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DESIGN OF A NOVEL PI FUNCTIONAL OBSERVER BASED LOAD FREQUENCY CONTROLLER FOR INTERCONNECTED POWER SYSTEM

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ABSTRACT

The increase in population has led to the increase in the demand of the power in terms the size and. To meet this demand a decentralized power structure has emerged. The main advantage of decentralized power system is to overcome the delay in decision making unlike the centralized power system. In the present paper, load frequency control (LFC) in the decentralized scenario is analyzed using state space. The stability of the power system can be observed through a state-feedback controller rather than being directly monitored by the system Instead of guessing the system states, a Functional Observer (FO) is made to evaluate the control input. The stability can also be guaranteed by using the suggested controller, as the observer gains can be calculated theoretically. An industry-standard IEEE test system is used to evaluate the effectiveness of the suggested methods. It has been found that functional observers perform more effectively than both functional and traditional state observers.

Keywords: *Inter Connected Power System, Load Frequency Control (LFC), PI Functional Observer, Leunberger Observer*

1. INTRODUCTION

In Science and Engineering estimation of the system's state and its analysis is a crucial aspect. Measuring the input and output values are a straightforward way to learn about the internal state of any given system. Dynamic state estimation (DSE) is the name given to the investigation of internal elements that lead to changes in the provided system in this method. [10] The majority of engineering areas (via. Electrical, Electronics, Civil, Mechanical, Aerospace, Chemical, etc. [18]) areas can use this DSE)

On the other hand, a sub system called observer Even though it is a component of another system, an observer only uses the system's input and output to estimate the internal states or circumstances of that system. This nomenclature is proposed by D.Luenberger initially in 1966[37]. State Observers, Functional Observers and Bounding Observers are often used [5]. Observer and state observer are the terms used in industrial applications, are interchangeable. Instead, Functional Observer employs probabilistic and statistical method in their work. These are typically offered in scaled down versions and are created for Linear Time Invariant (LTI) systems [3].

This Paper primarily discusses the use of above mentioned observers where Transmission line failures, generator failures, changes in demand (power), changes in system configuration, and other disturbances commonly occur in the power system. In order to bring the system to the equilibrium state i.e., to the stable state in a rapid way the proposed system is used. The absence of the feedback observers in the earlier methods is a big disadvantage. This lacks the continuous monitoring of the system. With the state feedback observers the continuous monitoring is easy. Therefore the Proposed method is more advantageous than the earlier methods.

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The power transported can be calculated using State Observers. The term "tie-lines" is frequently used to describe the transmission lines in use [7]. The same supply frequency must be used by all the units in any area of the Tie-Line.

All the areas and equipment operating in steady state are shielded from frequency changes and tie line changing by the Load Frequency Control (LFC) method [31]. This article major goal is to provide thorough examination of linear and Non-linear DSE method for LFC and detection of fault using phasor measurement units (PMU's) [35].These days the Power system is integrated with different types of generators , transmission network and measuring devices[11] which share the properties similar to that of conventional power system.

2. MULTI-AREA POWER SYSTEM MODEL

In this study, a linearized version of the model employed in [24] is considered. The i^{th} region of the N-area power system is depicted in Fig 1 and its state-space model is represented by

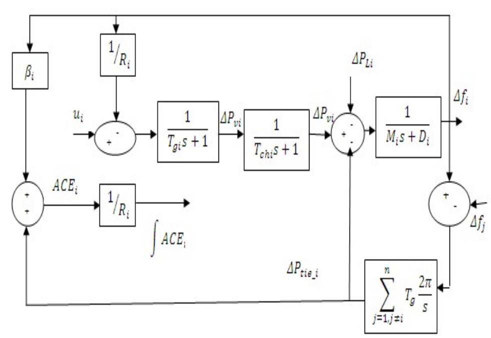

Figure 1: Dynamic model of the i_{th} area in a N-area LFC scheme

$$\dot{x}_i = A_i x_i + \sum_{j=1,j\neq i}^{N} \Delta A_{ij} x_j + B_i u_i + F_i d_i$$

