Disturbance Estimation and Accommodation for Load Frequency Control Using GPI Observer

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***Abstract*—This paper considers the problem of load frequency control (LFC) of power systems when the states of the system are not available for implementation and in the presence of unknown disturbances. Conventional proportional observer (PO) fails to solve this problem unless the disturbances are known or can be modeled. Therefore, we provide a detailed analysis of the generalized proportional integral observer (GPIO) for load frequency control of a single area power system. This study demonstrates that the proposed observer can reliably be used. Since the suggested observer is able to estimate both the states and unknown disturbances, it can be integrated in LFC with disturbance accommodation to ensure system stability and satisfy specified performance measures. Numerical examples are given to illustrate the advantage of GPI observer-based LFC for a single area power system model.**

I. Introduction

In a distributed and interconnected power system, matching the power generation and load within each area is essential. To keep the scheduled power interchange and system frequency at their nominal values for the steady operation of the power system, a careful design strategy within specified limits is required also known as load-frequency control (LFC). Conventional LFC uses a proportional-integral (PI) controller [1]. The main drawback of this controller is that the dynamic performance of the system is limited by its integral gain [2].

Significant efforts were devoted to developing system stabilization techniques by extending the conventional PI controller. However, the difficulty of this line of approaches is in PID design and tuning for load frequency control [3]–[5]. The goal of LFC is to maintain zero steady state frequency deviation, tracking the load demands, and at the same time maintaining acceptable overshoot and settling time on the frequency and tie line power deviations [6]. Considering the crucial role of LFC, designing advanced load frequency control methods such as optimal control [7], [8], variable structure control [9], and adaptive control [10] for a better performance has received considerable attention by many researchers. Recently, various optimization techniques have been employed to enhance the performance of different controllers [11]. However, in all these approaches, ensuring system stability while meeting user-defined objectives and constraints proves to be computationally expensive [12].

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Although these methods are expected to improve the load frequency control, they are difficult to apply in practice due to disturbances caused by unmeasured inputs, plant perturbations, or faulty actuators. These issues substantially degrade the overall control systems performance. In addition, if the disturbances are unknown, robust diagnosis of disturbances require intricate architectures. Effort of using observer based feedback controller for LFC has been reported in [13] using PO and PIO. The comparison showed minor differences in terms of transient response and convergence.

In this paper we show that improvement can be achieved by the so-called generalized proportional integral observer (GPIO), which has additional advantages in robust estimation on account of parameters variations and disturbances. The PIO was found useful in robust control design in [14]. However, its correct structure with complete design freedom was first introduced in connection to robust LTR design of observer-based optimal LQR [15]. Subsequently, it was also realized that PIO is capable of estimating unknown disturbances and faults [16], [17].

This paper provides analysis and design of GPIO for LFC in power systems. We demonstrate that this observer can effectively be used for observer-based controller design of LFC when unknown disturbance is included in the power system model. The GPIO has an additional fading term that distinguishes its structure from PIO and can influence the effect of transient on decaying the integral action over time. A model for a single area power system is considered and simulation results are given to show the effectiveness of GPI observer in stable estimation of unknown disturbance and its integration in LFC of closed-loop control system.

The rest of this paper is organized as follow: System model is described in Section II. In Section III, the structure of GPI observer is explained. Power system model and GPIO based disturbance accommodation for LFC are described in Sections IV and V, respectively. Section VI presents the simulation results followed by the conclusion in Section VII.

II. System Model and Proportional Observer

Consider the linear time-invariant system

$$\dot{x}(t) = Ax(t) + Bu(t) + Ed(t) \tag{1}$$

$$y(t) = Cx(t) \tag{2}$$

where $x(t) \in R^n, u(t) \in R^m, y(t) \in R^p$, and $d(t) \in R^r$ represent state, input, output, and disturbance, respectively.

