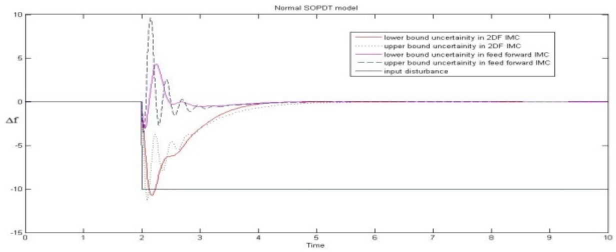

Fig. 6 Upper and Lower bound uncertain in SOPDT model

Integral Absolute Error (IAE)	SOPDT	SOPDT with Feed-Forward
Upper Bound Uncertain	7.505	2.540
Lower Bound Uncertain	7.540	1.661

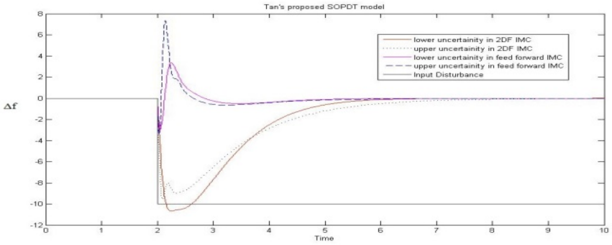

Fig. 7 Upper and Lower bound uncertain in Tan’s SOPDT model

Integral Absolute Error (IAE)	Tan’s SOPDT model	Tan’s SOPDT model with Feed-Forward
Upper Bound Uncertain	15.72	2.6049
Lower Bound Uncertain	15.7331	2.009

5. COMPARISONS AND RESULTS

For different values of feed forward filter constant ’ε’, remarkable results of disturbance rejection are shown in Fig. 8 for both model and we concluded that filter constant ’ε’ should be lie in between ε_1 to λ where ε_1 is minimum limit which is calculated from (4) and λ is 2DF filter constant. If we take ’ε’ less than ε_1, there is no remarkable change and if ’ε’ > λ, large change is spotted in terms of settling time and Integral Absolute Error (IAE) [8]. IAE at different value of ’ε’ are shown in Table 1.

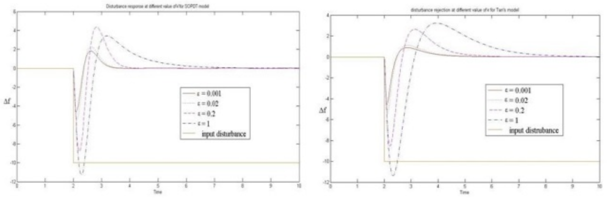

Fig. a

Fig. b

Fig.8. Disturbance rejection response at different value of ’ε’ for Fig. a) SOPDT model and fig. b) Tan’s model

TABLE 1

Integral Absolute Error (IAE) on different value of ’ ε’

Model	ε = 0.02	ε = 0.2
SOPDT model	2.41461	5.54506
Lower bound SOPDT	1.65106	2.47982
Upper bound SOPDT	2.54035	1.81193
Tan’s model	2.55655	6.50345
Lower bound Tan’s model	2.00932	2.76697
Upper bound Tan’s model	2.60496	1.52068

6. CONCLUSION

LFC Techniques using Feed-forward IMC increases robustness against parameter uncertainties as well as plant/model mismatch and external load change. Feed-forward IMC gives faster and smoother response than 2DF-IMC. Feed-Forward IMC on SOPDT shows better response than Tan‘s SOPDT model. The lower value feed forward filter constant has done better disturbance rejection and also tracks the set point fast.

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