$$y_i = C_i x_i \qquad (1)$$

x_i is the state vector; u_i is the control input; d_i is the vector of load disturbance; y_i is the output vector; $\Delta f_i, \Delta P_{mi}$, ΔP_{vi} and ΔP_{Li} are the mechanical output of the generator, the load, the valve position, and the frequency deviations, accordingly. M_i, D_i, T_{gi}, T_{chi}, and R_i signify the governor's time constant, the turbine's time constant, the speed drop, the generator's moment of inertia, and the generator's damping coefficient.; β_1 is frequency bias factor; T_{ij} is the tie-line synchronizing coefficient between the i^{th} and j^{th} control area; $\sum_{j=1,j\neq i}^{N} \Delta\alpha_{ij} x_j$ are the area-interactions $\alpha_i \in R^{n_i\times n_i}$., $\alpha_{ij} \in R^{n_i\times n_j}$, $B_i \in R^{n_i\times m_i}$,$F_i \in R^{n_i\times q_i}$,and $C_i \in R^{p_i\times n_i}i$ are known constant matrices. According to (1), The N-area power system's state-space model can be modelled as

$$\dot{x} = \alpha x + \Delta\alpha x + Bu + Fd$$

$$y = cx \qquad (2)$$

$$\Delta\alpha = [0\ \Delta\alpha_{12} \cdots \Delta\alpha_{1N}\ \ \Delta\alpha_{21} \vdots\ 0 \vdots \cdots \ddots\ \Delta\alpha_{2N} \vdots\ \ \Delta\alpha_{N1}\ \Delta\alpha_{N2}\ 0\ ]$$

$\alpha \in R^{n\times n}$, $\Delta\alpha \in R^{n\times n}$, $B \in R^{n\times m}$, $F \in R^{n\times q}$, and $C \in R^{p\times n}$, are known constant matrices, where $n = \sum_{t=1}^{N} n_i$, $m = \sum_{t=1}^{N} m_i$, $q = \sum_{t=1}^{N} q_i$, and $p = \sum_{t=1}^{N} p_i$

3. EMPLOYING FUNCTIONAL OBSERVERS FOR DSE AND LFC IN THE POWER SYSTEM

A functional observer (FO) model is implemented in a power system with two interconnected areas, connected by a single tie-line. This quasi-decentralized FO model is considered the most suitable for this network configuration [14]. The FO serves as the basis for creating a model that can observe the system's behaviour and dynamics. In this setup, the load frequency control (LFC) signal is generated using a control signal. Instead of constructing the control signal by combining individual state signals, the required signal is directly obtained from the functional observer (FO).

To monitor the power consumed, voltage magnitudes, phase angles, and current magnitude of the tie-line, Phasor Measurement Units (PMUs) are utilized. These devices provide accurate measurements and enable real-time monitoring of the system's electrical quantities.. Before actually designing the Novel Functional Observer (FO) the state estimation and different parameters like Peak overshoot, settling time etc., of different Observers are measured.

3.1 State Observer/Estimator

Because of data acquisition issues and cost limitations, it might not be possible to monitor every state variable under actual circumstances. In order to obtain state feedback [35] a state estimate method is needed for each state of the state vector.

Let $\hat{x}(t)$=estimate of the state vector x(t)

State Observer/Estimator

$\dot{x}=\alpha x+Bu$ (3)

$y=cx$ (4)

The state vector in this case is x, and the output is y. (It also contains a state vector x estimate). u is a representation of the control signal.

Open-loop Observer (L= [0], α obs= α)

$\hat{\dot{x}}(t)=\alpha\hat{x}(t)+Bu$ (5)

The observer fails due to disturbances in the system and modelling mistake of system.