The coefficient matrices in (1) and (2) are of appropriate sizes. Note that one can always extend the above model by including faults and unmodeled dynamics depending on the scenarios of interest. In section IV, we define the state space parameters for the power system associated with LFC. It is clear that when $d(t) = 0$, the conventional proportional observer (PO) given by

$$\dot{\hat{x}}(t) = (A - L_P C)\,\hat{x}(t) + L_P y(t) + Bu(t) \tag{3}$$

is sufficient to estimate the system states by proper selection of L_P such that $A - L_P C$ is stable. In fact, even if the disturbance $d(t) \neq 0$ admits a model e.g. $\dot{d} = Md$, then an augmented system can be constructed with the combined states $z = \left[x^\top d^\top\right]^\top$. This allows the PO structure to be modified to an extended proportional observer known as disturbance observer (DO) whereby the estimate of both states and disturbance can be obtained. On the other hand, if the disturbance is unknown, PO alone cannot be used since the disturbance term appears in its error dynamics $\dot{e} = (A - L_P C)\,e - Ed$. Although one can estimate the states by decoupling the disturbance through an unknown input observer (UIO) [18], the disturbance estimation and accommodation cannot be achieved in control design. Consequently, we take advantage of an alternative observer structure known as generalized proportional integral observer (GPIO).

III. Analysis of PI and GPI Observers

The drawback of PO can be resolved with PIO or GPIO. Depending on the assumptions made for the disturbance, one can use either PIO or GPIO, as will be described in this section. The structure of PIO is a special case of GPIO and will not be separately discussed. GPIO provides complete freedom for design parameters of the observer and can fit for any desired objectives. So, let us define the GPIO by

$$\dot{\hat{x}}(t) = (A - L_P C)\,\hat{x}(t) + L_P y(t) + Bu(t) + L_d w(t) \tag{4}$$

$$\dot{w}(t) = L_I[y(t) - C\hat{x}(t)] + L_f w(t) \tag{5}$$

Where $w(t) \in R^r$ represents the integral term and $\{L_P, L_I, L_f, L_d\}$ are the gain matrices defined as proportional, integral, fading, and direct integral parameter matrices, respectively. The GPIO equations (4), (5) can compactly be written as

$$\dot{z} = A_z z + L_z y + B_z u \tag{6}$$

where we dropped the time argument for simplicity of notation and define

$$z = \begin{bmatrix} \hat{x} \\ w \end{bmatrix}, A_z = A_x - L_x C_x, L_z = \begin{bmatrix} L_P \\ L_I \end{bmatrix}, B_z = \begin{bmatrix} B \\ 0 \end{bmatrix}$$

with

$$A_x = \begin{bmatrix} A & 0 \\ 0 & 0 \end{bmatrix}, L_x = \begin{bmatrix} L_P & -L_d \\ L_I & -L_f \end{bmatrix}, \quad C_x = \begin{bmatrix} C & 0 \\ 0 & I \end{bmatrix}$$

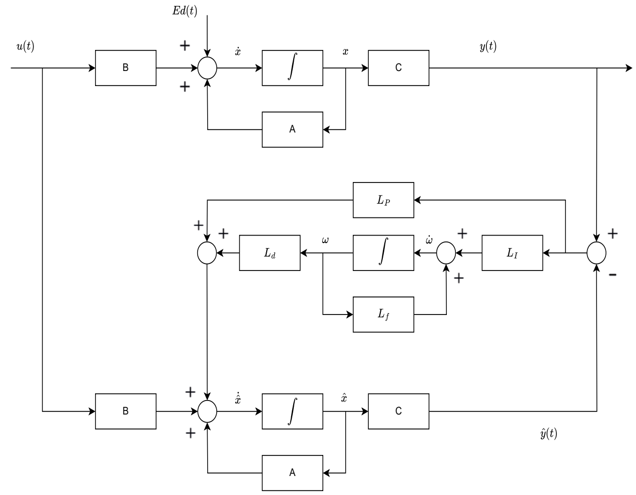

Fig. 1: GPIO structure with $w = \hat{d}$, $L_d = E$, $L_f = F$ for state and disturbance estimation.

