Design Of Functional Observer Based Load Frequency Controller For Inter-Connected Power System

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Abstract— **This paper presents a novel peculiar functional observer based on quasi-decentralized load frequency control scheme for power systems. The quasi-decentralized functional observers are designed to implement any given state feedback controller based on functional observer theory. The designed functional observers are decoupled from each other to have a simpler structure when compared to the state observer based schemes. The proposed design method is based on the network topology and the proposed functional observer scheme is further applied to a complex nonlinear power system.**

Index Terms— **Functional Observer, Load Frequency Control, Luenberger observer.**

I. INTRODUCTION

With the growing complications on interconnected power systems, load frequency control (LFC) problem has modernized interest in recent years [1]–[4]. LFC is a scheme that keeps the frequency of a network within satisfactory limits regardless of the load variations by balancing the power consumption and production. Furthermore, it has competence to bring any deviations (i.e., tie-line power deviations) of the entire power exchange back to zero, amongst interconnected areas. In general, LFC is implemented on selected generation units. Each of the controllers generates a control signal to a prime-mover when the loads fluctuate to match the power supply and demand.Through an integral control action of the area control error (ACE), tie-line power deviations are also brought out to zero. Even though a number of solutions and schemes have been proposed and developed in the last decade, for LFC considering time delays in power systems see [1], [4] and [7], soft computing based LFC schemes which have attracted considerable attention are reported in [8]–[13]. Also linear control based LFC schemes are reported in [5] and [6], a sliding mode technique is presented in [3] and LFC based on a model reduction technique is presented in [2]. For other methods of LFC, see [14]–[16], and in [17] a survey of various control schemes can be found.

Literature of LFC is based on approximating all generators in a given area into a single generation unit. Furthermore, the power distribution network including various bus bars and transmission lines are all lumped into one single entity in the analysis and design of controllers. With growing complexity of power distribution, assumptions which loose the network topology may not be the correct representative of a complex power network. The present paper makes no such simplified assumptions thus presenting a quasi decentralized functional observer scheme to control the frequency and tie-line power of a multi-area interconnected power system. In one of the previous paper [18], two-area linear systems connected with a single tie-line model was considered and for the generation of control signals, the application of quasi-decentralized functional observer is considered. Based on this preliminary work in [18], this paper further develops the functional observer (FO) theory for the LFC of interconnected power networks of higher order. In the LFC signal generation process, only the estimate of the control signal is required. Also using a functional observer, it is more congruent to directly estimate the proper required signal than estimating all the individual states and then re-combining those individual state estimates to construct the desired control signal [22]. Actually we consider a quasi-decentralized functional observer to generate the control signal. The proposed quasi-decentralized functional observer based controllers have simpler structures. Furthermore, the functional observability requirement is less stringent than the state observability requirement see [19] and [20]. The rest of paper is organized as follows; Section II the power system dynamic modeling is presented. Section III focuses on functional observer algorithm and functional observer based LFC. A case study of a complex power system including a comparing study on functional and Luenberger observer is given in Section IV and followed by a conclusion in Section V.

II. Dynamic Modelling Of Two Area Inter-Connected System

The block diagram of a two area thermal power system for load frequency control [9]-[16] is shown in Fig.1.Consider the dynamic model of a linear two area LFC in state-space representation is given by

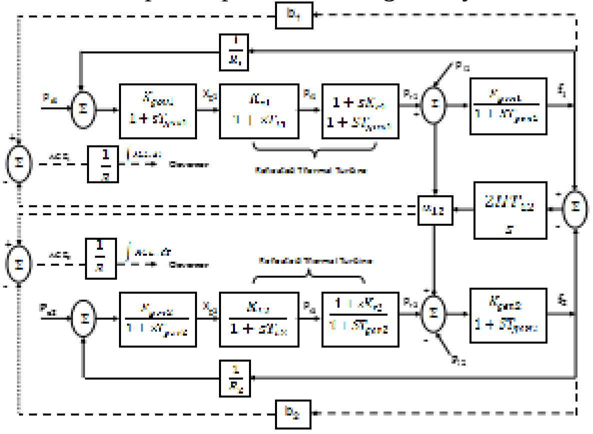

Figure.1.Block-diagram of two-area interconnected power system (TAIPS).