Open-Loop Estimation Error,

Estimation Error:

$\tilde{x}(t)=x(t)-\hat{x}(t)$ (6)

$\tilde{\dot{x}}(t)=\dot{x}(t)+(\hat{\dot{x}}(t))=A\alpha(t)$ (7)

Hence

$\tilde{x}(t)=e^{At}\tilde{x}(0)$ (8)

Error Dynamics:

Errors in the modelling process cannot be corrected. State matrix A, which is not stable and with an unbounded error.

$\tilde{\dot{x}}=\alpha\hat{x}+Bu+L(y-C\hat{x})$

$\tilde{\dot{x}}=\alpha_{obs}\hat{x}+Bu+Ly$ (9)

where, $\alpha_{obs}=\alpha-LC$ (10)

The matrix L is given Eigen values. To obtain the accurate estimation, it is necessary to simplify the equation with respect to an open-loop observer.

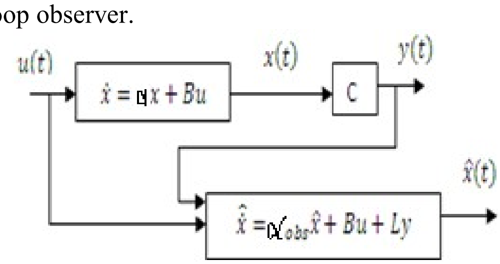

Figure 2: Block diagram of observer

Theorem1:

Unless the dual system (α^T, C^T) is subjected to control, the system (C,α) is observable [35]. As long as (α^T, C^T) is in control, Eigen values can be (stable) allocated randomly with the use of the state's feedback.

$\dot{x}=\alpha^T x+C^T u$ (11)

$u=-L^T x$ (12)

$\dot{x}=(\alpha^T-C^T L^T)x$ (13)

$(\alpha^T-C^T L^T)^T=\alpha-LC$ (14)

Similar Eigen values are obtained.

3.2 Functional Observer

Functional Observer performs better than State Observer when applied to load frequency control (LFC) [36].

Functional observer

$\dot{x}=\alpha x+Bu$ (15)

$y=Cx$ (16)

$z=Lx$ (17)

Where x,y, z ,w and u are functions of time 't'.

Here, $x\in R^n, u\in R^m$ are the vectors of the state considered, $y\in R^p$ is the obtained vector of the state and $z(t)\in R^r$ is the vector that is to be estimated. α $\in R^{nxn}$, B $\in R^{nxm}$, C $\in R^{pxn}$ and L $\in R^{rxn}$ are the matrices of the constants that are known. The proposed structure for a Functional Observer is a system that is dynamic and capable of asymptotically tracking the variable z(t):

$\dot{w}=Nw+Jy+Hu$ (18)

$\hat{z}=Gw+Ey$ (19)

The following are the definitions of α, B and C, the system matrices and N, J, H, D and E, the observer matrices

$\alpha\in R^{nxn}$ N$\in R^{qxq}$ B $\in R^{nxm}$

J$\in R^{qxp}$ C $\in R^{pxn}$ H $\in R^{qxm}$

L $\in R^{rxn}$ D $\in R^{rxp}$ E $\in R^{rxp}$

Theorem 2*:*

By using the q^{th} order Functional Observer of (18) and (19), Lx (t) is estimated,

Provided the following conditions are met:

N is a stability matrix

JC = P α -NP (20)

H = PB (21)

L = DP + EC (22)

In state estimation, the observer error is expressed as

e(t) ≜w- Px (23)

Where, w and x are functions of time't'.

By derivation, we get

$\dot{e}(t)=w(t)+P\dot{x}(t)$ (24)

$\dot{e}(t)=Nw(t)+JC\dot{x}(t)+Hu(t)-PAx(t)-PBu(t)$ (24)

Applying conditions (15) and (16) yields

$\dot{e}(t)$ =N e(t) (25)

The above solution is in the manner of an exponential function

$$e(t)=e^{Nt} \quad (26)$$

in which dynamics of the observer are organised by the variable named N in (26).