Theorem 1: Let the system (1), (2) be observable and assume that w represents the disturbance then (4), (5) is a generalized PI observer capable of estimating the states and disturbance of the system if and only if A_z is Hurwitz stable matrix.

Proof: It is easy to show that the error dynamics of GPIO can be obtained as

$$\begin{bmatrix} \dot{e} \\ \dot{w} \end{bmatrix} = A_z \begin{bmatrix} e \\ w \end{bmatrix} \tag{7}$$

where $e = \hat{x} - x$ and the observability of the pair $\{A_x, C_x\}$ guarantees to obtain $\{L_P, L_I, L_f, L_d\}$.

Note that if the fading term L_f is eliminated and $L_d = B$, the GPIO reduces to PIO structure as it was introduced in connection to LTR design associated with observe-based LQR [13]. On the other hand, if one is interested in using GPIO for disturbance estimation and accommodation, then w is replaced by $\hat{d}$ and $L_d = E$. In this case, the designer may also use the GPIO without the fading term $L_f = 0$ or by carefully selecting $L_f = F \neq 0$ depending on the additional knowledge of disturbance signal $d(t)$. Fig. 1 shows the structure of GPIO, when disturbance estimation is of interest.

IV. Power System Model and LFC

A. State Space Model

In this section, the case of a single generator supplying power to a single service area is considered. Since for the load frequency control problem the investigated power system is affected by small changes in load, it can be sufficiently represented by the linear model shown in Fig. 2 by linearizing the plant around the operating point [1], [2]. It is well-known that the load frequency control system consists of four major parts: Power system, Turbine, Governor, and Speed regulator, which are defined in Fig. 2. The associated gains for the first three blocks are K_P, K_T, K_G and the corresponding time constants are denoted by T_P, T_T, T_G; respectively. The speed regulator parameter of the governor is specified by R. The load disturbance, the reference input, and the output of the system are $\Delta P_D, \Delta P_C$, and ΔP; respectively. For the purpose of regulation, we consider a free governor operation i.e. $\Delta P_C = 0$.

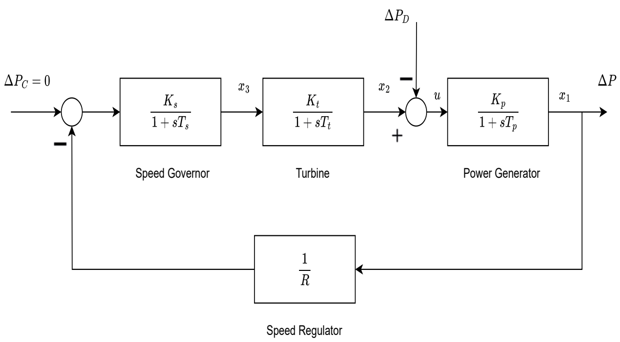

Fig. 2: Block diagram of power system model for LFC

Let us define the output of each block by state variables x_1, x_2, and x_3. The state x_1 represents the frequency variation of the system, the state x_2 is the output power of the turbine which is attached to the power generator by a shaft, and the state x_3 defines valve position of the governor, which controls the flow of the steam into the turbine.

Using the transfer functions associated with each block and defining the state variables x_1, x_2, and x_3 and assuming $K_G = K_T = 1$, one can write the state equation of the system as follows

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_P} & \frac{K_P}{T_P} & 0 \\ 0 & -\frac{1}{T_T} & \frac{1}{T_T} \\ -\frac{1}{RT_G} & 0 & -\frac{1}{T_G} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_G} \end{bmatrix} u + \begin{bmatrix} -\frac{K_P}{T_P} \\ 0 \\ 0 \end{bmatrix} \Delta P_D$$
$$y = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \tag{8}$$

