Improved Load Frequency Disturbance Rejection with Two Port Internal Model Control Structure

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Abstract—The main aim of this paper is to design a Robust controller based on Internal Model Control (IMC) for a Load Frequency control (LFC) problem in a Single Area Power System (SPS). A power system is susceptible to load changes, parameter uncertainties and various non-linearities. These problems are getting more significant as the power system becomes more interconnected and complex. An enhanced IMC (2P-IMC) is employed to improve performance and robustness. The proposed control method is simple and applied to SPS. The performance of the proposed 2P-IMC is compared with the IMC designed PID. All the digital simulations and modeling of a SPS is carried out in MATLAB.

Keywords—Internal Model Control (IMC), Two Port Internal Model Control (2P-IMC), Load Frequency Control (LFC), Robust Control.

TABLE I NOMENCLATURE

ΔP_d	Load power disturbance (p.u.MW).
ΔX_G	Incremental change in Speed governor valve.
ΔP_G	Incremental change in Alternator output.
Δf	Load frequency deviation (Hz).
K_p	Electrical system gain.
T_p	Electrical system Time constant (s).
T_t	Turbine time constant (s).
T_g	Speed governor time constant (s).
R	Regulation Constant (Hz/Pu MW)

I. Introduction

With the rapid growth in the power industry, the power system becomes more complex and more difficult to control. Usually the areas [5] are interconnected to maintain frequency in limits, which gives rise to the LFC problem. Existing control methods are not sufficient anymore due to increase in complexity of the system. More Emphasis has been given to the robustness of the controller in recent years due to its high-linearized nature. While designing the controller. The parameters tend to vary rather than being a fixed value due to the uncertainty.

Several advanced control methods have been proposed in the past for the LFC problem such as PID controllers tuned through Fuzzy logic controllers [6], optimization technique [7], [8], Intelligent control methods [9], sliding mode control [10], Recently the focus has shifted to advanced Robust control methods [11], [12]. Control methods based on the IMC structure is one such method, which shows significant results.

The PID Controllers modelled through IMC structure are popular in literature as it incorporates the simplicity of a PID controller and robustness of the IMC controller. Tan has proposed a PID tuning method using the IMC control structure and approximating the plant model as a SOPDT model [13]. And directly tuning a PID controller without droop characteristics and with droop characteristics for various turbine models as discussed in [14]. Based on this, Saxena et al [15] has proposed a controller based on two degree of freedom IMC (2DOF-IMC) [3]. They used the model order reduction techniques to simplify the higher order models, which brings simplicity to the controller design and gives better performance. Based on Saxena's work, Sondhi et al [16] has made use of fractional order PID (FOPID) controller instead of classic PID control to design a controller. All these controllers take advantage of IMC structure to design a controller.

Furthermore, Anwar et al [17] introduced direct synthesis approach for PID controller. Subsequently Bheem sonker et al [19] has introduced a control method which utilises both 2DOF-IMC and model order reduction techniques to design a controller to improve performance and robustness. A secondary loop has been introduced in the parallel path structure to further increase the disturbance rejection.

All the existing methods depend on the basic IMC structure, which provide a good set point and disturbance rejection. However, these methods require the disturbance dynamics to achieve the improved disturbance rejection. However, it is known that the disturbance models are not accurate and the control methods based on such inaccurate models fails to provide satisfactory performance

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improvement. In this direction, the IMC structure that does not use the disturbance dynamics and further assists in improving the disturbance rejection is of great importance. Two Port Internal Model Control (2P-IMC) is one such approach that is employed to improve the effect the load disturbance on the frequency deviation. Application of 2P-IMC techniques LFC problem has not been explored. This motivated to explore the feasibility of employing 2P-IMC into the LFC problem.

The 2P-IMC structure is identical to the IMC and in addition, a feedback controller provides the additional corrective action. The main advantage of this control structure is its improved robustness for parametric uncertainties and improved closed-loop response.

II. Modelling of Power System

In this study, single area power system (SPS) supplying power to an isolated area through a single generator is considered. Since, the load changes are relatively small [14], the complete system can be linearized around an operating point as shown in Fig. 1. The various components of the linear dynamic model are as governor ($G(s)$), turbine ($T(s)$), and load ($L(s)$) are modelled as follows.