The state variable representation of the system is advantageous compared to the conventional transfer function representation. The state vector x(t) contains the information about the past behavior of the system and the future behavior which is governed by the ordinary differential equation (1). The properties of the system are determined by the constant matrices A, B and C. Thus the study of the system can be carried out in the field of matrix theory which has many notational and conceptual advantages.

In any control system, the input vector u(t) is chosen by proper control schemes such that the system behaves in an acceptable manner. As the state vector x(t) contains all the essential information about the system, the selection of u(t) is done using some combinations of x(t) and u(t) is obtained from the relation

$$u(t) = -K\,x(t) \tag{3}$$

In a simplified manner, the power flow in the tie line can be considered as for Area 2 in a two area system consisting of reheat thermal turbines.

$P_{tie2}(t) = -P_{tie2}(t)$ from Fig. 1.

Let $x_i(t)$,$u_i(t)$,$d_i(t)$ and $y_i(t)$ (i=1,2) as state, control, load disturbance and output vectors

Where

$x_1(t) = [P_{tie1}\ \ f_1\ \ P_{r1}\ \ P_{g1}\ \ X_{g1}\ ]^T$ (4)

$x_2(t) = [f_2\ \ P_{r2}\ \ P_{g2}\ \ X_{g2}\ ]^T$ (5)

$u_i(t) = P_{ci}(t)$, $d_i(t) = P_{li}(t)$ (6)

$y_i(t) = [P_{tiei}\ \ f_i\ \ X_g\ ]^T$ (7)

From this, the representation for the two area interconnected power system is determined for an eleventh-order, 2-input, 2-disturbance, where

$$\dot{x}(t) = Ax(t) + Bu(t) + D_d(t) \tag{8}$$

From (7), the controlled feedback variables are provided by the integral of ACE's to ensure zero steady state values for tie line power and frequencies for the step change in load disturbances. Pole placement or optimal control by state feedback has been extensively covered in the literature [1]-[3].

III. FUNCTIONAL OBSEVER

A Functional observer uses recurring theme in state feedback control, i.e., only a linear function is enough rather than the complete state vector information. The primary aim of the literature is to produce observer with more stability and further reduced order noticing the affect on the performance due to the change in design.

The result to this problem is firstly presented by Luenberger. It states that A single linear state function of a linear system can be reconstructed by an observer with v-1 eigen values that may be chosen arbitrarily (where v is the observability index). For any completely observable system, v-1<n-m, it is often the case that the order v-1 of a linear functional observer is less than the order n-m of the reduced-order observer. As a consequence, observing a linear function of the states may result in a significant reduction in observer order compared to the entire state vector.

Fig. 2 shows a block diagram representation of the QDFO implementation for LFC of a two area interconnected power system. The flow of information from one area to another area is represented by the dotted lines. The two FO's are decoupled from each other. Thus, there is no transfer of data between them.

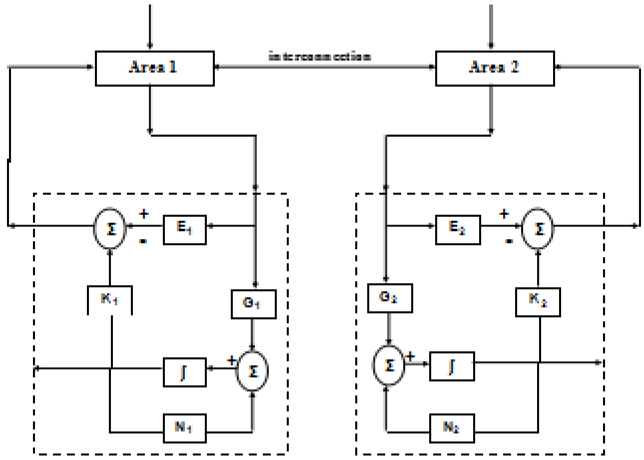

Figure. 2. Block diagram implementation of QDFO's for the two area interconnected power system.

A system involves many problems in decision making, monitoring, fault detection, and control which rely on the knowledge of state variables and time-varying parameters that cannot be measured directly. In such situations, the estimation of states and parameters in dynamic systems is a vital prerequisite. Hence observers that use the input and output signals can be employed to estimate the unknown states. Many estimation techniques are available for the construction of observers for linear models such as the Kalman filter and its variants.