On the application of the conditions,

$$e(t) = w - Px \quad (27)$$

By simplifying,

$$e(t) = \hat{z} - Lx = D(w-Px) \quad (28)$$

The above equation should asymptotically approach zero. Note that α and N has no common Eigen values, but P has a single solution. And, X and e can be derived easily from the above conditions.

$$\dot{x}(t) = \alpha x(t) + Bu(t) = \alpha x(t) - B(Dw(t) + Ey(t))$$

$$\dot{x}(t) = (\alpha + BL)x(t) + (BD)e(t) \quad (29)$$

$$\dot{e}(t) = Ne(t) \quad (30)$$

This results in a composite system similar to the full-state observer as

$$[\dot{x}(t) : \dot{e}(t)] = [K_1 ; K_2 : K_3\ K_4][x(t) : e(t)] \quad (31)$$

Where, $K_1 = \alpha + BL \quad K_2 = BD$

$K_3 = 0 \quad K_4 = N$

Apart from the fact that instead of -Kx(t) the control law is assigned with Lx(t) and the difference in representation, they are identical to each other. Considering the given constraints, achieving a functional state of the system requires an r^{th} order observer, where the order r should be minimized. The observer matrices must be designed to facilitate ease of assigning Eigen value and easiness of the control algorithm, enabling easy application. In order to estimate the order, the ranks of the matrix are considered into account.

$$rank[L\alpha\ C\alpha\ \ C\ L\ ] = rank[C\alpha\ C\ L\ ] \quad (32)$$

$$rank[sL - L\ C\ L\ ] = rank[C\alpha\ C\ L\ ] \quad s \in C, R(s) \geq 0 \quad (33)$$

When the ranks on both the left-hand side (LHS) and the right-hand side (RHS) are equal, the condition is considered satisfied. According to the findings of the author in reference [21], this condition is equivalent to the detectability of the pair (F, G)

Where

$$F = L\alpha L^{+} - L\alpha(I - L^{+}L)[C\alpha(I - L^{+}L)\ C(I - L^{+}L)\ ]^{+}[CA\alpha\ C\ L^{+}\ ] \quad (34)$$

$$G = (I - [C\alpha(I - L^{+}L)\ C(I - L^{+}L)\ ][C\alpha(I - L^{+}L)\ C(I - L^{+}L)\ ]^{+})[C\alpha L^{+}\ CL^{+}\ ] \quad (35)$$

Where, L+ denotes the Moore-Penrose generalized inverse of matrix L. Furthermore, if matrices J, H, and E satisfy Theorem 1, a Hurwitz matrix N can be expressed as follows.

$$N = F - ZG \quad (36)$$

Where, the matrix Z is obtained through a pole placement method to ensure stability of the system, specifically F - ZG. E and K matrices are derived based on the given equation.

$$[E : K\ ] = L\underline{\alpha}\Sigma^{+} + Z(I - \Sigma\Sigma^{+}) \quad (37)$$

Where,

$\bar{\alpha} = \alpha(I - L^{+}L), \quad \bar{C} = C\,(I - L^{+}L)$

and $\Sigma = \bar{C}\ \bar{\alpha}\ \bar{C}$

Matrix J, H are obtained according to

$$J=K+NE \quad (38)$$

$$H=(L-EC)B \quad (39)$$

By employing this algorithm, it becomes straightforward to compute all the necessary observer parameters, ultimately leading to the construction of a functional observer in the specified form.