$$G(s) = \left(T_g s + 1\right)^{-1} \tag{1}$$

$$T(s) = (T_t s + 1)^{-1} \tag{2}$$

$$L(s) = K_p\left(T_p s + 1\right)^{-1} \tag{3}$$

The dynamic relation between the frequency variation (Δf) with the load disturbance (ΔP_d) and plant input in open loop can be given as

$$\Delta f(s) = P(s)u(s) + D(s)\Delta P_d(s) \tag{4}$$

When the droop behaviour is absent, the SPS operates as in open-loop configuration and the component in eq (4) are

$$P(s) = G(s)T(s)L(s) \tag{5}$$

$$D(s) = L(s) \tag{6}$$

Similarly, when the droop behaviour is added in the form of feedback as shown in Fig. 1, the SPS operates as in closed-loop configuration and the component in eq (4) are

$$P(s) = \frac{G(s)T(s)L(s)}{1 + G(s)T(s)L(s)/R} \tag{7}$$

$$D(s) = \frac{L(s)}{1 + G(s)T(s)L(s)/R} \tag{8}$$

The LFC problem is a disturbance rejection problem where the control law is: $u(s) = -K(s)\Delta f(s)$. Here, $K(s)$ is the controller used to reduce the effect of load variation on the output frequency deviation. This can be either a PID controller or any other advanced controller. In this work, IMC with a two-port control (2P-IMC) [21] structure is adopted to achieve the objective.

III. Two Port IMC structure

The two-port IMC structure is shown in Fig. 2. It consists of two loops.

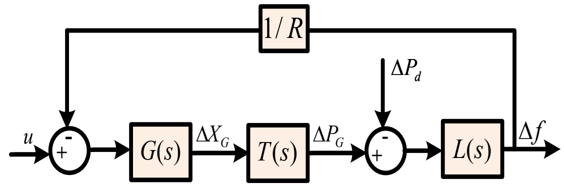


Fig. 1. Block diagram of SPS with linear dynamic models

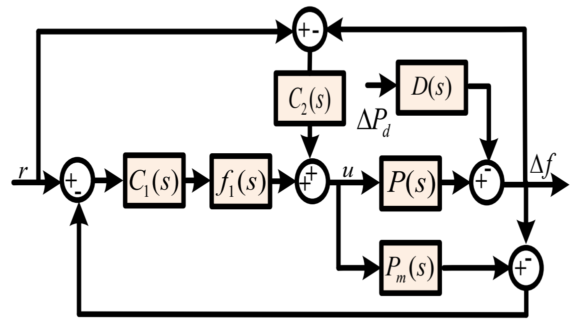


Fig. 2. Internal model control with a two-port control structure (2P-IMC)

(1) The bottom loop is identical to the conventional IMC structure

(2) The upper loop is the conventional feedback control structure.

In Fig. 2 $P(s)$ represents the SPS, $P_m(s)$ represents the linear model, $C_1(s)$ represents internal model controller, $C_2(s)$ represents the complementary controller. $D(s)$ represents disturbance model, Δf represents the measured output (frequency deviation).

The combination of bottom and upper loop is the two-port internal model control system. IMC is a model-based control strategy where the difference between the plant model and the plant gives the model-plant mismatch (MPM) and the disturbance estimate. The internal model controller.

$C_1(s)$ is used to reduce the MPM and the effect of load disturbance on the output. The feedback controller on the top provides additional control input that is necessary to further improve the load disturbance rejection.

The dynamics of closed loop control with 2P-IMC as shown in Fig. 2 are given as follows:

$$\Delta f(s) = P^{2P-IMC}(s)r(s) + D^{2P-IMC}(s)\Delta P_d(s) \tag{9}$$

$$P^{2P-IMC}(s) = \frac{[C_1(s) + C_2(s)]P(s)}{1 + C_1(s)[P(s) - P_m(s)] + C_2(s)P(s)} \tag{10}$$

$$D^{2P-IMC}(s) = \frac{D(s)[1 - C_1(s)P_m(s)]}{1 + C_1(s)[P(s) - P_m(s)] + C_2(s)P(s)} \tag{11}$$

The 2P-IMC controller ($C_1(s)$) is chosen as

$$G_{c1}(s) = P_m^{-1}(s) \tag{12}$$

For controller design, only the minimum phase part is considered. $f_1(s)$ is a low pass filter used to shape the closed-loop response and makes the controller proper and practically realizable.

$$f_1(s) = (\lambda_1 s + 1)^{-n} \tag{13}$$

Where, λ_1 is the tuning parameter, and n is the order of the filter.

When the actual plant model and predicted model are identical, the disturbance rejection is improved by a factor of $(P(s)C_2(s) + 1)$ compared to the classic IMC structure. In this work, the complementary controller, $C_2(s)$ is chosen as a proportional controller. Due to the superior disturbance rejection capabilities, the 2P-IMC structure is employed to tackle the LFC problem effectively.

IV. Results and Simulation Studies

A. Steam Turbine Without Droop Charecteristics

Consider a SPS feeding power to the load using a single generator and its linear dynamic model is shown in Fig. 1. The plant parameters of the nominal model are chosen as follows [14]:

$$K_p = 120,\ T_p = 20,\ T_t = 0.3,\ T_g = 0.08 \tag{14}$$

In this work, to provide the unbiased comparison with the proposed 2P-IMC, a PID controller is chosen as a reference from [14].