For the purpose of comparison with previous results we consider the typical values for parameters used in for the LFC model as described in Section VI [2], [13]. The third order model defined in (8) can be extended to a fourth order model by considering an integral action on the state of frequency variation x_1 i.e. $\dot{x}_4 = k_i x_1$. This leads to the following state space representation

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_P} & \frac{K_P}{T_P} & 0 & 0 \\ 0 & -\frac{1}{T_T} & \frac{1}{T_T} & 0 \\ -\frac{1}{RT_G} & 0 & -\frac{1}{T_G} & 0 \\ k_i & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_G} \\ 0 \end{bmatrix} u + \begin{bmatrix} -\frac{K_P}{T_P} \\ 0 \\ 0 \\ 0 \end{bmatrix} \Delta P_D \tag{9}$$

with $y = x_1$.

B. State Feedback Design of LFC

The power flow from generator passes through several stations, which are connected by transmission lines. Frequency variation usually propagates in this process and affects the smooth operation of power systems. Load frequency control is a proper procedure to maintain the frequency deviation within acceptable tolerance. Applying the state feedback control law $u = -Kx = -K_1x_1 - K_2x_2 - K_3x_3$ to (8), the characteristic equation of the closed-loop system can easily be derived and represented by a qubic equation $s^3 + a_1s^2 + a_2s + a_3 = 0$. The coefficients a_1, a_2, and a_3 are in terms of the known parameters, and the feedback gains K_1, K_2, and K_3. One way to design the control law is to apply Hurwitz stability condition and obtain the feasible solution to ensure stability and possibly to improve the performance. However, the procedure is not systematic and a more reliable approach is to apply optimal control using LQR. Nevertheless, let us obtain the allowable range of feedback gains for stability of the third order system (8). The necessary and sufficient conditions for stability in terms of a_1, a_2, and a_3 are $a_1 > 0, a_2 > 0, a_3 > 0$, where

$$\begin{aligned} a_1 &= \frac{T_PT_G + T_TT_G + T_TT_P(1+K_3)}{T_TT_PT_G} \\ a_2 &= \frac{T_P(K_2+K_3+1) + T_T(K_3+1) + T_G}{T_TT_PT_G} \\ a_3 &= \frac{R\,(K_1K_P + K_2 + K_3 + 1) + K_P}{RT_TT_PT_G} \end{aligned} \tag{10}$$

Using the numerical values defined for the third order system (8), the range for the stability of the controllable gains can be obtained as $K_1 \in [-0.097, 10], K_2 \in [-10, -7]$, and $K_3 \in [-10, 2]$. If one considers the gravitational search algorithm (GSA) proposed in [19], one can obtain $K_1 = 9.72371, K_2 = -9.00402$, and $K_3 = -9.85103$ with respect to objective function defined for GSA.

On the other hand, if LQR is applied with the performance index

$$J = \int_0^x \left(x^\top Qx + u^\top Ru\right) dt \tag{11}$$

the feedback gain is given by

$$K_p = R^{-1}B^\top P \tag{12}$$

where P is the solution of algebraic Riccati equation

$$A^TP + PA - PBR^{-1}B^TP + Q = 0 \tag{13}$$

and $\{Q, R\}$ are the positive definite weighting matrices.

V. Disturbance Accommodation with GPI Observer-Based Controller

The problem of LFC becomes even more challenging when unknown disturbances are present and may cause undesirable effect on the performance of power systems. Accommodation of disturbances has been studied for many years motivated by [20] (see also its correction in 1973). There are various methods available for disturbance estimation and accommodation and many approaches have been developed [21], [22]. One may refer to these references and the associated citations. In this paper, we take advantage of GPI observer for the purpose of accommodation in LFC. Most available results on LFC assume that all states of the system are available for measurement. However, due to a number of reasons such as physical constraints, sensor placement, and cost, it is desirable to use observers to estimate the states of power systems. Unfortunately, conventional proportional observer (PO) cannot be used if unknown disturbances are incorporated in the system as we elaborated in the introduction. Consequently, we provided complete development of generalized proportional integral observer (GPIO), which can reliably be Observer-based LFC.