$$\dot{w}(t) = Nw + Jy + Hu \quad (40)$$

$$\hat{z}(t) = w + Ey \quad (41)$$

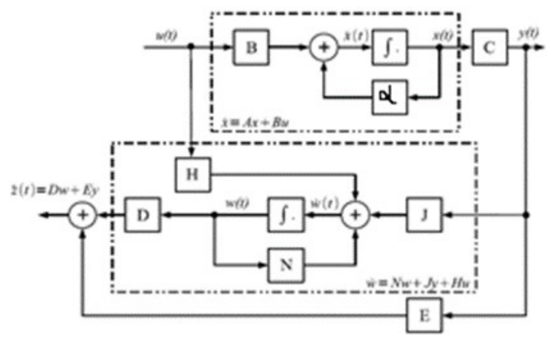

Figure 3: Schematic of a Functional Observer

3.3 Functional observer with a Conventional Controller

Simple presumptions (One approach is to integrate transmission lines and multiple bus bars into a single unified unit, approximating all generators in a particular region into one producing unit, etc.) may not be adequate for such a complicated power system to function when the distribution network becomes more complex. Without making these assumptions, we analyze a semi-distributed functional observer method in this research for cross-line power and frequency management in multi-area interconnection power networks [13]. The creation of control signals and the use of the semi-distributed functional observer were also taken into consideration using a two-domain linear system coupled to a single connection line model. The F0 [3] technique to LFC in highly linked power grids is further

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developed as a result. Estimating the control signal is required during the LFC signal generation procedure. Using a functional observer to directly estimate the desired signal is more sensible than estimating each individual state and then combining these estimates linearly to generate the control signal [5]. Here, a semi-dispersive functional observer for producing control signals is taken into consideration. A functional observer (FO) estimation technique utilizes PMU measurements of voltage, current, phase angle, and tie-line power measurements [2]. The proposed FO-based controller is characterized by its straightforward design and performance that is comparable to full-order observers. Additionally, functional observability standards are fewer strict than governmental standards, because analysis and design take the complete network topology into account [1 2].

4. DESIGN OF FO BASED CONTROLLER

Let the estimate of e be ê.

$$\dot{\hat{e}} = \alpha\hat{e} - B\Gamma_c^T\hat{e} + \Gamma_o(e_1 - \hat{e}_1) \quad (42)$$

Where, $\Gamma_0 \equiv [\gamma_1^o, \gamma_2^o, \dots, \gamma_n^o]^T \epsilon R^n$ is the gain vector of the observer.

Observer error,

$$\dot{\tilde{e}} = \alpha_o\tilde{e} + B(g(x)(u^* - u_{PID} - u_d - u_s) - d) \quad (43)$$

Assuming the observability of (C, α), the gain vector of the observer Γ_o could be rigorously selected to be Hurwitz, accompanied by a symmetric positive definite matrix P and a positive definite matrix Q_o. If we consider the Laplace transform L(.) of $\tilde{e}_1$, the resulting transform function may be expressed as L($\tilde{e}_1$) by choosing $M(s)$ such that $M(s) = s^m + b_1 s^{m-1} + \dots + b_m,\ m < n$ and $M^{-1}(s)$ is a proper stable transfer function and $N(s)M(s)$ is a proper SPR transfer function. Hence $L(\tilde{e}_1)$ can be written as:

$$L(\tilde{e}_1) = N(s)M(s)M^{-1}(s)L(g(x)(u^* - u_{PID}) - d) - N(s)M(s)M^{-1}(s)L(g(x)u_d) - N(s)M(s)M^{-1}(s)L(g(x)u_s) + N(s)M(s)L(u^* - u_{PID}) - d) - L(u^* - u_{PID}) \quad (44)$$

Represent the function φ such that

$$L(\varphi) = M(s)^{-1}L(g(x)(u^* - u_{PID}) - d) - L(u^* - u_{PID}),$$

Hence, the dynamic equation can be written as

$$\tilde{e}_1 = C_m^T\tilde{e} \quad (45)$$

Where, $B_m = [0, 0, \dots, 0, 0, \dots, b_1, b_2, \dots b_m]^T \epsilon R^n$, $C_m = [1, 0, \dots 0]^T \epsilon R^n$

For further analysis, there is necessity of 2 assumptions mentioned below:

Assumption 1: The uncertain non-linear function $f(x)$ for the states is bounded by a upper bound function $f^u(x)$, i.e., $f(x) \le f^u(x)$. The uncertain non-linear function $g(x)$ related with the input is bounded by $g_l \le \| g(x) \| \le g^u$ where both upper and lower boundaries g^u and g_l are positive constants.