To carry out the simulations, the plant model given in eq (5) with the parameters from (14) is considered. It is given as follows:

$$P(s) = \frac{120}{0.48s^3 + 7.624s^2 + 20.38s + 1} \tag{15}$$

From (13), it can be seen that the plant model has 3 real poles. The plant can be split into two components.

$$P(s) = P^+(s)P^-(s) \tag{16}$$

Where, $P^-(s)$ represents the minimum phase component that consists of all poles and zeros in the left half side of s-plane and $P^+(s)$ denotes the non-invertible part that includes RHP zeros which in this case is 1.

$$P^+(s) = 1 \tag{17}$$

$$P^-(s) = \frac{120}{0.48s^3 + 7.624s^2 + 20.38s + 1} \tag{18}$$

Using (13) the internal model controller integrated with a filter is given below.

$$C_1(s)f_1(s) = \frac{0.48s^3 + 7.624s^2 + 20.38s + 1}{(120)(0.01 + 1)^3} \tag{19}$$

Here, the tuning parameters of filter are chosen as λ_1=0.01, n = 3. The Complementary controller $C_2(s)$ = 0.5.

A step change of 1% in the load disturbance is applied at t = 1 sec and the responses are shown in Fig. 3(a) for the nominal plant parameters. It can be seen from Fig. 3(a) that the dynamic response is significantly improved with the proposed 2P-IMC in terms of undershoot and the settling time in comparison to the PID.

B. Steam Turbine with Droop Charecteristics

A typical power system is considered.

$$K_p = 120,\ T_p = 20,\ T_t = 0.3,\ T_g = 0.08,\ R = 2.4 \tag{20}$$

Using the above parameters, the linear plant model is given below [14].

$$P(s) = \frac{2.3518}{(0.075s + 1)(0.125s^2 + 0.324s + 1)} \tag{21}$$

From (21), it can be seen that the plant model consists of a real pole and 2 complex conjugate poles. Since the plant is of minimum phase.

$$P^+(s) = 1 \tag{22}$$

The minimum phase component is given as

$$P^-(s) = \frac{2.3518}{(0.075s + 1)(0.125s^2 + 0.324s + 1)} \tag{23}$$

The minimum phase component of the plant model is considered for the 2P-IMC controller design and is integrated with a filter as given below.

$$C_1(s)f_1(s) = \frac{s^3 + 15.88s^2 + 42.46s + 106.3}{250(0.01 + 1)^3} \tag{24}$$

Where λ_1 = 0.01, n = 3. The complementary controller is tuned as $C_2(s)$ = 0.1.

When the SPS is operated without droop, with the 2P-IMC, the load disturbance is quickly rejected than the PID with significantly less deviation and the response is shown in Fig. 3(a). Similarly, when the droop is added, the frequency deviation response takes slightly long time than with the 2P-IMC than without droop. However, it can be observed that with 2P-IMC, the frequency deviation response reaches quickly than the PID in the presence of the droop and with very less deviation. It can be seen in Fig. 3(b).

From Fig. 3, it can be observed that 2P-IMC controller has better disturbance rejection than the conventional PID controller. A SPS is known to be a highly uncertain system [16], the controllers designed using the nominal parameters are further extended to verify the robustness. The robustness of the controllers is discussed below.

C. Uncertainity analasis.

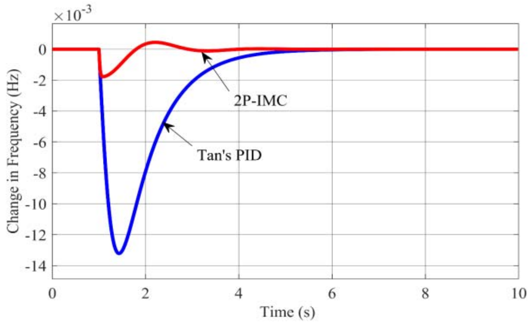
In practice, the uncertain power system parameters are considered to be in a certain range [15]. Such an uncertainty causes an MPM which needs to be handled effectively by proposed controller.