However there is no generalized procedure for the design of estimators for nonlinear systems as it involves high computational costs. One such model which facilitates the stability analysis and observer design for such systems can be represented by a special type of a dynamic nonlinear model.[11].

special type of a dynamic nonlinear model.[11].

Consider a linear time-invariant system described by

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (9)$$

$$y(t) = Cx(t) \quad (10)$$

$$z(t) = Lx(t) \quad (11)$$

A functional observer is a dynamical system that can track z(t) asymptotically and has the following structure,

$$\dot{w}(t) = Nw(t) + Jy(t) + Hu(t) \quad (12)$$

$$\hat{z}(t) = Gw(t) + Ey(t) \quad (13)$$

The system matrices *A*, *B* and *C* and observer matrices *N*, *J*, *H*, *D* and *E* are defined as follows:

$A \in R^{nxn}$ $N \in R^{qxq}$

$B \in R^{nxm}$ $J \in R^{qxp}$

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

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

Theorem-1

The completely observable qth order functional observer of (12) and (13) will estimate Lx(t) if and only if the following conditions hold:

N is a stability matrix

JC = PA-NP (14)

H = PB (15)

L = DP + EC (16)

Now we will define the observer error in estimating the states as

$$e(t) \triangleq w(t) - Px(t) \quad (17)$$

If we take the derivative and substituting the observer and system equations, we obtain

$$\dot{e}(t) = \dot{w}(t) + P\dot{x}(t) = Nw(t) + JCx(t) + Hu(t) - PAx(t) - PBu(t) \quad (18)$$

Applying conditions (14) and (15) yields

$$\dot{e}(t) = Nw(t) + (PA - NP)x(t) + Bu(t) - PAx(t) - PBu(t)$$

$$= Nw(t) - NPx(t)$$

$$= Ne(t) \quad (19)$$

The differential equation solution is an exponential function of the form,

$$e(t) = e^{Nt} \quad (20)$$

On applying conditions, we get the result as,

$$\lim_{t \to \infty} e(t) = w(t) - Px(t) \quad (21)$$

on further simplification, we get

$$e_z(t) = \hat{z}(t) - Lx(t)$$

$$= Dw(t) - ECx(t) - Lx(t)$$

$$= D(w(t) - Px(t)) \quad (22)$$

As the above equation is expected to reach zero asymptotically, we can clearly say that A and N do not share a common eigen value and also ensuring P has unique solution. Now we can derive X and e by using above defined conditions

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

$$= Ax(t) + BDw(t) + BECx(t)$$

$$= Ax(t) + BDw(t) + B(L - DP)x(t)$$

$$= (A+BL)x(t) + (BD)e(t) \quad (23)$$

$$\dot{e}(t) = Ne(t) \quad (24)$$

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

$$\begin{bmatrix} \dot{x}(t) \\ \dot{e}(t) \end{bmatrix} = \begin{bmatrix} A+BL & BD \\ 0 & N \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} \quad (25)$$

Aside from the variation in notation and the fact that the control law is Lx(t) instead of -Kx(t), they are similar to each other. If we consider the constraints, the functional state reconstruction almost revolves around constructing the least possible rth order observer provided all the observer matrices must satisfy the conditions without compromising other favorable aspects of observer, such as freedom of eigen value assignment and algorithm simplicity, so that it can be readily implemented in practice.

To satisfy the conditions of order estimation, we take the ranks into consideration.

$$rank \begin{bmatrix} LA \\ CA \\ C \\ L \end{bmatrix} = rank \begin{bmatrix} CA \\ C \\ L \end{bmatrix} \quad (26)$$

$$rank \begin{bmatrix} sL - LA \\ C \\ L \end{bmatrix} = rank \begin{bmatrix} CA \\ C \\ L \end{bmatrix} \quad s \in C, R(s) \quad (27)$$

Whether, condition is satisfied when the ranks on the LHS and RHS are equal. The author in [21] shows that this condition is equal to the delectability of the pair (F, G), where

$$F = LAL^+ - LA(I - L^+L) \begin{bmatrix} CA(I - L^+L) \\ C(I - L^+L) \end{bmatrix}^+ \begin{bmatrix} CAL^+ \\ CL^+ \end{bmatrix} \quad (28)$$

$$G = \left(I - \begin{bmatrix} CA(I - L^+L) \\ C(I - L^+L) \end{bmatrix} \begin{bmatrix} CA(I - L^+L) \\ C(I - L^+L) \end{bmatrix}^+ \right) \begin{bmatrix} CAL^+ \\ CL^+ \end{bmatrix} \quad (29)$$

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 is given by

N=F–ZG (30)

where matrix Z is obtained by any pole placement method so that F -ZG is stable.