Assumption 2: The function φ is bounded by $\| \varphi \| \le \varepsilon$ where ε is a positive constant.

On differentiation of V w.r.t to t, we get

$$\dot{V} = \frac{1}{2}\left((\tilde{e}^T\alpha_0^T P\tilde{e} + \tilde{e}^T P\alpha_0\tilde{e}) + (u^* - u_{PID} + \varphi - \tilde{u}_d - \tilde{u}_s)^T B_m^T P\tilde{e} + \tilde{e}^T P B_m(u^* - u_{PID} + \varphi - \tilde{u}_d - \tilde{u}_s)\right) \quad (46)$$

But it is given that,

$$\alpha_0^T P + P\alpha_0 = -Q \quad (47)$$

And $$PB_m = C_m \quad (48)$$

Where, $Q = Q^T > 0$. Substituting (47), (48) and (45) in (46) we get,

$$V \le -\frac{1}{2}|\tilde{e}^T Q\tilde{e}| + |e_1||u^* - u_{PID}| + \tilde{e}_1(\varphi - \underline{u}_d) - \tilde{e}_1\underline{u}_s \quad (49)$$

From the above assumptions, u_d can be designed such that $\tilde{e}_1(\varphi - \underline{u}_d) \le 0$.

$$u_d = \varepsilon + k, \quad (50)$$
$$if\ \tilde{e}_1 \ge 0\ and\ \varphi > 0\ 0$$
$$if\ \tilde{e}_1 \ge 0\ and\ \varphi < 0\ 0$$
$$if\ \tilde{e}_1 \ge 0\ and\ \varphi > 0 - (\varepsilon + k),$$
$$if\ \tilde{e}_1 \ge 0\ and\ \varphi < 0$$

Where, k is a positive constant. Substituting u_d in (49),

$$\dot{V} \le -\frac{1}{2}|\tilde{e}^T Q\tilde{e}| + |\tilde{e}_1||u^* - u_{PID}| - \tilde{e}_1\tilde{u}_s$$
$$V \le -\frac{1}{2}\lambda_{min}(Q)|\tilde{e}_1|^2 + |\tilde{e}_1||u^* - u_{PID}| - \tilde{e}_1\tilde{u}_s \quad (51)$$

$\dot{V} \le$ −1/2 λ_min (Q) |e ̃_1 |^2 + |e ̃_1 |(1/|g_1 | (|f^u (x ̂)| + |y_m^((n)) | + |Γ_e^T e ̂ |) + |u_PID |) − e ̃_1 u_s) (52)

$$V_d(K_{PID}) \le -\frac{1}{2}\lambda_{min}(Q)|\tilde{e}_1|^2 + |\tilde{e}_1|\left(\frac{1}{|g_1|}\left(|f^u(\hat{x})| + |y_m^{(n)}| + |\Gamma_e^T\hat{e}|\right) + |u_{PID}|\right) \quad (53)$$

If K_{PID} estimated by MGA results in $V_d(K_{PID}) < 0$, $\dot{V} < 0$ is satisfied: given that u_s is not applied to the input in (12). On the other hand, if $V_d(K_{PID}) > 0$, u_s should be applied leading to the

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condition $\dot{V} < 0$.
To mitigate the destabilizing effect caused by the inclusion or exclusion of u_s in the PID controller, a gate function can be introduced.

5. RESULTS AND DISCUSSIONS

The method employed has been simulated using Simulink (Matlab) and the demand increase for the first area is ΔP_{D1} and second area is ΔP_{D2}. Both the first area's demand (ΔP_{D1}) and the second area's demand (ΔP_{D2}) have been evaluated against input perturbations. Figures 4 to 6 demonstrate how the system reacts more rapidly in terms of control, which also eliminates frequency variations. Therefore, in terms of control and frequency damping, under all operational conditions, the theoretical model outperforms the FOWO and Full order Luenberger Observer (FOLO). Table 1 presents a quantitative analysis of the performance resilience under different operating conditions. It includes the settling time, undershoot, and overshoot values determined for various operational points. The numerical results are displayed for the operating point with a 10% band of step load change. The recommended PI Functional Observer (PIFO) outperforms both the FOWO and LO, as shown in Table 1.