Since the GPIO is estimating both states and unknown disturbance, an indirect approach for disturbance accommodation is based on equivalent input disturbance cancellation. To illustrate this approach, let us assume for simplicity that $E = B$ in Fig. 1 and applying the state feedback control law $u = u_0 - \hat{d} = \hat{x} - \hat{d}$ to $\dot{x} = Ax + B[u + d]$.

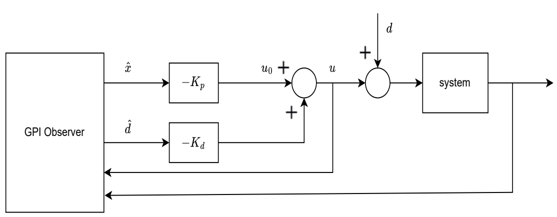

Fig. 3: Indirect GPIO based disturbance accommodation

In the following we provide a direct approach to disturbance accommodation using GPIO based optimal control.

A. *GPIO Based Controller*

Applying the state feedback control law

$$u(t) = v(t) - K_p\hat{x}(t) - K_d\hat{d}(t) \tag{14}$$

to the system (1), (2) and the GPIO (4), (5) as specified in Fig. 1, we obtain the combined control loop system.

$$\begin{bmatrix} \dot{x} \\ \dot{\hat{x}} \\ \dot{\hat{d}} \end{bmatrix} = \begin{bmatrix} A & -BK_p & -BK_d \\ L_PC & A - L_PC - BK_p & E - BK_d \\ L_IC & -L_IC & F \end{bmatrix} \begin{bmatrix} x \\ \hat{x} \\ \hat{d} \end{bmatrix} + \begin{bmatrix} E \\ 0 \\ 0 \end{bmatrix} d + \begin{bmatrix} B \\ B \\ 0 \end{bmatrix} v \tag{15}$$

where we used the parameters of GPIO with $w = \hat{d}, L_d = E$, and $L_f = F$. If we define $e = \hat{x} - x$ and $\varepsilon = \hat{d} - d$, the first equation of (15) leads to

$$\dot{x} = (A - BK_p)\, x - BK_pe - BK_d\varepsilon + (E - BK_d)\, d + Bv \tag{16}$$

suppose $E - BK_d = 0$, which requires $E \in R(B)$, then

$$K_d = B^gE \tag{17}$$

where $B^g = (B^TB)^{-1}B^T$ is the generalized inverse of B and (15) reduces to

$$\begin{bmatrix} \dot{x} \\ \dot{e} \\ \dot{\varepsilon} \end{bmatrix} = \begin{bmatrix} A - BK_p & -BK_p & -BK_d \\ 0 & A - L_PC & E \\ 0 & -L_IC & F \end{bmatrix} \begin{bmatrix} x \\ e \\ \varepsilon \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ \dot{d} - Fd \end{bmatrix} + \begin{bmatrix} B \\ 0 \\ 0 \end{bmatrix} v \tag{18}$$

Equation (18) clearly shows the separation property of GPIO-based state feedback controller. Consequently, the eigenvalues of composite matrix in (18) is the union of those in $A - BK_p$ and those of GPIO eigenvalues. According to the theorem 1, the steady state estimation errors approach zero i.e. $\lim_{t\to\infty} e(t) = 0$ and $\lim_{t\to\infty} \varepsilon(t) = 0$. Therefore, the effect of error in (18) or equivalently in (16) can be neglected and we have the closed loop system.