Matrices E and K are obtained according to

$$[E \quad K] = L\bar{A}\Sigma^+ + Z(I - \Sigma\Sigma^+) \quad (31)$$

where $\bar{A} = A(I - L^+L)$, $\bar{C} = C(I - L^+L)$

and $\Sigma = \begin{bmatrix} C\bar{A} \\ \bar{C} \end{bmatrix}$

and matrix J is obtained according to

J=K+NE (32)

Whilst matrix H is obtained according to

H=(L-EC)B (33)

By using this algorithm we can easily compute all the required observer parameters which results in a functional observer of the form

$$\dot{w}(t) = Nw(t) + Jy(t) + Hu(t) \quad (34)$$

$$\hat{z}(t) = w(t) + Ey(t) \quad (35)$$

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IV. RESULTS AND DISCUSSION

In order to verify the proposed technique, the results from the Matlab / Simulink are used for the increase in demand of the first area **Δ**PD1 and second area **Δ**PD2. In this condition, for which perturbation is applied to both the areas. In this case, a step change is applied to both the first area **Δ**PD1 and the second area **Δ**PD2. The frequency variation of the first area **Δ**f1 is shown in Figs. 3–8, using the method employed, the changes in frequency are quickly nullified to zero. Hence, QDFO are superior to Luenberger observer as it has the best performance in control and damping of frequency in all responses.

The performance for the above cases is shown tabulated at a particular operating condition and shown in Table 1. In this study, settling time, overshoot and undershoot are obatained for different operating points by calculation. The results from the simulation are shown for 10% band of step load change for the operating point of Appendix A. From the Table 1, it is found that the performance of the proposed QDFO is far superior to the Luenberger observer

Table 1: Δf_1 response performance in various control strategies

Operating point	Controller	Over shoot (P.U)	Under shoot (P.U)	Setting time (sec)
1	Full order Luenberger Observer	0.05211	-0.06554	5.213
	Quasi Decentralized Functional Observer	0.04539	-0.06088	5.111
2	Full order Luenberger Observer	0.09419	-0.09907	4.994
	Quasi Decentralized Functional Observer	0.06718	-0.0868	4.796
3	Full order Luenberger Observer	0.03961	-0.05186	6.369
	Quasi Decentralized Functional Observer	0.03681	-0.4921	6.251
4	Full order Luenberger Observer	0.09231	-0.09644	6.321
	Quasi Decentralized Functional Observer	0.06	-0.07916	5.051
5	Full order Luenberger Observer	0.0414	-0.05384	6.309
	Quasi Decentralized Functional Observer	0.03804	-0.05119	6.126
6	Full order Luenberger Observer	0.06955	-0.08092	5.154
	Quasi Decentralized Functional Observer	0.0551	-0.07296	5.088

In Fig.3 to Fig.8 are the comparison of **Δ**f_1 (t) responses for various observers in terms of nominal values. The simulation results show that the proposed method QDFO is robust to change in the parameter of the system and has good performance as compared to Luenberger observer in all of the operating conditions.

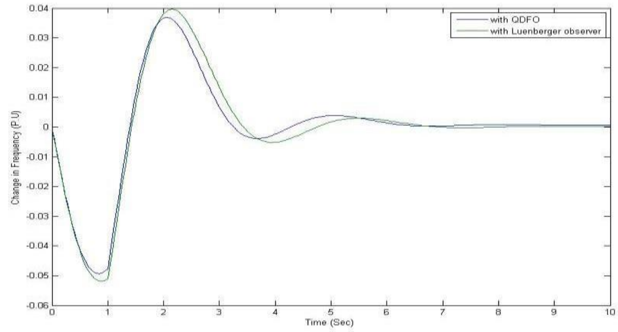

Figure. 3.Change in frequency with step increase in demand at operating point 1.