From the Table 1 it can be observed that the PI Functional Observer has less settling time than the other observers. From the results obtained it is PIFO settles 27% faster than FOLO and settles 48% faster than FOWO. Also the Overshoot and Undershoot values at different operating points have been improved in PIFO than FOLO and FOWO.

Table 1: $f_1(t)$ Response in Various Strategies of Performance

Operating point	Controller	Over shoot (P.U)	Under shoot (P.U)	Settin g time (sec)
1	PI Functional Observer	0.09419	-0.0990	4.758
	Full order Luenberger Observer	0.1220	-0.0990	6.505
	Functional Observer without controller	0.1073	-0.0990	9.187
2	PI Functional Observer	0.1039	-0.1147	4.616
	Full order Luenberger Observer	0.1163	-0.1147	6.125
	Functional Observer without controller	0.1214	-0.1147	6.967
3	PI controller based Functional Observer	0.1025	-0.1108	4.804
	Full order Luenberger Observer	0.1143	-0.1108	6.326
	Functional Observer without controller	0.1188	-0.1108	7.241

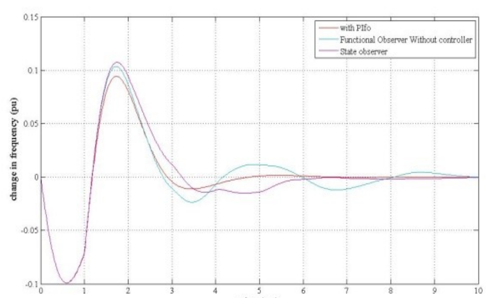

Figure 4: Frequency variation resulting from a step rise in demand at OP 1 (OP refers to operating point)

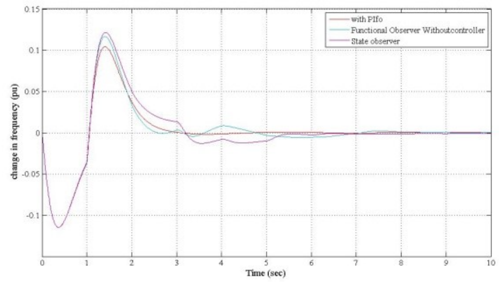

Figure 5: Frequency variation resulting from a step rise in demand at OP 2

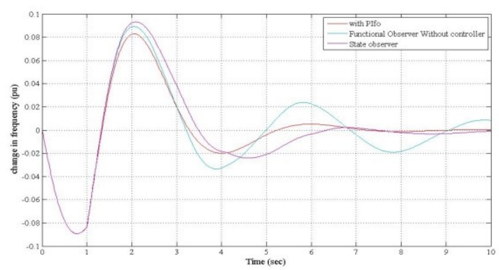

Figure 6 : Frequency variation resulting from a step rise in demand at OP 3

6. CONCLUSIONS

The load frequency control has been addressed in this paper employing the utilization of a PI Functional Observer (PIFO) as a viable approach for addressing the multi-area power system. A comparative performance evaluation was conducted on a usual two-area thermal power system with reheat capability. The objective was to assess its ability to attenuate disturbances and accurately track reference frequencies under various load conditions. During the evaluation, the suggested Observer model's performance was compared to that of a Functional Observer, which operates without a conventional controller, and a Luenberger Observer. Various operating conditions were considered, and the evaluation was based on criteria such as settling time and maximum overshoots/undershoots. The proposed Observer here shows the robustness in terms of stability and consistency in performance.

Though the required parameters achieved are better than the other observers but the complexity of the system will be more as the system size increases. This is not considered in this paper.

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