$$\dot{x}(t) = (A - BK_p)\, x(t) \tag{19}$$

$$y(t) = Cx(t) \tag{20}$$

where we eliminated the reference variable i.e. $v = 0$. Note that when the disturbance is constant, there is no need for the fading term and the equation (18) simplifies since $\dot{d} = 0$. What remains to be done is the design of the state feedback $u = -K_px$ such that (19) is asymptotically stable and minimizes the quadratic performance index (11). Choosing the Lyapunov function as $V(x) = x^\top Px$ and using standard technique one can guarantee stability and satisfy the following upper bound of the performance index

$$J = \int_0^\infty \left(x^\top Px + u^\top Pu\right) dt \leqslant x^\top(0)Px(0) \tag{21}$$

if the following inequality holds

$$\left(A - BK_p\right)^\top P + P\left(A - BK_p\right) + Q + K_p^\top RK_p < 0 \tag{22}$$

Furthermore, in order to find the minimal cost function, we may minimize γ, where $\gamma > x_0^\top Px_0$ is required, i.e. $x_0^\top Px_0 - \gamma < 0$.

B. LMI Formulation of GPIO

The above euqation (22) can be reformulated in terms of LMI which is numerically preferable. The following theorem provides the detailed procedure.

Theorem 2: The system (19) is asymptotically stable satisfying the cost control performance index (21), if the following LMI is feasible with variable X and Y:

$$\min \gamma$$
$$\text{s.t.}$$
$$\begin{bmatrix} AX + XA^\top - BY - Y^\top B^\top & X & Y^\top \\ X & -Q^{-1} & 0 \\ Y & 0 & -R^{-1} \end{bmatrix} < 0 \tag{23}$$

$$\begin{bmatrix} -\lambda & x_0^\top \\ x_0 & -X \end{bmatrix} < 0 \quad \text{and } X > 0 \tag{24}$$

where $X = P^{-1}$ and the stale feedback gain can be obtained as $K_p = YX^{-1}$.

Proof: Multiplying (22) from left and right by $P^{-1} = X$ and applying Schur complement formula one can establish the equivalence of (22) and (23). The equivalence of (24) and $x_0^\top P x_0 - \gamma < 0$ can also be verified again by Schur complement formula. i.e. for a symmetric matrix M partitioned as

$$M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}, \quad M_{21} = M_{12}^T$$

$M < 0$ if and only if $M_{11} - M_{12}M_{22}^{-1}M_{21} < 0$. So, by defining $M_{11} = -\gamma, M_{12} = X_0^T$, and $M_{22} = -X = \left(-P^{-1}\right)$ (24) reduces to $x_0^\top P x_0 - \gamma < 0$.

Remark: If the condition $E - BK_d = 0$ i.e. $E \in R(B)$ is not satisfied, we can still apply the procedure by imposing the condition $\min \|E - BK_d\|$ which is equivalent to a least square solution for K_d.

VI. Simulation Results

Simulation results for the power system described in section IV using disturbance accommodation techniques introduced in section V are presented here. For a better comparison between discussed methods, LFC for the power system model described in section IV is studied using both PO and GPI observers.

In this study, we used typical values of the power system parameters: $K_P = 120, K_G = 1, K_T = 1, T_P = 20, T_G = 0.08, T_T = 0.3$ s, and $R = 2.4$.

Fig. 4 shows the step response for the power system discussed in section IV in which the under-damped property of the model is apparent.

GPI observer is developed for a single area power system modeled in section IV and the disturbance $\Delta P_D = 0.01 p.u.$ is injected to the systems at $t = 1s$. For an optimal observer design, the gain should be calculated in such a way that the error dynamics should regulate to zero.

While PO observer is not able to estimate the disturbance, Fig. 5 demonstrates fast disturbance estimation using GPI observer because of the incorporation of the additional fading term in the GPIO framework. The output frequency of the system using PO and GPIO control strategies is shown in Fig. 6 demonstrating reduced overshoot and improved settling time when using GPIO.