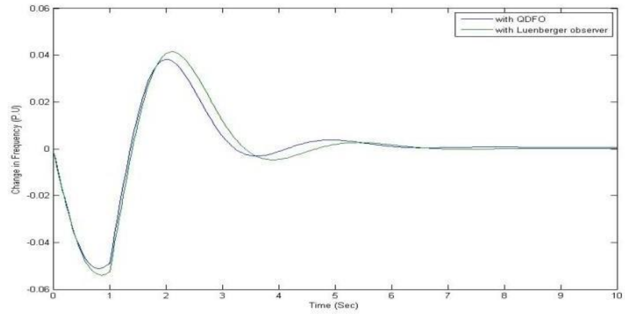

Figure.4. Change in frequency with step increase in demand at operating point 2.

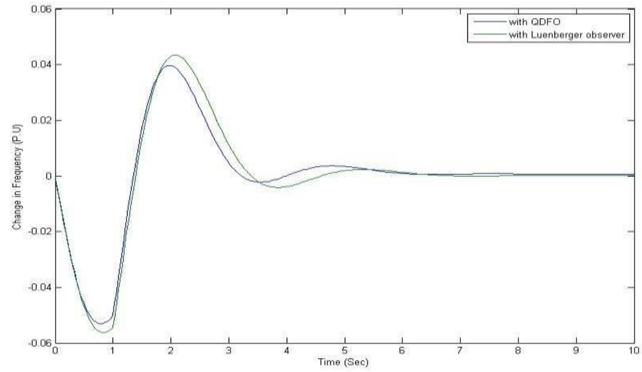

Figure. 5. Change in frequency with step increase in demand at operating point 3.

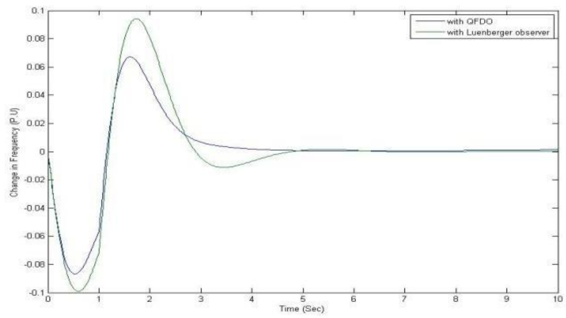

Figure. 6. Change in frequency with step increase in demandat operating point 4.

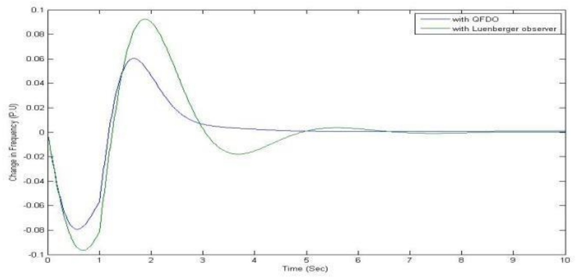

Figure. 7.Change in frequency with step increase in demand at operating point 5.

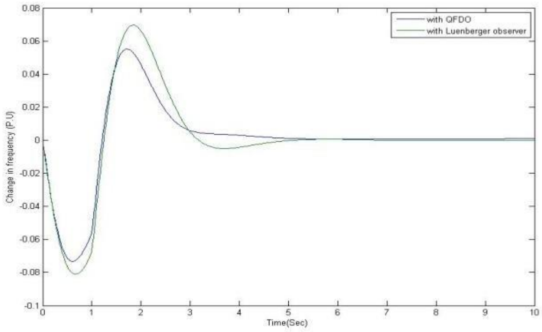

Figure. 8. Change in frequency with step increase in demand at operating point6.

V. CONCLUSIONS

In this paper, the solution of a load frequency control problem is obtained by using QDFO for a multi-area power system. The two area interconnected reheat thermal power system with system parameter uncertainty is chosen for the testing of the proposed observer. The results from the simulation shows that the designed observer guarantees the robust stability and performance. The proposed method is used to test the precise reference frequency tracking and disturbance attenuation under a wide range of parameter uncertainty and varying load conditions. To find the robustness of the proposed observer, it is compared with Luenberger observer in terms of settling time, maximum overshoot and undershoots under different operating conditions.

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