$\delta_1 = \frac{1}{T_p} = [0.0331, 0.1]$, $\delta_2 = \frac{K_p}{T_p} = [4, 12]$,

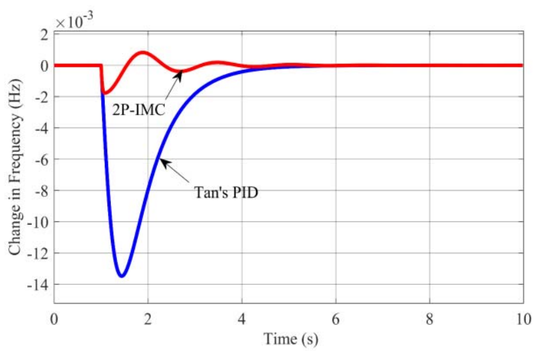
$\delta_3 = \frac{1}{T_t} = [2.564, 4.762]$, $\delta_4 = \frac{1}{T_g} = [9.615, 17.857]$,

$\delta_5 = \frac{1}{RT_g} = [3.081, 10.639]$.

From Fig. 4(a) the dynamic response is significantly improved with the 2P-IMC, showing its robustness to the upper bound variations in the plant parameters. Similarly, it can be seen from Fig. 4(b) that, the proposed 2P-IMC exhibits a better performance but a little sluggish compared to open

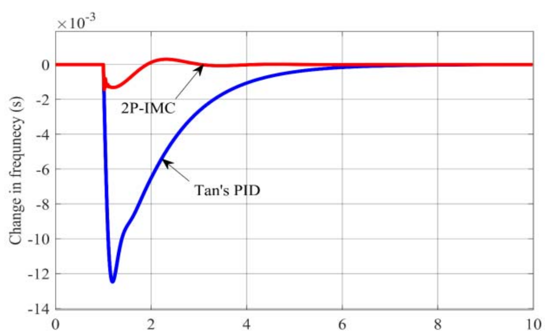


(a)

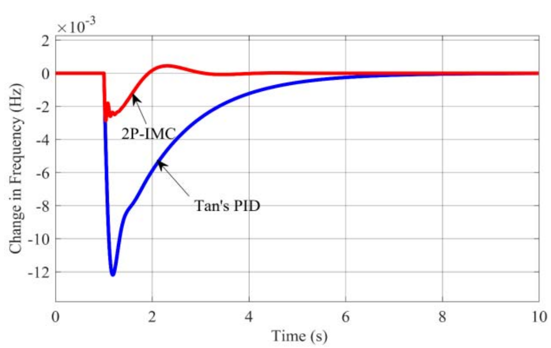


(b)

Fig. 3. Frequency deviation of a SPS using 2P-IMC for steam using nominal parameters. (a) Without Droop (b) With Droop.

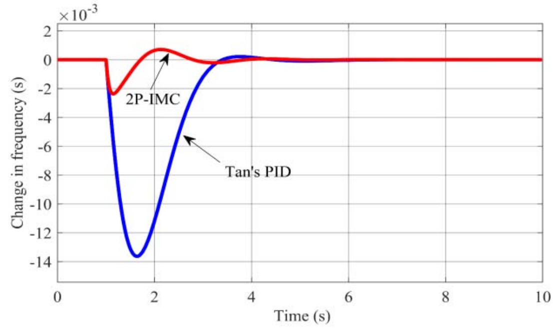


(a)

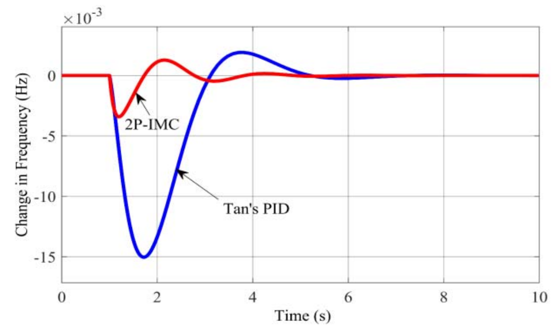


(b)

Fig. 4. Frequency deviation of a SPS using 2P-IMC for steam using upper bound parameters. (a) Without Droop (b) With Droop.



(a)



(b)

Fig. 5. Frequency deviation of a SPS using 2P-IMC for steam using lower bound parameters (a) Without Droop (b) With Droop.

loop configuration.

In case of lower bound, there is a significant improvement in the frequency deviation response for the lower bound variation in the plant parameters using the 2P-IMC and its response is depicted in Fig 5 for without droop and with droop.

Thus, from simulation studies it can be concluded that the proposed 2P-IMC for the LFC exhibits a significant improvement in the nominal conditions and as well as the variations in the plant parameters.

V. Conclusion

In this paper, an extended control strategy based on the IMC structure is investigated for the single area power system application with and without the droop characteristics. The additional feedback loop is appended to the conventional IMC structure to achieve better disturbance rejection.

The simulations are carried on the linear model of the SPS to validate the strength of the 2P-IMC controller. The obtained results are compared with an existing PID Controller and it can be observed that using the proposed method, the settling time and the overshoot are improved greatly compared to existing PID Currently, the proposed control method is being validated on a multi area power system.

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