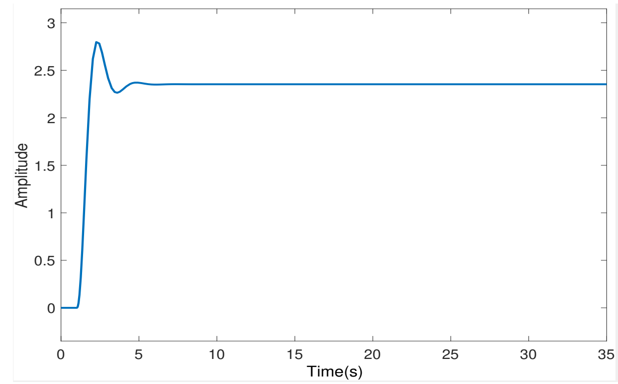

Fig. 4: Step response of third order power system model

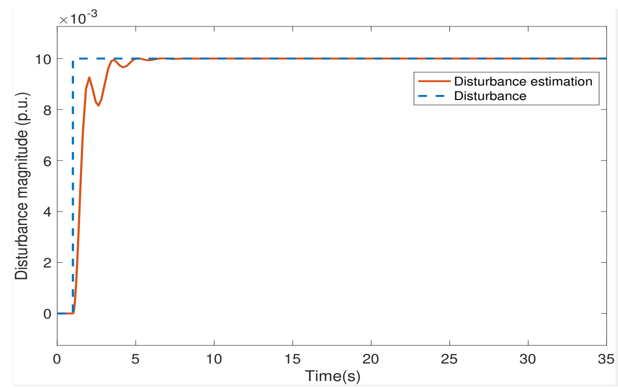

Fig. 5: Disturbance (dashed) and GPIO estimation of disturbance (solid)

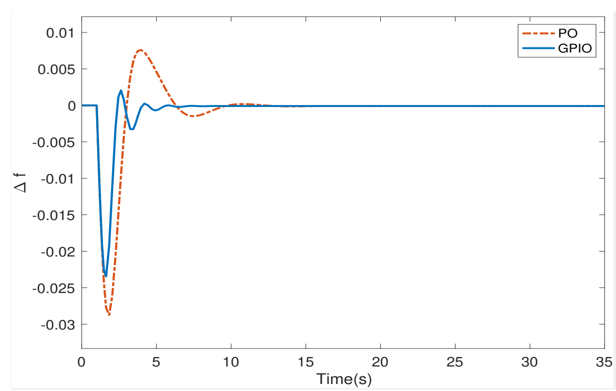

Fig. 6: Response of LFC system with PO (dashed) and GPIO (solid)

VII. Conclusion

In this paper, a generalized proportional integral observer (GPIO) is introduced for load frequency control (LFC) of a single area power system. This study demonstrates that GPI observer can improve the LFC of the system in certain aspects. Since GPIO is able to estimate both the states and unknown disturbances it can be integrated in LFC with disturbance accommodation to ensure the system stability and to satisfy the specified performance measures. Specifically, by understanding the form of disturbance in power systems using GPIO, a more effective decision-making, enhancement of the system's reliability, and contribution to the overall resilience of power systems becomes feasible. Future analysis could explore the performance of various GPIO configurations in response to more complex and unforeseen disturbances.

REFERENCES

[1] P. S. Kundur and O. P. Malik, *Power system stability and control*. McGraw-Hill Education, 2022.

[2] W. Tan, "Tuning of pid load frequency controller for power systems," *Energy Conversion and Management*, vol. 50, no. 6, pp. 1465–1472, 2009.

[3] M. Hossaiin, T. Takahashi, M. Rabbani, M. Sheikh, and M. Anower, "Fuzzy-proportional integral controller for an agc in a single area power system," in *2006 International Conference on Electrical and Computer Engineering*. IEEE, 2006, pp. 120–123.

[4] J. Talaq and F. Al-Basri, "Adaptive fuzzy gain scheduling for load frequency control," *IEEE Transactions on power systems*, vol. 14, no. 1, pp. 145–150, 1999.

[5] Y.-H. Moon, H.-S. Ryu, J.-G. Lee, K.-B. Song, and M.-C. Shin, "Extended integral control for load frequency control with the consideration of generation-rate constraints," *International journal of electrical power & energy systems*, vol. 24, no. 4, pp. 263–269, 2002.

[6] H. Shayeghi, H. Shayanfar, and A. Jalili, "Load frequency control strategies: A state-of-the-art survey for the researcher," *Energy Conversion and management*, vol. 50, no. 2, pp. 344–353, 2009.

[7] M. Calovic, "Linear regulator design for a load and frequency control," *IEEE Transactions on Power Apparatus and Systems*, no. 6, pp. 2271–2285, 1972.

[8] C. E. Fosha and O. I. Elgerd, "The megawatt-frequency control problem: A new approach via optimal control theory," *IEEE Transactions on Power Apparatus and Systems*, no. 4, pp. 563–577, 1970.

[9] N. Bengiamin and W. Chan, "Variable structure control of electric power generation," *IEEE Transactions on Power apparatus and systems*, no. 2, pp. 376–380, 1982.

[10] C.-T. Pan and C.-M. Liaw, "An adaptive controller for power system load-frequency control," *IEEE Transactions on Power Systems*, vol. 4, no. 1, pp. 122–128, 1989.

[11] M. M. Gulzar, D. Sibtain, M. Alqahtani, F. Alismail, and M. Khalid, "Load frequency control progress: A comprehensive review on recent development and challenges of modern power systems," *Energy Strategy Reviews*, vol. 57, p. 101604, 2025.

[12] A. Ghosh, A. K. Ray, O. Singh, and M. Jamshidi, "Optimized load frequency controller performances with a reduced number of decision variables: A gravitational search algorithm-based method," *IEEE Systems, Man, and Cybernetics Magazine*, vol. 9, no. 1, pp. 48–57, 2023.

[13] A. A. Hussein, S. S. Salih, and Y. G. Ghasm, "Implementation of proportional-integral-observer techniques for load frequency control of power system," *Procedia Computer Science*, vol. 109, pp. 754–762, 2017.

[14] S. Beale and B. Shafai, "Robust control system design with a proportional integral observer," *International Journal of control*, vol. 50, no. 1, pp. 97–111, 1989.

[15] H. H. Niemann, J. Stoustrup, B. Shafai, and S. Beale, "Ltr design of proportional-integral observers," *International Journal of Robust and Nonlinear Control*, vol. 5, no. 7, pp. 671–693, 1995.

[16] A. Oghbaee, B. Shafai, and S. Nazari, "Complete characterisation of disturbance estimation and fault detection for positive systems," *IET Control Theory & Applications*, vol. 12, no. 7, pp. 883–891, 2018.

[17] S. Nazari and B. Shafai, "Distributed proportional-integral observers for fault detection and isolation," in *2018 IEEE Conference on Decision and Control (CDC)*. IEEE, 2018, pp. 6328–6333.

[18] Y. Guan and M. Saif, "A novel approach to the design of unknown input observers," *IEEE Transactions on Automatic Control*, vol. 36, no. 5, pp. 632–635, 1991.

[19] E. Rashedi, H. Nezamabadi-Pour, and S. Saryazdi, "Gsa: a gravitational search algorithm," *Information sciences*, vol. 179, no. 13, pp. 2232–2248, 2009.

[20] C. Johnson, "Accomodation of external disturbances in linear regulator and servomechanism problems," *IEEE Transactions on automatic control*, vol. 16, no. 6, pp. 635–644, 1971.

[21] Q. Mei, J. She, F. Wang, and Y. Nakanishi, "Disturbance rejection and control system design based on an improved equivalent-input-disturbance approach," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 3, pp. 2876–2886, 2022.

[22] W. Tan and C. Fu, "Linear active disturbance-rejection control: Analysis and tuning via imc," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 4, pp. 2350–2359, 2015.